2. Wake and Weather Information Systems for Aerodromes

2.1 Prediction of Dynamic Pairwise Wake Vortex Separations for Approach and Landing

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Design and performance of the Wake Vortex Prediction and Monitoring System WSVBS are described. The WSVBS has been developed to tactically increase airport capacity for approach and landing on single runways as well as closely-spaced parallel runways. It is thought to dynamically adjust aircraft separations dependent on weather conditions and the resulting wake vortex behavior without compromis>ing safety. Dedicated meteorological instrumentation and short-term numerical terminal weather prediction provide the input to the prediction of wake-vortex behavior and respective safety areas. LIDAR monitors the correctness of WSVBS predictions in the most critical gates at low altitude. The WSVBS is integrated in the arrival manager AMAN of DLR. Performance tests of the WSVBS have been accomplished at Frankfurt airport in winter 2006/07 and at Munich Airport in summer 2010. Aircraft separations for landings on single runways have been compared employing the concepts of either heavy-medium weight class combinations or dynamic pairwise separations where individual aircraft type pairings are considered. For the very conservative baseline setup of the WSVBS the potential capacity gains of dynamic pairwise operations for single runways appear to be very small. On the other hand, the consideration of individual aircraft types and their respective wake characteristics may almost double the fraction of time when radar separation could be applied.

Introduction

Aircraft trailing vortices may pose a potential risk to following aircraft. The empirically motivated separation standards between consecutive aircraft which were introduced in the 1970s still apply. These aircraft separations limit the capacity of congested airports in a rapidly growing aeronautical environment. The most likely growth scenario within a Eurocontrol study (Euurocontrol 2008) indicates that in the year 2030 airport capacity will lag demand by some 2.3 million IFR flights. This is opposed by an estimate of annual savings of US $ 15 million per year and airport that could be achieved by the introduction of a wake-vortex advisory system (Hemm et al. 1999). A survey on wake-vortex advisory systems and modifications of procedures that are meant to increase airport capacity is available in Elsenaar et al. 2006.

DLR has developed the Wake Vortex Prediction and Monitoring System (WirbelSchleppen-Vorhersage-und -BeobachtungsSystem WSVBS, Gerz et al. 2005, Gerz et al. 2009, Holzäpfel et al. 2009-1) to tactically increase airport capacity for approach and landing. The WSVBS is thought to dynamically adjust aircraft separations dependent on weather conditions and the resulting wake vortex behavior without compromising safety. For this purpose it predicts wake vortex transport and decay and the resulting safety areas along the glide slope from final approach fix to threshold. The design of the WSVBS for closely-spaced parallel runways systems has been described in detail in Holzäpfel et al. 2009-1. During a performance test at Frankfurt airport in winter 06/07 capacity-improving wake-vortex separation concepts of operation could have been used in 75% of the time and continuously applied for at least several tens of minutes (Gerz et al. 2009). It was found that the system ran stable and the predicted minimum separation times were totally confirmed by Lidar measurements of wake vortex transport. From fast-time simulations the eventual capacity gain for Frankfurt was estimated to be 3% taking into account the real traffic mix and operational constraints in the period of one month.

Initially, the system has been particularly adapted to the closely-spaced parallel runway system of Frankfurt airport. Meanwhile the WSVBS has been further developed to predict dynamic pairwise separations for landings on single runways. The concept of dynamic pairwise separations corresponds to the favoured procedure foreseen in the final development stage of NextGen (Lang 2010, FAA 2011) and SESAR (SESAR 2010, Steen et al. 2010). The elements of the WSVBS are generic and can well be adjusted to other runway systems and airport locations.

This paper, which has been presented previously (Holzäpfel et al. 2011) describes the design of the WSVBS with all its components and their interaction and the extension of the WSVBS to the prediction of dynamic and time-based separations for individual aircraft type pairings landing on single runways. The performance of the dynamic pairwise separations setup is analysed employing data gathered during a three-month measurement campaign at Frankfurt Airport in winter 2006/07 and another three-month measurement campaign accomplished at Munich Airport in summer 2010. The baseline setup of the WSVBS for dynamic pairwise separations is compared to a number of alternative setups. This analysis evaluates which capacity gain could be achieved theoretically with the dynamic pairwise separations concept and how much this theoretical maximum is reduced by conservative uncertainty allowances of the components of the WSVBS that consider statistical variations of aircraft flight tracks, meteorological parameters, wake vortex behavior, and resulting safety areas.

System Overview and Topology

Figure 1 delineates the components of the WSVBS and their interplay. The bottleneck of runway systems prevails in ground proximity because there stalling or rebounding wake vortices may not descend below the flight corridor. Therefore, in that domain the best wake prediction skill is required which here is achieved based on measurements of meteorological conditions with a SODAR/RASS system and an ultrasonic anemometer (USA).

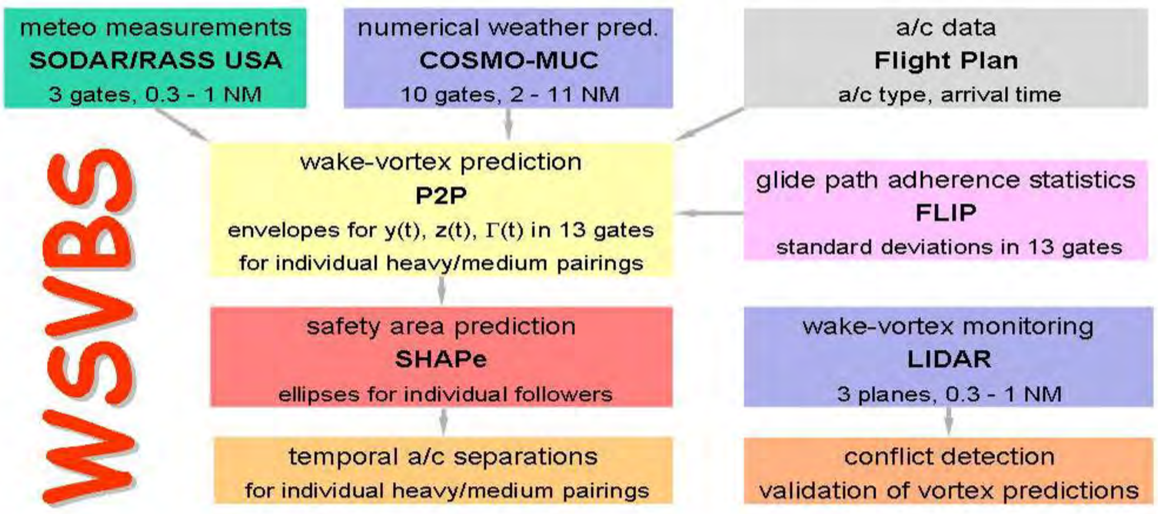

Figure 1. Flowchart of the WSVBS.

Because it is not possible to cover the whole glide slope with such instrumentation, the meteorological conditions in the remaining area are predicted with a numerical weather prediction system (COSMO-MUC) leading to wake predictions with increased uncertainty bounds. Based on glide path adherence statistics (FLIP) the probabilistic wake vortex model P2P predicts upper and lower bounds for position and strength of vortices generated by heavy aircraft. These bounds are expanded by the safety area around a vortex that must be avoided by follower aircraft for safe and undisturbed flight (SHAPe). Wake vortex and safety area predictions can be conducted optionally based upon either weight class combinations (heavy/medium) or individual aircraft type pairings according to the flight plan. The instant when the safety areas do not overlap with the flight corridor define the temporal separation between an individual aircraft pairing. The LIDAR monitors the correctness of WSVBS predictions in the most critical gates at low altitude. The components of the WSVBS will be described in detail later, together with their respective references.

The WSBVS concept requires that all aircraft are established on the glide slope at the final approach fix (FAF) which is situated 11 NM before the touchdown zone (TDZ). The wake-vortex evolution is predicted within 13 gates along the final approach. In ground proximity the gate separation of 1 NM is reduced to 1/3 NM to properly resolve the interaction of wake vortices with the ground. Figure 2 delineates the runway with the employed geodetic coordinate system and the gates 10 -13 next to the ground.

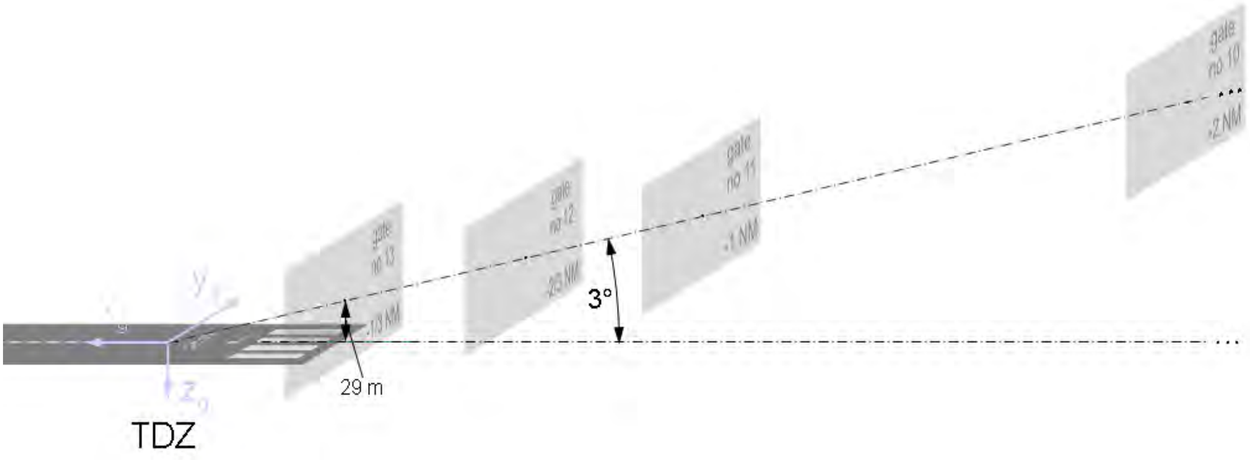

Figure 2. Zoom on gates 10 to 13.

System Components

It is planned to adjust the different system components to consistent probability levels such that the WSVBS will meet accepted risk probabilities as a whole. Since a comprehensive risk assessment of the WSVBS is still pending, we currently employ by default 95.4% probabilities (two standard deviations, 2σ, for Gaussian distributions) as a basis for the probabilistic components of the WSVBS. In the following the components delineated in the flowchart of Figure 1 are described in detail.

Meteorological Data

For prediction of wake-vortex behavior along the final approach path meteorological conditions with good accuracy must be provided for the complete considered airspace with a forecast horizon of 1 hour. A combination of measurements (employing the persistence assumption) and numerical weather predictions accounts for the required temporal and spatial coverage.

For approach and landing the largest probability to encounter wake vortices prevails at altitudes below 300 ft (Critchly & Foot 1991, Holzäpfel et al. 2009-2, Elsenaar et al. 2006). There, stalling or rebounding vortices may not clear the flight corridor vertically and weak crosswinds may be compensated by vortex-induced lateral transport which may prevent the vortices to quit laterally. Since vortex decay close to the ground is not very sensible to meteorological conditions (Holzäpfel & Steen 2007), the most important mechanism that may allow for reduced aircraft separations is lateral transport of wake vortices by crosswind.

Frech & Holzäpfel (2008) demonstrates that the best wake-vortex prediction skill of lateral transport in ground proximity is achieved employing SODAR wind measurement data. Only if it is assumed that the measured wind would persist longer than about one hour, the lateral vortex transport predicted with input from numerical weather prediction would yield on average superior results. Because it is not feasible to cover the complete final approach path with instrumentation we employ SODAR/RASS data for wake prediction in the bottleneck at low altitudes (gates 11 – 13) whereas for the less critical area aloft (gates 1 – 10) we use COSMO-MUC data which yields minor wake prediction skill.

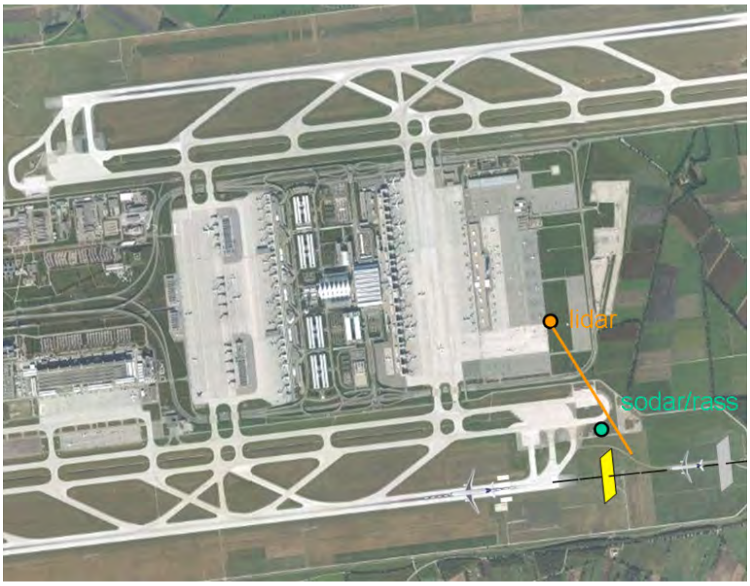

Figure 3. Sketch of instrumentation set-up at Munich Airport.

Figure 3 shows runway 26L of Munich airport with the locations of the employed sensors and the two lowest gates for the prediction of wake vortex behavior. Close to the lowest gate (yellow) a METEK SODAR with a RASS extension provides 10-minute averages of vertical profiles of the three wind components, vertical fluctuation velocity, and virtual temperature with a vertical resolution of 20 m. The SODAR/RASS system is complemented by an ultrasonic anemometer (USA) mounted on a 10 m mast. Eddy dissipation rate (EDR) profiles are derived from vertical fluctuation velocity and the vertical wind gradient employing a simplified budget equation (Frech 2004). A spectral analysis of the longitudinal velocity measured by the sonic is used to estimate EDR by fitting the -5/3 slope in the inertial sub-range of the velocity frequency spectrum.

For the area which was not covered by measurements (the more remote 10 gates from 2 to 11 NM) numerical weather predictions were conducted with the model COSMO-MUC (Dengler et al. 2009, see Section 2.5).

Approach Corridor Dimensions

For the definition of approach corridor dimensions we employ as baseline the glide path adherence statistics of the FLIP study (Frauenkron et al. 2001), an investigation of the navigational performance of ILS (Instrument Landing System) approaches at Frankfurt airport. FLIP provides statistics of 35,691 tracks of precision approaches on Frankfurt ILS of runways 25L/R. It does not differentiate between manual and automatic approaches. The study indicates that the measured flight path deviations are much smaller than specified by ICAO localizer and glide slope tolerances. The employed corridor dimensions decrease monotonically when approaching the runways and are kept constant within a distance of 2 NM from TDZ (see Figure 4).

Investigations of arrival flight track data at the airports St. Louis (Hall & Soares 2008), Atlanta (3,394 approaches, Zhang et al. 2009), and Chicago (1,112 approaches, Zhang et al. 2009) indicate that the lateral aircraft deviations below a distance of 2 NM from TDZ are significantly smaller than assumed in the FLIP study (see Figure 4). Therefore, we alternatively apply a fit to the to the lateral RMS deviations found in the studies of Hall & Soares and Zhang et al. which is effective at distances from the TDZ below 3.3 NM and retain the FLIP statistics for larger distances:

$$\begin{aligned}\sigma_{y,fit} &= 2.76\,\mathrm{m} + 3.85\,\mathrm{m/NM}\cdot x[\mathrm{NM}]; \quad x < 3.3\,\mathrm{NM}\\ \sigma_{y,FLIP} &= 11.5\,\mathrm{m} + 1.23\,\mathrm{m/NM}\cdot x[\mathrm{NM}]; \quad x \geq 3.3\,\mathrm{NM}\end{aligned}$$

The approach corridors in the different gates consist of ellipses (see green ellipse in Figure 7). Vertical and horizontal semi axes of these ellipses correspond to two standard deviations derived from glide path adherence statistics, respectively. For Gaussian distributions two standard deviations (2σ) correspond to a probability of 95.4% that an aircraft does not leave the corridor in one dimension (either laterally or vertically). For ellipsoidal corridors this probability reduces to 86.5% assuming statistical independence of lateral and vertical positions.

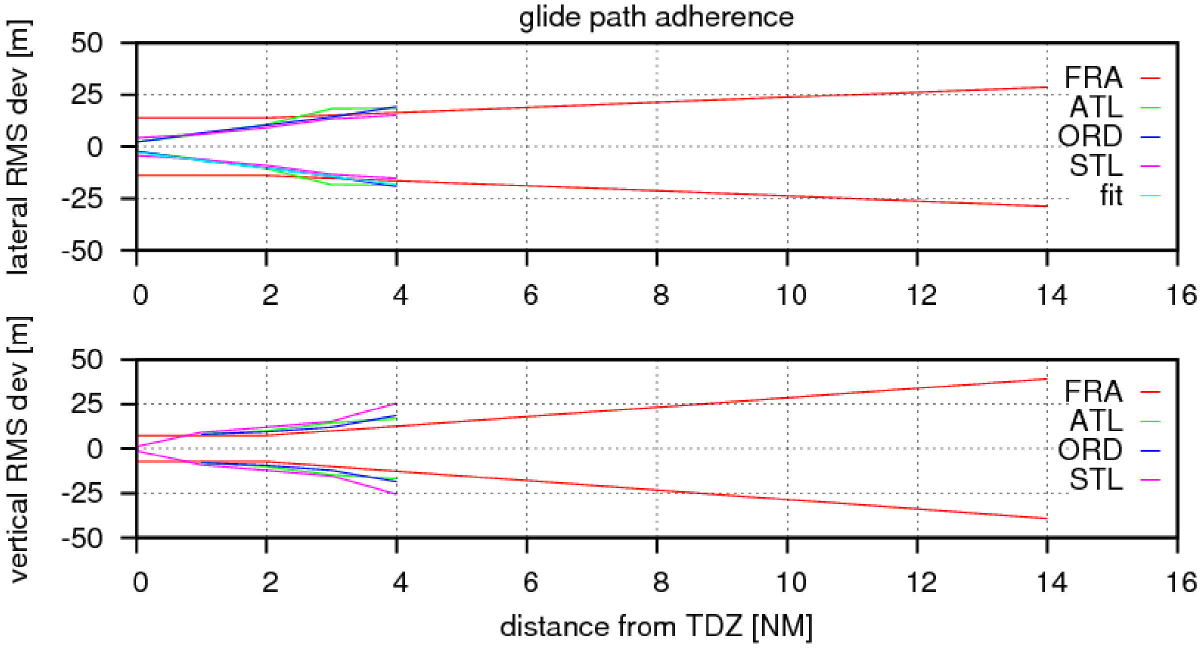

Figure 4. Lateral and vertical RMS deviations of aircraft from the glide path at the airports FRA, ATL, ORD, and STL.

Representation of Aircraft Types

The latest version of the WSVBS also predicts conservative separations for individual aircraft pairings as it is foreseen in the final development stages of NextGen and SESAR. This approach requires that the approaching aircraft types are known. During the Munich campaign the WSVBS provided predictions for all heavy leader and medium follower aircraft types that were scheduled to land within the same five minute interval according to the flight plan. So far the WSVBS may predict separations between the following individual heavy leader aircraft types (aircraft designators according to ICAO): A306, A310, A332, A333, A343, A346, B744, B762, B763, B764, B772, B773, B77W, IL96, MD11 and the medium follower aircraft types A319, A320, A321, AT43, AT45, AT72, B462 , B463, B712, B733, B734, B735, B736, B737, B738, B752, B753, CRJ1, CRJ2, CRJ7, CRJ9, D328, DH8D, E145, E170, E190, F100, F70, MD82, MD83, RJ1H, RJ85, SB20, SF34.

For each generator aircraft type the envelopes for wake vortex behavior are predicted assuming a maximum and a minimum initial circulation value that could occur during approach and landing. The minimum circulation assumes an aircraft weight corresponding to the operational empty weight (OEW) plus the fuel weight for one hour of flight plus the weight of 10% of the maximum amount of passengers combined with the flight speed at the final approach fix (FAF) of about 200 kts (103 m/s). The maximum circulation is based upon maximum landing weight (MLW) and a landing speed of 70 m/s (136 kts).

In order to keep the system as simple as possible and, thus, to minimize additional workload for controllers, the WSVBS may alternatively consider aircraft weight class combinations. The relevant combinations are heavy followed by heavy (HH) and heavy followed by medium (HM) aircraft. Conservative measures for initial circulation, wing span, and final approach speed as function of the maximum take-off weight are taken to characterize the classes (Holzäpfel et al. 2009-1).

Wake-Vortex Prediction

Wake-vortex prediction is conducted with the Probabilistic Two-Phase wake-vortex decay model (P2P) which is described in detail in Holzäpfel (2003). Applications, assessments and further developments are reported in Frech & Holzäpfel 2008, Holzäpfel & Robins 2004, Holzäpfel 2006, and Holzäpfel & Steen 2007. P2P 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 ground proximity. P2P has been validated against data of over 10,000 cases gathered in two US and six European measurement campaigns.

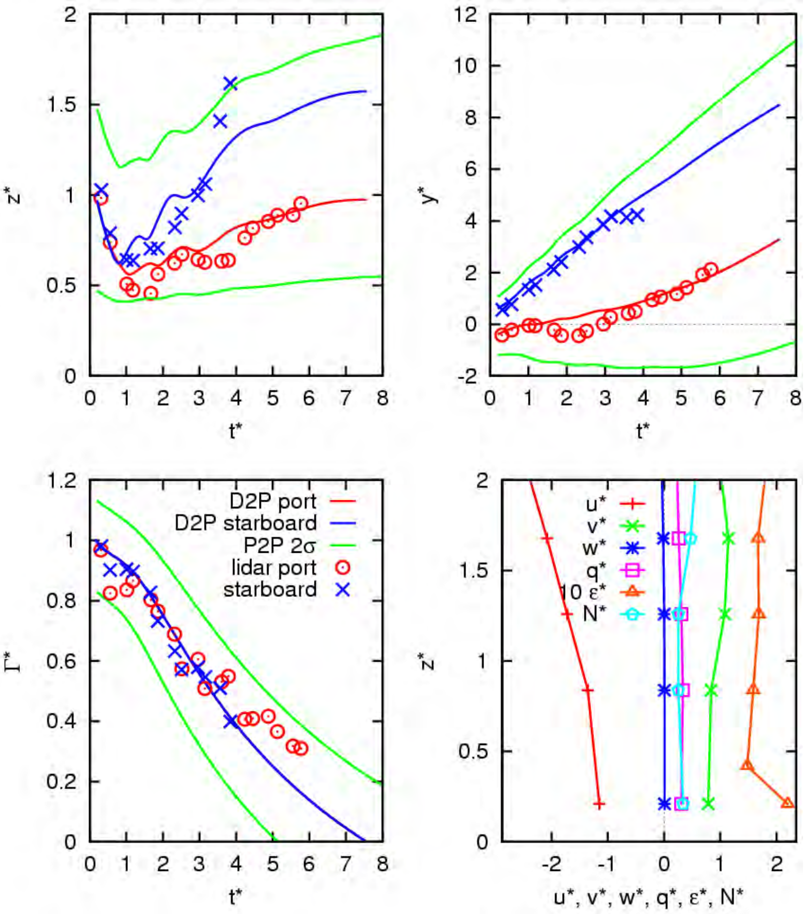

Figure 5. Evolution of normalized vertical and lateral positions and circulation of wake vortices in ground proximity. Measurements by lidar (symbols) and predictions with the P2P wake vortex model (lines). Red and blue lines denote deterministic behavior; green lines are probabilistic envelopes (95.4%). Right below vertical profiles of measured meteorological parameters. Normalizations based on initial values of vortex spacing, circulation, and time needed to descend one vortex spacing.

Precise deterministic wake vortex predictions are not feasible operationally. Primarily, it is the nature of turbulence that deforms and transports the vortices in a stochastic way and leads to considerable spatiotemporal variations of vortex position and strength. Moreover, the variability of environmental conditions must be taken into account. Therefore, the output of P2P consists of confidence intervals for vortex position and strength. Figure 5 illustrates asymmetric vortex rebound characteristics caused by crosswind in ground proximity.

For the time being, the confidence intervals for y, z, and Γ are adjusted by default to 2σ-probabilities. The respective uncertainty allowances are achieved by a training procedure which employs statistics of measured and predicted wake vortex behavior (Holzäpfel 2006). Note that the training procedure implicitly considers the quality of the meteorological input data. As a consequence, uncertainty allowances of wake-vortex predictions based on the high-quality SODAR/RASS measurements in the lowest three gates are smaller than uncertainty allowances applied to wake-predictions at higher altitudes which are based on COSMO-MUC input.

Safety-Area Prediction

Once the potential positions of the wake vortices at each gate are known, safe distances between wake vortex core positions and the follower aircraft need to be assigned. The Simplified Hazard Area (SHA) concept (Hahn et al. 2004, Schwarz & Hahn 2006) predicts distances which guarantee safe and undisturbed operations. The SHA-concept assumes that for encounters during approach and landing the vortex induced rolling moment constitutes the dominant effect and can be used to define a safety area representing the entire aircraft reaction. Then encounter severity can be characterized by a single parameter, the required Roll Control Ratio, RCR_{req}, which relates the wake vortex induced rolling moment to the maximum available roll control power.

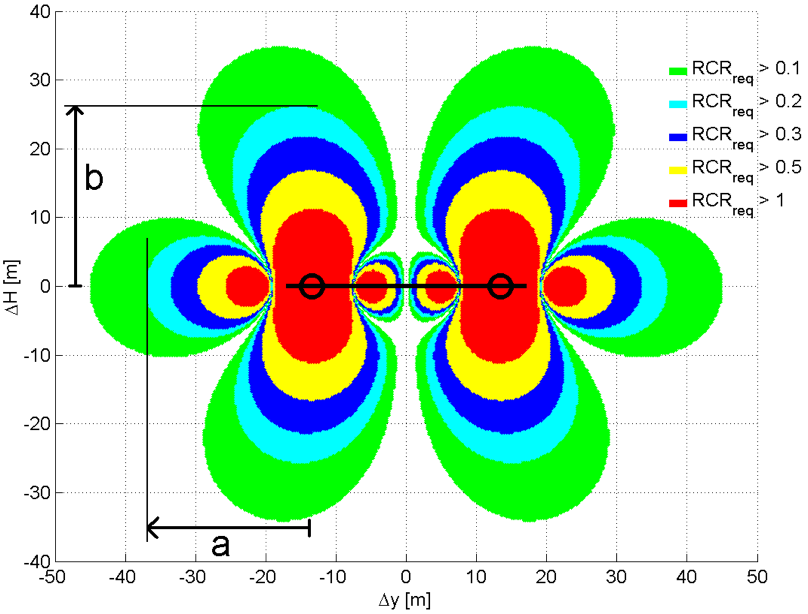

Figure 6. Roll control power required to compensate wake-vortex induced rolling moments. Horizontal and vertical allowances a and b for $RCR_{req} < 0.2$.

In Figure 6 the red areas with $RCR_{req} > 1$ denote regions where the roll control capability of the encountering aircraft is exceeded. Full flight simulator investigations (Schwarz & Hahn 2006) yield acceptable results for manual control for a value of $RCR_{req} = 0.2$. Results from real flight tests, using DLR's fly-by-wire in-flight simulator ATTAS, support this conclusion (Schwarz & Hahn 2005). In Figure 6 the lines a and b denote the resulting distances between vortex centres and follower aircraft for $RCR_{req} < 0.2$ which are added to the wake vortex envelopes.

As for wake vortex prediction either individual wake vortex and follower aircraft pairings are considered or wake vortex envelopes representing the heavy category combined with the follower categories medium or heavy. In order to represent the follower aircraft weight classes heavy and medium all relevant aircraft parameters (wing span, wing area, airspeed, lift gradient, maximum roll control power, and taper ratio) are conservatively combined to mimic the worst case scenarios. The values of the worst case parameter combinations are again derived from envelopes of aircraft parameters as function of MTOW, similarly as it was described for the wake vortex predictor before. This method of using MTOW based aircraft parameters for the determination of simplified hazard areas is called SHAPe (Simplified Hazard Area Prediction, Hahn et al. 2004).

System Integration

Here we describe how the above introduced components are combined for the prediction of adapted aircraft separations. First components within a single gate are considered. Then it is explained how the minimum temporal aircraft separations are derived from the predictions within all the gates. Finally, the temporal prediction cycle which defines parameters like update rate and prediction horizon is sketched.

Figure 7 illustrates the process seen in flight direction in control gate 11 for a heavy leader aircraft and a vortex age of 100 s. The different ellipses are defined by the respective sums of vertical and horizontal probabilistic allowances of the components approach corridor, vortex area prediction, and safety area prediction. Note that horizontal and vertical dimensions in Figure 7 are in scale. The dark blue corridor of possible vortex positions indicates that superimposed to vortex descent a southerly cross-wind advects the wake away from runway 26L.

Because the lateral vortex position can only be predicted less precisely (uncertainty and variability of crosswind) than vertical position, the aspect ratio of the vortex area ellipse exceeds a value of eight. Out of ground effect this aspect ratio is much smaller because there uncertainties regarding vortex descent are increased (Holzäpfel & Steen 2007). Safety area margins for large and small follower aircraft are added to the vortex corridors, resulting in overall safety areas to be avoided. One important aspect is that the safety corridors are not static but move depending on wake transport. Further, they grow due to vortex spreading and shrink according to wake decay.

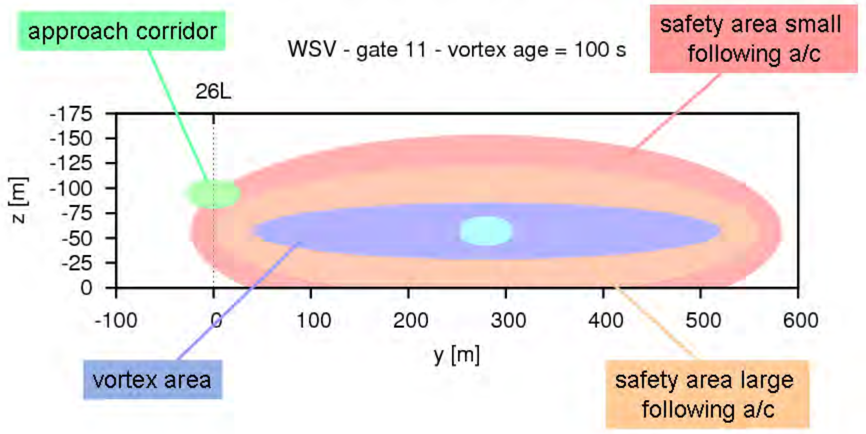

Figure 7. Ellipses denoting approach corridor dimensions, vortex areas, and safety areas in gate 11 for a vortex age of 100 s and runway 26L.

For aircraft pairings on approach to the same runway, the time interval between the passage of the generator aircraft through a gate and the time when a safety area does no longer overlap with the approach corridor (gate obstruction time) determines the minimum temporal separation for that gate. For a closely-spaced parallel runway system, the question is whether the safety areas reach the neighboring approach corridor within the prediction horizons or not. Our example in Figure 7 illustrates that after 100 s the safety area for a large following aircraft has just left the approach corridor, yet the gate is blocked for a small follower aircraft, because the respective safety corridor still overlaps with the approach corridor.

One prediction sequence comprises 13 gates along the glide path. The cases with maximum vortex ages with conflicts (gate obstruction times) define minimum aircraft separation times, MST. For dynamic pairwise landings on a single runway the predicted MST have the following format:

31-Aug-2010 Tue 1345 A343 AT72 81
31-Aug-2010 Tue 1320 A332 B738 89
31-Aug-2010 Tue 1320 A332 D328 96
31-Aug-2010 Tue 1320 A332 A320 89

Date, scheduled landing time, leader aircraft type, follower aircraft type, and predicted aircraft separation time in seconds. In the time frame from 13:20 to 13:25 a heavy A332 and three medium follower aircraft types are scheduled to land such that three individual separation times are suggested. Every 10 minutes new SODAR/RASS and COSMO-MUC data are available. When new weather data is available WSVBS predictions are initiated. The predictions are available 20 min prior to landing. The predictions could also be provided for longer lead times at the expense that the uncertainty allowances of the wake vortex corridors in gates 11-13 driven by SODAR/RASS meteorological input data would need to be increased. Wake-vortex monitoring is used to identify potential erroneous predictions of the WSVBS. For this purpose DLR's 2 µm pulsed Doppler LIDAR is operated in vertical scan mode with elevations between -0.5° to 6° to detect and track the vortices alternately in the lowest and most critical gate (see Figure 3).

Performance and Improved Capacity

The baseline setup of the WSVBS for pairwise dynamic separations is compared to a number of alternative setups listed in Table 1. This analysis may contribute to set the scene for a discussion which capacity gain could be achieved theoretically with the pairwise dynamic separations concept and how much this theoretical maximum is reduced by conservative uncertainty allowances of the components of the

WSVBS that consider statistical variations of aircraft flight path, meteorological parameters, wake vortex behavior, and resulting safety areas.

The analysis is based on the field campaign data gathered from 23 June 2010 to 8 September 2010 at Munich airport. In that time frame WSVBS predictions for 7300 landings of individual leading heavy aircraft and medium type follower aircraft on runway 26L have been conducted. The investigated scenarios are listed in Table 1. Setup 1 denotes the baseline scenario of the WSVBS where the uncertainty allowances of the approach corridor dimensions and probabilistic wake vortex predictions are set to 2σ (95.4%). Setup 2 neglects the safety area (SHAPe) and herewith investigates the contribution of the safety area on the potential capacity gain. Setup 3 assumes long-lived vortices (llv) by delaying the onset of rapid vortex decay by one time unit $t_0 = b_0 / w_o$ where b_0 denotes the initial wake vortex separation and w_0 the initial wake vortex descent speed. Setups 4 and 5 assume perfect (deterministic) wake vortex prediction capabilities where the uncertainty allowances of wake vortex behavior can be neglected without or with safety areas, respectively. These scenarios can also be considered as a reference for the potential capacity gain that could be achieved if the real wake vortex behavior would be perfectly known. Setups 1 – 5 always assume the same approach corridor dimensions. Setups 6 and 7 now consistently vary the uncertainty allowances of all probabilistic components between 1σ (68.3%) and 3σ (99.7%). These setups may provide an indication of the bandwidth of reasonable uncertainty allowances. Finally, setup 8 corresponds to the baseline setup 1 but employs the reduced lateral the flight corridor width (rw) at distances below 3.3 NM to the TDZ (gates 9 -13).

Table 1. Survey on investigated scenarios.

setup	1	2	3	4	5	6	7	8
approach corridor	2σ	2σ	2σ	2σ	2σ	1σ	3σ	2σ rw
wake-vortex prediction	2σ	2σ	2σ llv	0σ	0σ	1σ	3σ	2σ
safety area	yes	no	yes	no	yes	yes	yes	yes

Table 2 lists the average minimum separation times (MST) in which pairwise separations for landings on single runways could have been reduced either below ICAO separation (125 s) or radar separation (70 s) and their respective frequency of use. For the standard setup of the WSVBS in only 1.1% (4.0%) of the time the aircraft separations could have been reduced below radar (ICAO) separation. Setup 2 indicates that the consideration of a safety area around the vortex centers, which guarantees safe and undisturbed flight, noticeably reduces the potential capacity gain. However, even with neglected safety areas the frequency of use of 2.6% for radar separation still is small. The comparison of setups 1 and 3 indicates that the increased lifetimes of the vortices in setup 3 have only a minor effect on the frequency of use of the WSVBS because mainly vortex transport out of the approach corridor (and not vortex decay) enables reduced separations.

Table 2. Minimum separation times (MST) and frequency of use for different scenarios.

setup	1		2		3		4		5		6		7		8	
MST below [s]	70	125	70	125	70	125	70	125	70	125	70	125	70	125	70	125
average MST [s]	59	87	53	80	60	87	50	82	52	93	53	87	-	-	56	83
frequency of use [%]	1.1	4.0	2.6	6.7	1.0	3.8	16.2	49.3	6.2	38.1	7.4	34.1	0.0	0.0	1.6	4.7

Notably, even deterministic wake vortex predictions and the neglect of safety areas in setup 4 only allow for 16.2% (49.3%) reductions of aircraft separations below radar (ICAO) separation. This is that at radar separation the vortices have not left the approach corridor in at least one of the considered gates in more than 80% of the cases. Setup 5 employs deterministic wake vortex prediction and considers the safety areas. So even if the meteorological input data and the resulting wake vortex predictions would be perfect, reductions of aircraft separations below radar (ICAO) separation could safely be achieved only in 6.2% (38.1%).

Setup 6, employing 1σ-uncertainty allowances for both aircraft and wake corridors, indicates that also the approach corridor dimensions play an important role. The fraction of time for radar separations or less is with 7.4% even slightly higher than the 6.2% achieved with deterministic wake vortex predictions combined with 2σ-approach corridor dimensions (setup 5). On the other hand, setup 7 employing 3σ-uncertainty allowances is obviously far too conservative. Setup 7 would allow in only one case out of 7300 to reduce aircraft separations to 128 s. Finally, setup 8 confirms the relatively large impact of the flight corridor dimensions on the achievable reductions of aircraft separations: the reduced lateral flight corridor widths in the lowest gates may increase the fraction of radar separation by almost 50% compared to the baseline setup 1.

Figure 8 delineates the history of arrivals for which dynamic pairwise aircraft separations could have been reduced either below ICAO separation (125 s) or radar separation (70 s) for the baseline case (setup 1, above) and the deterministic wake vortex predictions without safety areas (setup 4, below). Additionally, predicted aircraft separations below 180 s are shown. The small fraction of 7% of the arrivals in which aircraft separations could have been reduced below 180 s indicates one more time that the baseline setup 1 of the WSVBS is designed very conservatively. In contrast, for the non-conservative setup 4 the fraction of arrivals with reduced separations and the respective durations are significantly higher.

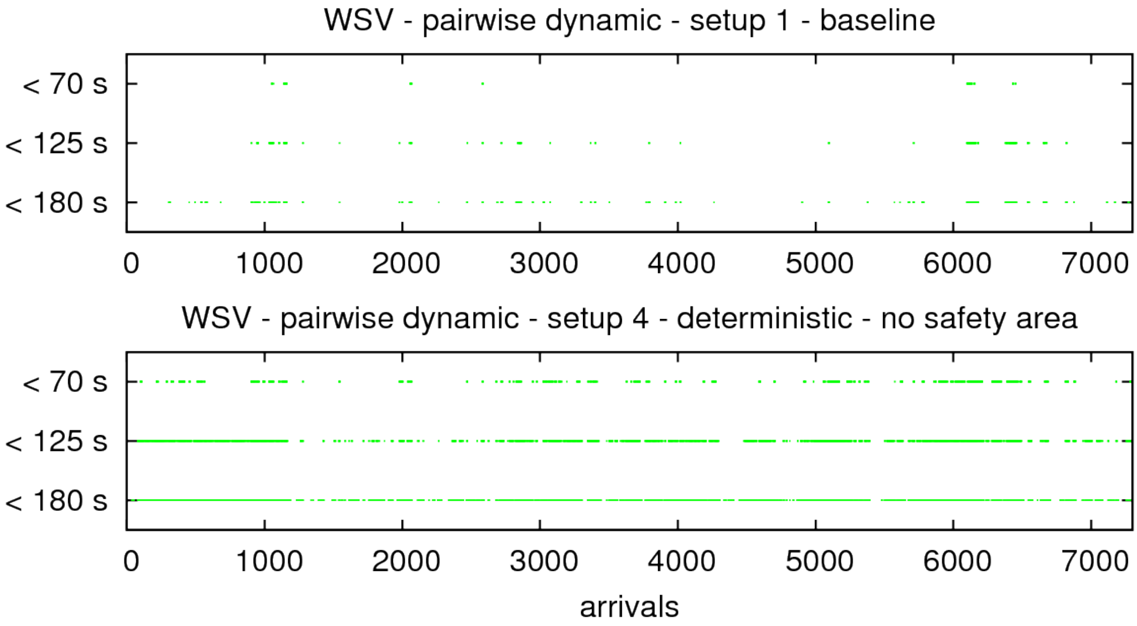

Figure 8. History of potential usage of dynamic pairwise separations for the 7300 arrivals during the Munich campaign.

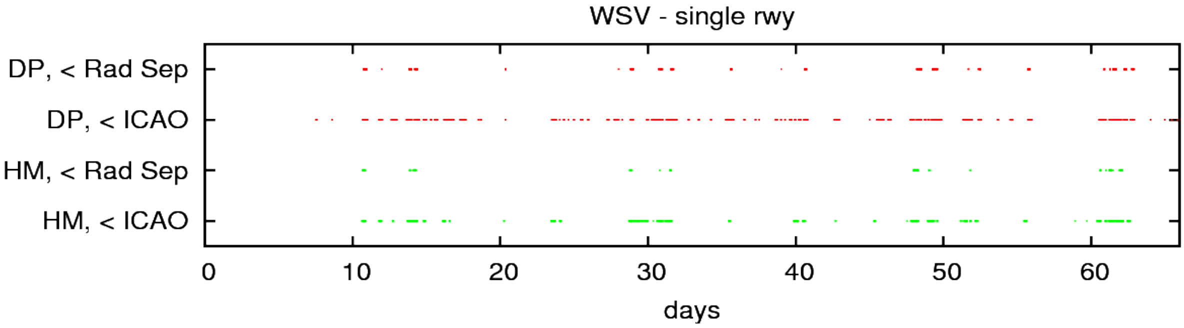

Figure 9. History of potential usage of ICAO separations or radar separations for heavy/medium aircraft weight class combinations (HM, green) or dynamic pairwise separations (DP, red) during the 66 days of the Frankfurt campaign. (From Gerz et al. 2009.)

A comparison of the potential benefits of dynamic pairwise separations and heavy/medium aircraft weight class based separations has been conducted employing the weather data gathered during the demonstration campaign of the WSVBS at Frankfurt airport in the year 06/07 (see Figure 9). For this purpose the Frankfurt traffic mix of a single representative day has been used. The fraction of time for radar separations is almost doubled from 1.5% for heavy/medium pairings to 2.8% for dynamic pairwise separations. For the latter aircraft separations could have been reduced below the ICAO standards in 10.6% of the time. During the Munich campaign dynamic pairwise separations reduced below the ICAO standards could have been applied only in 4.0% of the arrivals (see Table 2). This comparison indicates that the Frankfurt trial benefited from the strong wind periods occurring during January and February 2007. This highlights that the capacity gains found in this study strongly depend on the weather conditions prevailing during the respective measurement campaign and may differ significantly for other periods of the year and/or other airport locations.

For the interested reader Figure 10 reveals which gates impede reduced aircraft separations for the setups 1, 4, 6, and 8. In the baseline case (setup 1) gate 13 (the one closest to the runway threshold where aircraft fly at 29 m above ground) hinders WSVBS operations in 41%. In 57% gates 11 – 13 where the wake vortex predictions are driven by SODAR/RASS measurements limit reduced separations. On one hand, this is further evidence for the bottleneck close to the ground. On the other hand, this also means that only in 43% of the landings improved numerical weather prediction could increase the usage period of the WSVBS.

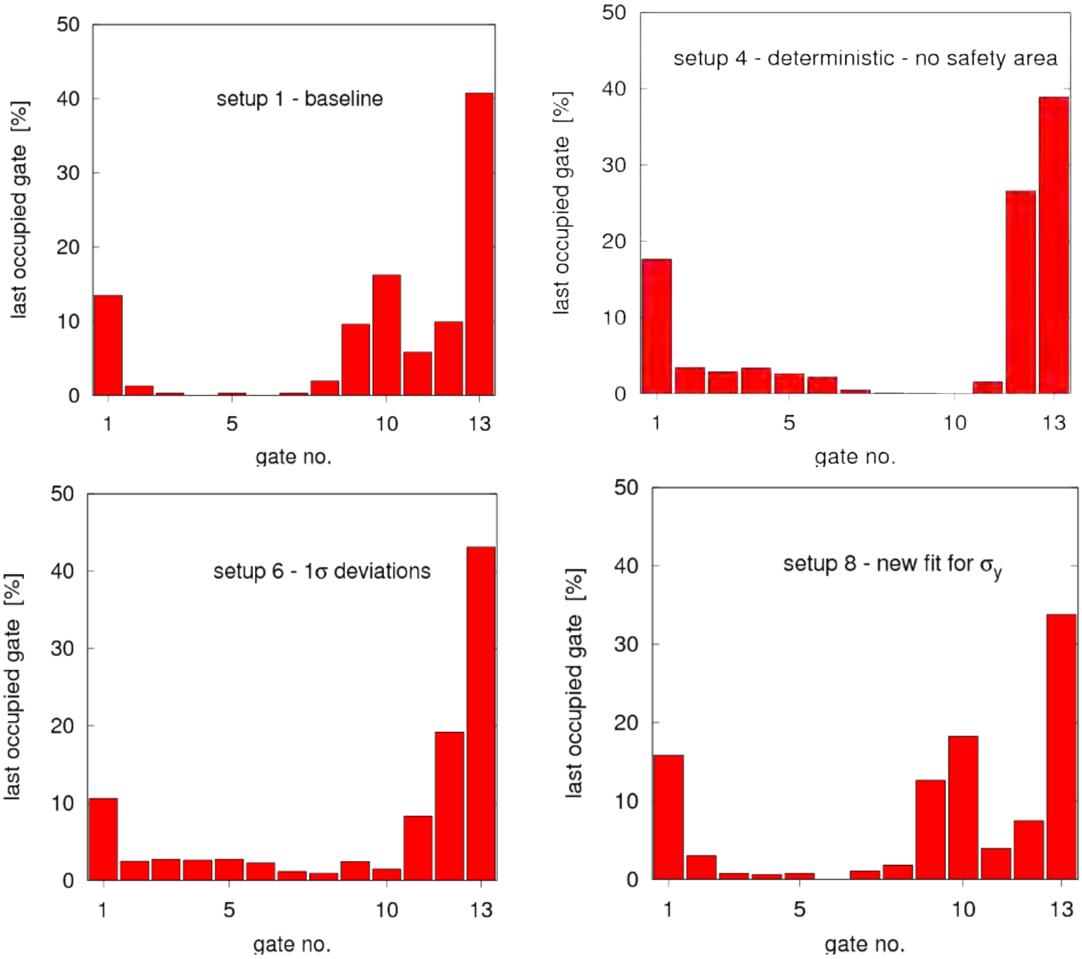

Figure 10. Last gates impeding reduced aircraft separations for four different system setups.

Interestingly though, gate 1 (the farthest-out gate at 1077 m height) blocks reduced separations in almost 14% of the cases. This is attributed to the fact that the first approach corridor features the largest dimensions. Further, gate 10 impedes reduced separations in 16% of the time. At this gate two effects appear decisive. First, it is the lowest gate employing numerical cross-wind predictions, which lead to larger uncertainty allowances of vortex position compared with predictions using actual wind measurements. Second, the aircraft vortices are shed at 190 m height where ground effect still contributes to the lateral wake vortex transport for the aircraft with the largest wing spans.

Furthermore, Figure 10 indicates that reduced uncertainty allowances for wake vortex prediction further increase the dominance of the gates 11 - 13 in ground proximity (setup 4 – deterministic: 67%, setup 6 - 1σ deviations: 71%). On the other hand, gate 10 becomes non-relevant. In contrast, the reduced lateral flight corridor dimensions in setup 8 diminish the blocking effect of the lowest gates 11 – 13 from 57% in the baseline case to 45%. It has also been investigated whether the wake vortex predictions initialized with a maximum or a minimum circulation value (see above) block the gates for longer times. It appears that both wake vortex prediction runs are of similar importance. Interestingly, the wake predictions based on the minimum circulation block the gates slightly more frequently which probably can be attributed to the reduced wake vortex descent speed in the gates out of ground effect.

Figure 11 demonstrates the principle of operation of the WSVBS (setup 1) and variations of it (setups 2, 4) for a case with strong crosswind where extremely short aircraft separations between a leading B762 and a following A321 have been predicted. Figure 11 right below shows vertical profiles of wind and potential temperature indicating excellent agreement between the measured (SoRa) and predicted (COSMO) wind profiles. The crosswind (green) rises from 7.0 m/s at 10 m height to a maximum of 17 m/s at 450 m height. Also due to the veering of the wind with height (Ekman spiral) the crosswind then decreases again to 6.0 m/s at the highest gate at 1077 m above ground. Due to this particular wind profile either gate 1 and/or gate 13 are cleared at last from wake vortices or safety areas. For the baseline setup the WSVBS predicts that the safety areas (Figure 11, top right, blue) have left the flight corridor (dashed lines) laterally in gate 1 already at only 37 s. For probabilistic wake vortex prediction and neglect of the safety areas (setup 2, P2P, red) this time reduces to 30 s and it is further reduced to 17 s for deterministic wake vortex predictions without safety areas (setup 4, D2P, green). The three plots on the left side indicate that for all considered setups neither vortex descent nor vortex decay would allow for the achieved short separations.

In order to further assess the benefits of dynamic pairwise separations compared to weight class based separations we evaluate the sensitivity of the predicted separations on the aircraft type combinations. The results recapitulated here only for the baseline case are similar for the other setups. For a given heavy leader aircraft at a given environmental situation the separation times of the different medium follower aircraft landing within the five minutes increment of the flight plan vary only slightly. On average this variation amounts to 6 s. Little surprising, maximum variations reaching up to about 40 s may occur when a heavy leader aircraft (e.g. B744) is followed either by a relatively heavy medium type aircraft (e.g. A321, MTOW = 83 t) or a relatively light medium type aircraft (e.g. DH8D, MTOW = 29 t). For the same follower aircraft and different heavy leader aircraft at a given environmental situation the separation times vary stronger. On average this separation time difference amounts to 13 s where maximum variations may reach up to about 60 s. An example for this are leading B77W (MTOW = 352 t) and A310 (MTOW = 150 t) followed by a SB20 (MTOW = 23 t).

From the high percentage of cases in which the wake vortices have not left the flight corridor (setups 4 and 5 employing deterministic wake vortex predictions) one may conclude that even under ICAO separations it is daily practice that approaching aircraft fly close to not fully decayed wake vortices. This finding is also corroborated by long-term lidar measurements of wake vortices at Charles de Gaulle airport. There it was found that in 3% of the cases the vortices were at least as close as 25 m to following landing aircraft within one gate close to the threshold (Treve 2011). The observations at Charles de Gaulle airport imply that a non-negligible number of landing aircraft could theoretically encounter the wake vortex core regions where the exerted rolling moments have maximum strength. This raises the question which mechanisms secure the safety of current operations and which mechanisms allow pilots even to land at radar separation under VFR conditions. It is not likely that the pilots are always successful at flying upwind and/or above the vortices in particular close to the threshold.

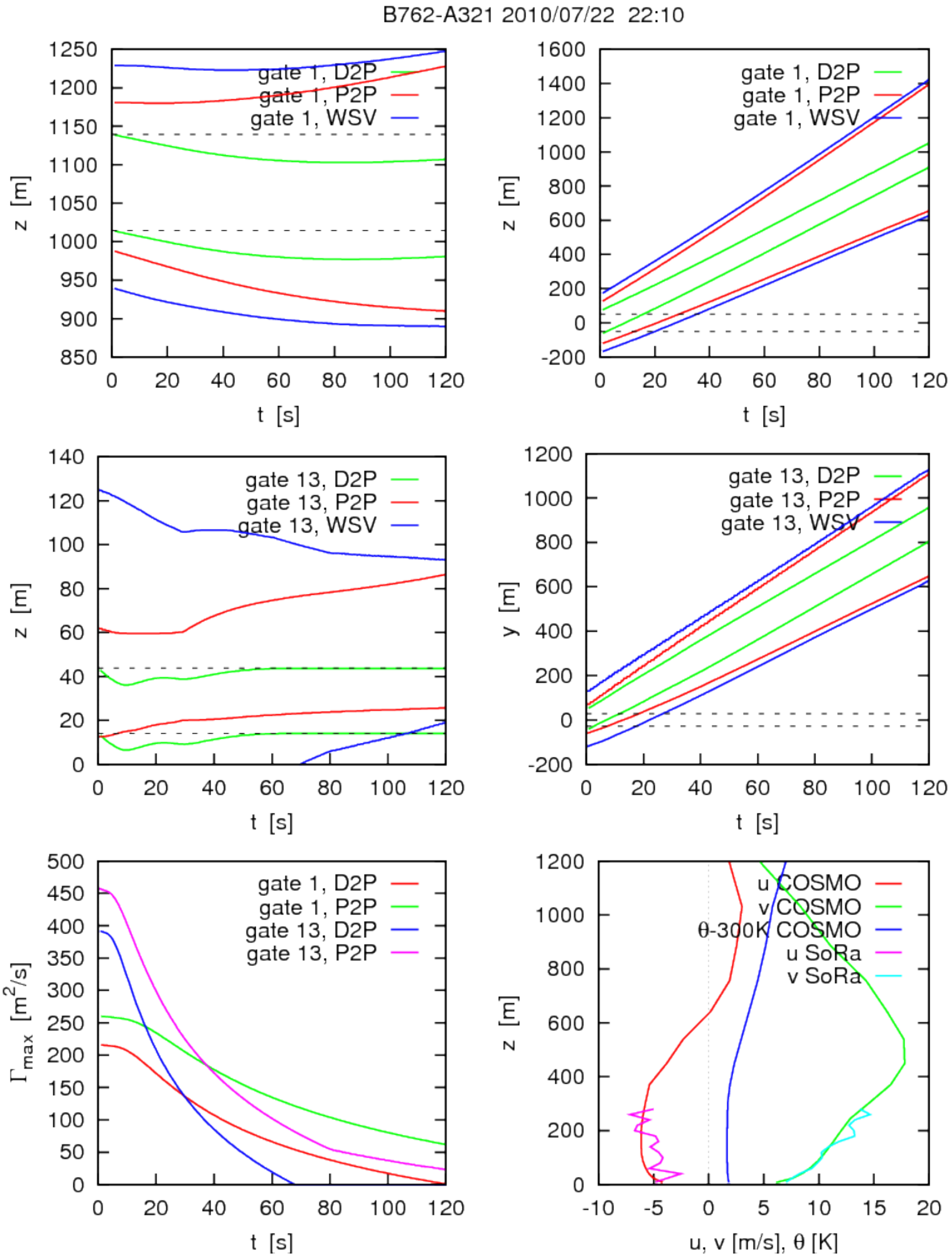

Figure 11. Predicted envelopes of wake vortex evolution and safety areas in gates 1 and 13 for strong crosswind case and setups 4 (D2P), 2 (P2P), and 1 (WSV).

Candidate explanations for the small number of critical encounters in real life are: (i) the deformation of the vortices that may alleviate vortex encounters by reducing the impact times of adverse forces and moments (Crouch & Loucel 2005, Hennemann & Holzäpfel 2011, Holzäpfel et al. 2010, Vechtel 2011), (ii) the dimensions of the flight corridor. The comparison of setups 5 and 6 indicates that the approach corridor dimensions have a strong impact on the frequency of potential reduced separations, (iii) the “self-protection mechanism” that tends to deviate an encountering aircraft from the vortex center, (iv) effects of the more or less generally prevailing headwind that may support effective vortex descent (by advecting the vortices along the inclined flight track towards higher glide path positions where the follower aircraft passes by) and vortex decay in a way which is not yet adequately considered in the WSVBS, or (v) end effects that weaken the wake vortices when they propagate along the vortex centers after touch down (Moet et al. 2005).

Conclusions

The Wake Vortex Prediction and Monitoring System WSVBS with all its components and their interactions has been described. The WSVBS consists of components that consider meteorological conditions, aircraft glide path adherence, aircraft parameter combinations representing either aircraft weight categories or individual aircraft types, the resulting wake-vortex behavior, the surrounding safety areas, wake vortex monitoring, and the integration of the predictions into the arrival manager. The elements of the WSVBS are generic and thus could well be adjusted to the runway systems at Frankfurt and Munich airports. The WSVBS predicts the concepts of operations and procedures established by DFS and it further predicts temporal separations for closely spaced parallel runways as well as for in-trail traffic.

A specific feature of the WSVBS is the usage of both measured and predicted meteorological quantities as input to wake vortex prediction. In ground proximity where the probability to encounter wake vortices is highest, the wake predictor employs measured environmental parameters that yield superior prediction results. For the less critical part aloft, which can not be monitored completely by instrumentation, the meteorological parameters are taken from dedicated numerical terminal weather predictions. For the Munich campaign the weather prediction quality was further improved by employing hourly updated time-based ensemble predictions with the assimilation of precipitation Radar, SYNOP, TEMP, and AMDAR data. The wake vortex model predicts envelopes for vortex position and strength which implicitly consider the quality of the meteorological input data. This feature is achieved by a training procedure which employs statistics of measured and predicted meteorological parameters and the resulting wake vortex behavior.

The WSVBS combines various conservative elements that presumably lead to a very high overall safety level of the WSVBS:

a) Wake vortex prediction as well as safety area prediction employs worst case combinations of aircraft parameters.

b) The wake vortex model assumes that the aircraft are situated on the envelopes of the approach corridors. Likewise, the safety area model assumes that the wake vortices are situated along the wake vortex envelopes. As a consequence the probability to actually encounter wake vortices at the edges of the safety areas is outermost small.

c) The most critical gate determines the possible aircraft separation.

d) A LIDAR that scans the most critical gates at low altitude monitors the correctness of suggested aircraft separations.

The combination of these conservative measures certainly leads to a very high but currently unknown overall safety. Once the methodology of a comprehensive risk analysis will be established, it is planned to adjust all components to appropriate and consistent confidence levels. Possibly, this will enable to somewhat relax the current stringent safety allowances of the WSVBS with the benefit of increased operation times with reduced separations. The primary purpose of the risk analysis, of course, is to convince all stakeholders of the usefulness and capabilities of the system

The WSVBS has demonstrated its functionality at Frankfurt airport in the period from 18/12/06 until 28/02/07. At Munich airport the WSVBS has demonstrated the feasibility of dynamic pairwise separations for the first time (23/6/10 – 15/9/10). These performance tests indicate that

i. the system runs stable - no forecast breakdowns occurred,
ii. in Frankfurt aircraft separations could have been reduced for the closely-spaced parallel runway system in 75% of the time compared to ICAO standards,
iii. reduced separation procedures could have been continuously applied for at least several tens of minutes and up to several hours occasionally,
iv. the Frankfurt predictions were correct as for about 1100 landings observed during 16 days no warnings occurred from the LIDAR,
v. the consideration of dynamic pairwise separations may almost double the times operating at radar separation compared to weight class combinations,
vi. an assessment of the sensitivity of the predicted dynamic pairwise separations on the aircraft type combinations indicates a higher sensitivity on the heavy leader aircraft types than on the medium follower aircraft types,
vii. the impact of the flight corridor dimensions on the achievable reductions of aircraft separations turns out to be relatively large. So the existing and in future expected improvements of navigational performance may substantially support the performance and introduction of new wake vortex advisory systems,
viii. the potential capacity gains of dynamic pairwise operations for single runways appear to be very small for the baseline setup of the WSVBS. A sensitivity analysis of eight different setups of the WSVBS indicates that the baseline setup of the WSVBS features a very conservative design. On the other hand, it is found that for perfect weather data and perfect wake vortex predictions the vortices have frequently not left the flight corridor when the follower aircraft passes the respective gates. Nevertheless, current operations are safe. A number of candidate explanations for the small number of critical encounters in real life is suggested. Deepened understanding of the high percentage of close approaches to wake vortices without severe consequences is prerequisite to an optimal setup of a wake vortex advisory system.

The WSVBS may also be further developed to provide warnings in situations where the routinely applied aircraft separations may not be sufficient in order to further increase safety during approach and landing.

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