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The Wake Vortex Prediction and Monitoring System WSVBS

Design and Performance at Frankfurt and Munich Airport

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***Abstract*— 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 behaviour without compromising safety. Dedicated meteorological instrumentation and short-term numerical terminal weather prediction provide the input to the prediction of wake-vortex behaviour 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. Within 66 days of performance test at Frankfurt airport it was found that the system ran stable and the predicted minimum separation times were correct. The capacity improving concepts of operation could have been used in 75% of the time. 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. 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. The consideration of individual aircraft types and their respective wake characteristics may almost double the fraction of time when radar separation could be applied.**

Keywords* - *wake vortex advisory system, separation, airport capacity, safety, meteorology, concept validation, dynamic pairwise separations

I. Introduction

Aircraft trailing vortices may pose a potential risk to follower 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. Capacity limitations are especially drastic and disagreeable at airports with two closely-spaced parallel runways (CSPR) like Frankfurt Airport (Germany) where the potential transport of wakes from one runway to the adjacent one by crosswinds impedes an independent use of both runways.

The most likely growth scenario within a Eurocontrol study [2] 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 [16]. A survey on wake-vortex advisory systems and modifications of procedures that are meant to increase airport capacity is available in [27].

DLR has developed the Wake Vortex Prediction and Monitoring System (Wirbelschleppen- Vorhersage- und Beobachtungssystem WSVBS [11], [12], [21]) 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 behaviour without compromising safety. The system predicts wake vortex transport and decay and the resulting safety areas along the glide slope from final approach fix to threshold. 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. Dynamic pairwise separations are the favoured procedure foreseen in the final development stage of NextGen and SESAR [6], [26], [23]. The elements of the WSVBS are generic and can well be adjusted to other runway systems and airport locations.

This paper describes the design of the WSVBS with all its components and their interaction and the promising performance during a three-month measurement campaign at Frankfurt Airport in winter 2006/07 and another three-month measurement campaign at Munich Airport in summer 2010.

II. System Overview and Topology

Fig. 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 ultra sonic anemometer (USA).

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 (NOWVIV) 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. The instant when the safety areas do not overlap with the flight corridor define temporal aircraft separations that are translated into established procedures by the arrival manager (AMAN). LIDAR monitors the correctness of WSVBS predictions in the most critical gates at low altitude.

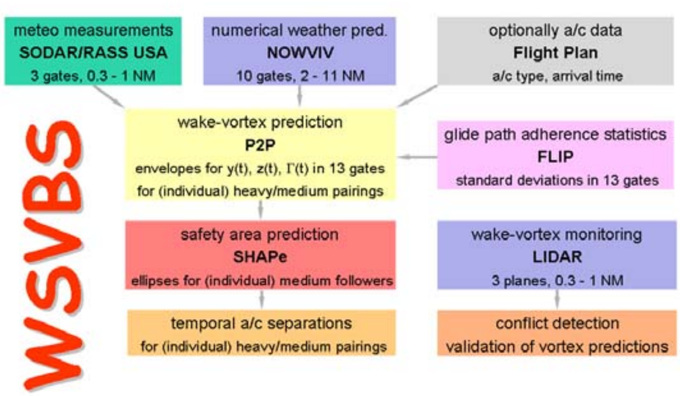

Figure 1. Flowchart of the WSVBS

The WSBVS 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. Fig. 2 delineates the parallel runway system in Frankfurt with the employed geodetic coordinate system and a few gates next to the ground. The parallel runways and consequently also the gate centres are laterally and axially spaced by 518 m and 226.5 m.

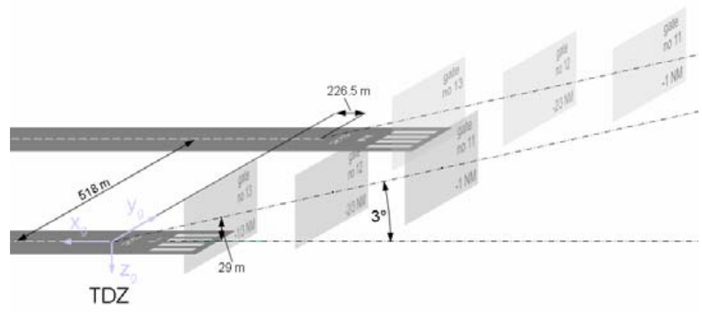

Figure 2. Flowchart of the WSVBS

III. 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 95.4% probabilities (two standard deviations, 2σ, for Gaussian distributions) as a basis for the probabilistic components of the WSVBS.

The following sections describe the components delineated in the flowchart in Fig. 1 in detail.

A. *Meteorological Data*

For prediction of wake-vortex behaviour 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.

Figure 3 shows runways 25L and 25R of Frankfurt airport with the locations of the employed sensors and the local operation centre (LOC) which is situated in the observer house of the German weather service (DWD). Close to the LOC midway between the glide paths 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 [8]. 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.

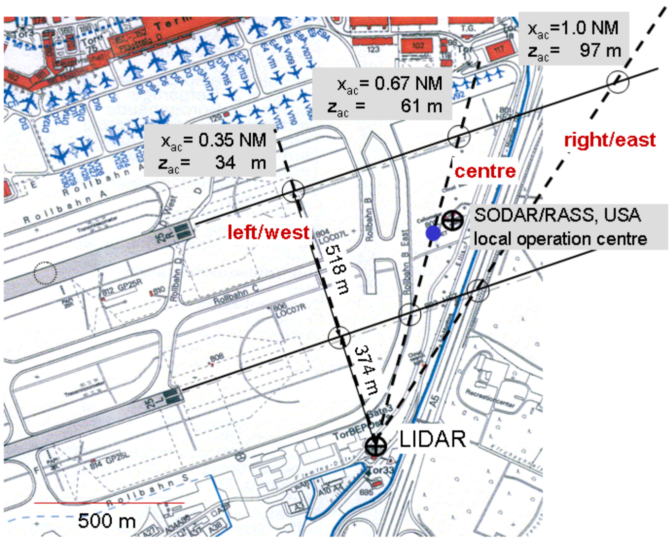

Figure 3. Sketch of instrumentation set-up at Frankfurt Airport. x_{ac}, z_{ac} denote the distance to touch-down zone (TDZ) and the height of landing aircraft in the three vertical LIDAR scan planes (dashed lines). Map reprinted by courtesy of Fraport AG.

The non-hydrostatic mesoscale weather forecast model system NOWVIV (NOwcasting Wake Vortex Impact Variables) is used to predict meteorological parameters in the area which is not covered by measurements (the more remote 10 gates from 2 to 11 NM). NOWVIV has been successfully employed for predictions of wake vortex environmental parameters in several field campaigns [21]. Detailed descriptions of NOWVIV and its nowcasting skill are available in [9], [10], [11].

Within the forecast system NOWVIV, the meso-scale model MM5 [13] predicts the meteorological conditions for the Frankfurt terminal area in two nested domains with sizes of about 250 x 250 km² and about 90 x 90 km² centred on Frankfurt airport with grid distances of 6.3 km and 2.1 km, respectively. 60 vertical levels are employed such that in the altitude range of interest ($z < 1100$ m above ground) 26 levels yield a vertical resolution varying between 8 m and 50 m.

Initial and boundary data are taken from the operational weather prediction model COSMO-DE (formerly Local Model, [5]) 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 are employed.

NOWVIV ran twice a day (at 00 and 12 UTC) on a dedicated LINUX cluster at University of Stuttgart. Profiles of meteorological data were extracted at gates 1 through 10 with an output frequency of 10 minutes. The meteorological quantities comprised the three wind components, air density, virtual potential temperature, turbulent kinetic energy, eddy dissipation rate (EDR), and pressure.

During the Munich campaign the numerical weather predictions were conducted by a derivate of the COSMO-DE model called COSMO-MUC [4]. The assimilation of local measurement data from precipitation radar, SYNOP (surface synoptic observations), TEMP (radiosonde observations), and AMDAR improved the prediction quality. Time-lagged ensemble predictions with prediction horizons of six hours have been launched each hour. So for each instant in time the meteorological conditions were available as an average of six prediction runs. Further, the spread of the six ensemble members indicates the predictability of the respective meteorological situation.

For approaches the largest probability to encounter wake vortices prevails at altitudes below 300 ft [3], [22], [27]. 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 almost not sensible to meteorological conditions [20], the most important mechanism that may allow for reduced aircraft separations is lateral transport of wake vortices by crosswind.

Ref. [9] 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 NOWVIV input 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 we use NOWVIV or COSMO-MUC data which yields minor wake prediction skill.

B. *Approach Corridor Dimensions*

For the definition of approach corridor dimensions we employ the glide path adherence statistics of the FLIP study [7], 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.

The approach corridors in the different gates consist of ellipses (see green ellipses in Fig. 6). 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.

C. 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 [6], [26], [23]. This approach requires that the approaching aircraft types are known. So far the WSVBS predicts separations of all individual heavy leader aircraft (aircraft designators according to [1]: A306, A310, A332, A333, A343, A346, B744, B762, B763, B764, B772, B773, B77W, IL96, MD11) and medium follower aircraft (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) combinations that are scheduled to land within the same five minute interval according to the flight plans of Frankfurt or Munich airport.

For each generator aircraft type the envelopes for wake vortex behaviour 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 only consider aircraft weight class combinations. For Frankfurt airport 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 characterise the classes [21].

D. Wake-Vortex Prediction

Wake-vortex prediction is conducted with the Probabilistic Two-Phase wake-vortex decay model (P2P) which is described in detail in [17]. Applications, assessments and further developments are reported in [8], [18], [19], and [20]. 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.

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. Fig. 4 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 to 2σ-probabilities. The respective uncertainty allowances are achieved by a training procedure which employs statistics of measured and predicted wake vortex behaviour [19]. 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 NOWVIV or COSMO-MUC input.

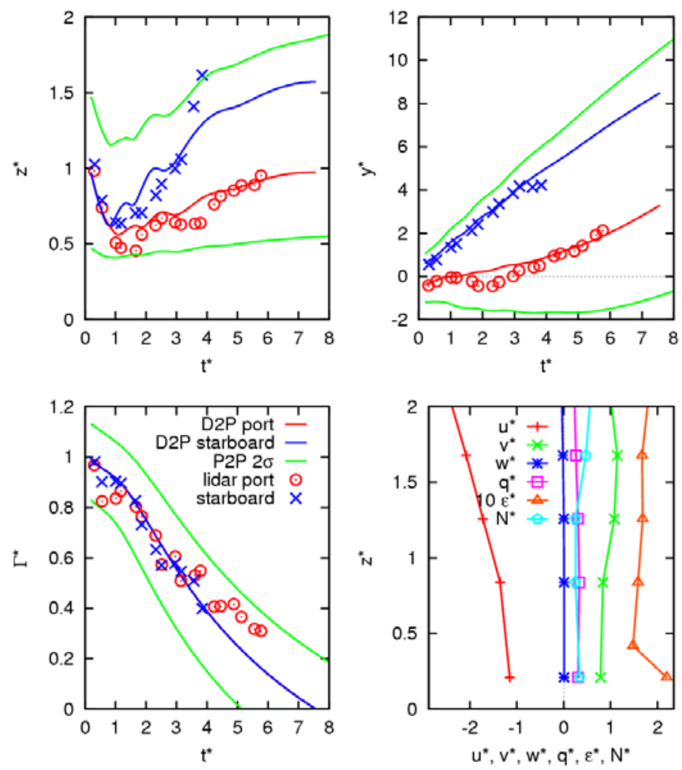

Figure 4. Evolution of normalised vertical and lateral positions and circulation in ground proximity. Measurements by lidar (symbols) and predictions with the P2P wake vortex model (lines). Red and blue lines denote deterministic behaviour; green lines are probabilistic envelopes (95.4%). Right below vertical profiles of measured meteorological parameters. Normalisations based on initial values of vortex spacing, circulation, and time needed to descend one vortex spacing.

E. 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 [15], [25] 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, RCRreq, which relates the wake vortex induced rolling moment to the maximum available roll control power.

In Fig. 5 the red areas with RCRreq > 1 denote regions where the roll control capability of the encountering aircraft is exceeded. Full flight simulator investigations yield acceptable results for manual control for a value of RCRreq = 0.2 [25]. Results from real flight tests, using DLR's fly-by-wire in-flight simulator ATTAS, support this conclusion [24]. In Fig. 5 the lines a and b denote the resulting distances between vortex centres and follower aircraft for RCRreq < 0.2 which are added to the wake vortex envelopes.

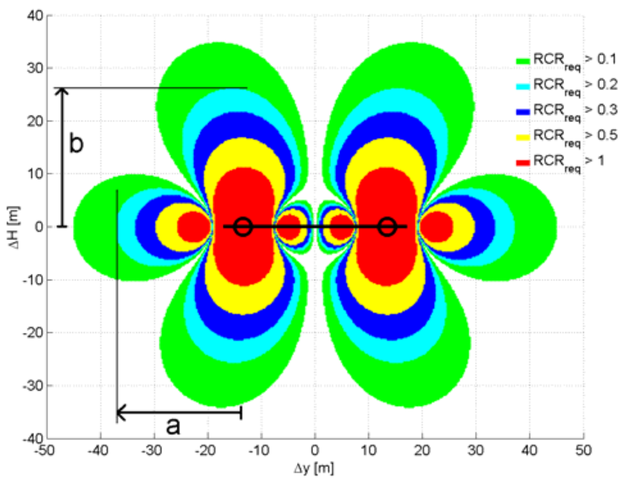

Figure 5. Roll control power required to compensate wake-vortex induced rolling moments. Horizontal and vertical allowances a and b for $RCR_{req} < 0.2$.

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) [15].

IV. SYSTEM INTEGRATION

This section describes how the above introduced components are combined for the prediction of adapted aircraft separations. Sub-Section A considers components within a single gate, Sub-Section B then explains how the minimum temporal aircraft separations are derived from the predictions within all the gates. Finally, Sub-Section C sketches the temporal prediction cycle which defines parameters like update rate and prediction horizon.

A. *Components in a Single Gate*

Fig. 6 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 Fig. 6 are in scale. The dark blue corridor of possible vortex positions indicates that superimposed to vortex descent a southerly cross-wind advects the wake from runway 25L to 25R.

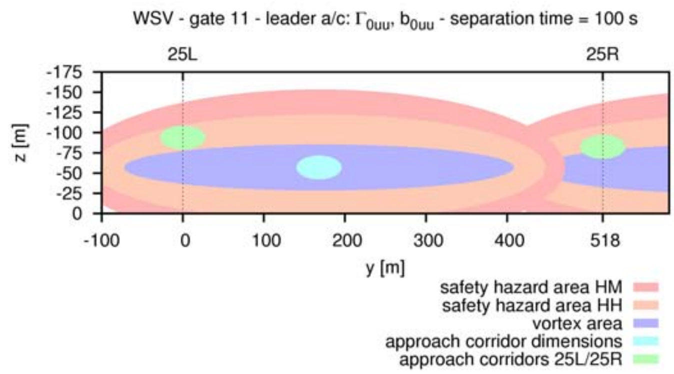

Figure 6. Ellipses denoting approach corridor dimensions, vortex areas, and safety areas in gate 11 for a vortex age of 100 s and the Frankfurt CSPR runway system.

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 [20]. Safety area margins for aircraft pairings HH and HM 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.

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 the parallel runway system, the question is whether the safety areas reach the neighbouring approach corridor within the prediction horizons or not. The prediction horizons of 100 s for HH and of 125 s for HM are derived from the temporal equivalents to ICAO separations used by the DLR Arrival Manager (AMAN).

Our example in Fig. 6 illustrates that after 100 s the vortex area has just left the approach corridor of runway 25L, yet the gate is blocked as both safety corridors still overlap with the approach corridor. On the other hand, after 100 s the safety envelopes for HH and HM have not reached glide path corridor 25R. However, at 125 s the HM envelope obviously will reach the glide path 25R, so that this runway can be used independently from 25L only by heavy aircraft. Safety areas from 25R in turn will not reach the corridor 25L, so 25L can be used independently from 25R for both follower weight categories.

B. Complete Domain

One prediction sequence comprises 13 gates for each runway. For the CSPR system three runway combinations (generator and follower on single runway (25L25L or 25R25R), generator on 25L and follower on 25R (25L25R), and vice versa) are considered. The cases with maximum vortex ages with conflicts (gate obstruction times) define minimum aircraft separation times, MST. The output of the WSVBS consequently consists of the matrix shown in Tab. 1.

Note that the MST in Tab. 1 are consistent with the situation displayed in Fig. 6. In Tab. 1 a MST = 0 s means that no aircraft separation with regard to wake vortices is needed, i.e. vortices do not reach the adjacent runway. In practise the aircraft separations can then be reduced to radar separation (for example 70 s).

TABLE I. MINIMUM SEPARATION TIMES FOR DIFFERENT RUNWAY AND WEIGHT CATEGORY COMBINATIONS

rwy comb.	MST HH [s]	MST HM [s]
25L25L	100	125
25L25R	0	125
25R25L	0	0
25R25R	100	125

The predicted MST are translated into four modes or concepts of operation for aircraft separation which have been established by the German Air Navigation Safety Provider DFS to be applied to the dependent parallel runway system at Frankfurt Airport under instrumented meteorological conditions (IMC) [14]:

• "ICAO" – standard procedure under IMC with 4 NM for a HH aircraft pair and 5 NM for a HM pair across both runways;

• "Staggered" (STG) – procedure where both runways can be used independently from each other but obeying the radar (minimum) separation of 2.5 NM;

• "Modified Staggered Left" (MSL) – aircraft on right (windward) runway keep 2.5 NM separated from aircraft of left (lee) runway;

• "Modified Staggered Right" (MSR) – aircraft on left (windward) runway keep 2.5 NM separated from aircraft of right (lee) runway.

For dynamic pairwise landings on a single runway the predicted MST have the following format:

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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
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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. The predictions are available 20 min prior to landing.

C. Prediction Cycle

Every 10 minutes new SODAR/RASS and NOWVIV data are available. Then the WSVBS for aircraft weight classes predicts MST matrices for a 60 min horizon with 10 min-increments. For planning purposes this guarantees availability of predictions for at least 45 min in advance. The last 10 min of the predictions are not touched to ensure the stability of the system.

Based on the MST, landing procedures are eventually recommended. Fig. 7 displays the full MST information as it is available in the WSVBS. In addition to the four procedures which were defined by DFS, such a display allows also survey possible reduced separations for aircraft flying in-trail and it further distinguishes HH and HM aircraft pairs. The sketched example reads that not only the DFS procedure MSL can be used (no wake-vortex separation required for runway combination 25L25R but full ICAO separation for 25R25L), but that also aircraft which follow each other on the same runway (in-trail) can be radar-separated. The meteorological reason for that case is a strong northerly crosswind that clears both runways quickly from vortices of the leading aircraft.

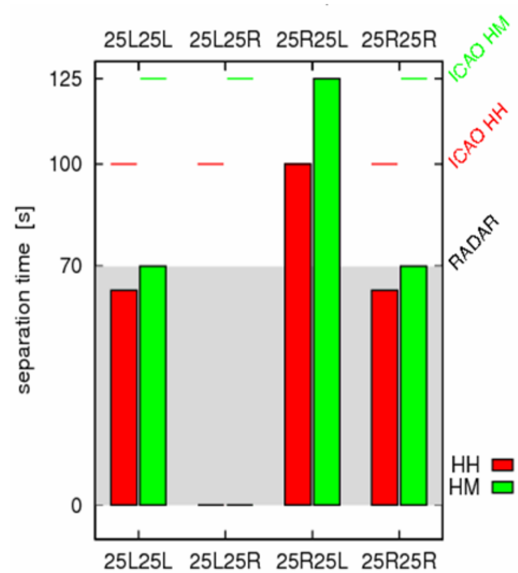

Figure 7. Display of full MST information and derived arrival procedures for Frankfurt Airport on 2007-Jan-25 at 15:10 UTC.

V. WAKE-VORTEX MONITORING

Wake-vortex monitoring is used to identify potential erroneous predictions of the WSVBS. For this purpose DLR's 2 µm pulsed Doppler LIDAR has been operated in vertical scan mode with elevations between 0° to 6° to detect and track the vortices alternately in the three lowest and most critical gates of runway 25R (see Fig. 3).

VI. Performance and Improved Capacity

A detailed description of the integration of the WSVBS predictions into ATC procedures, the employed controller displays (HMI), and the achieved capacity gain is available in Ref. [12]. Here only a condensed description of these aspects is given.

To check if the WSVBS products and the proposed features on the displays fulfil ATC requirements, are well designed and easy to use, and will eventually improve capacity at Frankfurt Airport, we performed real-time and fast-time simulations using the Air Traffic Management and Operations Simulator (ATMOS II) and the SIMMOD tool of DLR Institute of Flight Guidance at DLR Braunschweig, respectively. During a period of one week real-time simulations were carried out at the simulator ATMOS II under the assistance of five air traffic controllers from DFS. The investigations aimed at evaluating the behaviour and efficiency of the WSVBS on a real time controller working position and to inquire the controller's judgement of the system.

By means of a systematic questionnaire the controllers from DFS were interviewed with respect to aspects as acceptance of the simulation environment, acceptance of the WSVBS, procedural regulations and human interface, operational appliance. The participating controllers generally agreed with the WSVBS system and procedures. In particular, the system does not interfere with their normal working procedures.

We also performed fast-time simulations to obtain capacity figures for the different concepts of operation utilised by WSVBS under real world conditions. To establish a baseline, the simulations were initially performed using ICAO separations. The simulations were then matched with separations derived from WSVBS and re-run. The simulations included flight plans with realistic distributions of wake vortex categories, demand peaks throughout the day, weather data, and the WSVBS proposals for a period of one month.

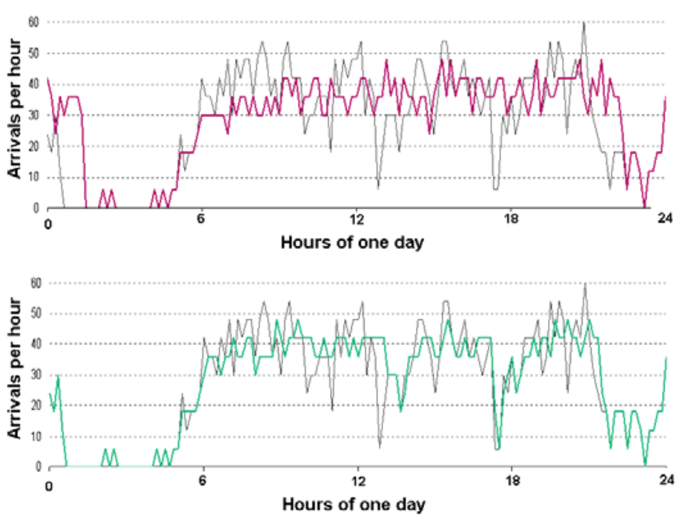

Figure 8. Traffic flow (arrivals per hour) during a day at Frankfurt Airport. Top: demand (grey) vs. ICAO standards (red); bottom: demand vs. WSVBS utilisation (green).

Fig. 8 shows traffic demand and traffic flow for a "heavily loaded" day at Frankfurt with 721 arrivals. Using the WSVBS predictions, MSR separations could be used for 76.4% of the day, with intermittent use of ICAO separations in the morning hours. The peak demand exceeds capacity in both scenarios. However, the WSVBS flow closely follows the demand flow whereas the ICAO flow is unable to cope with the demand and accumulates delayed flights which can only be served in the late evening hours. When taking into account the real traffic mix and operational constraints in the period of one month we received a net capacity gain of slightly larger than 3%.

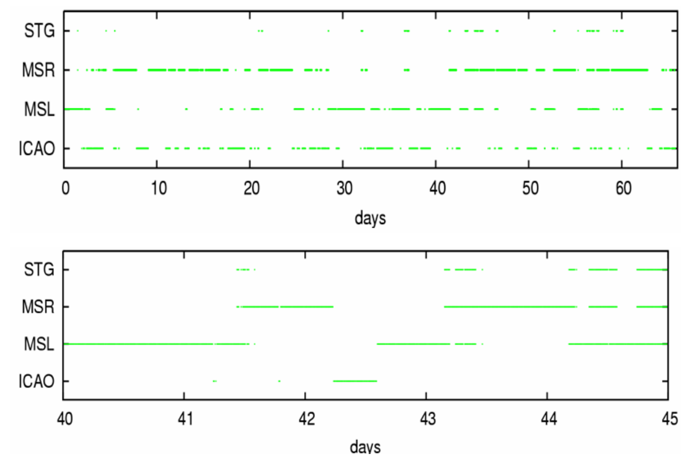

Figure 9. History of usage of the 4 DFS operation modes during the 66 days of the campaign at Frankfurt. Top: full period; bottom: zoom on five days.

Fig. 9 summarises the history of DFS operation modes as proposed by the WSVBS for the CSPR during the 66 days of performance at the airport. In 75% of the time the DFS modes, which allow improving capacity or punctuality of landing aircraft, could have been deployed. The focus on five days (Fig. 9 lower panel) indicates that each mode can be deployed throughout a significant fraction of time.

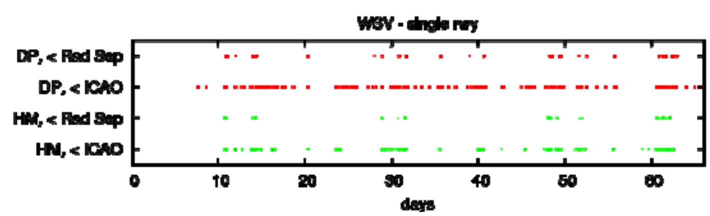

Figure 10. Usage of separations below ICAO separations or Radar Separations for Heavy/Medium aircraft class combinations (green) or Dynamic Pairwise separations (red) during the 66 days of the Frankfurt campaign.

Fig. 10 delineates the history of periods of time in which aircraft separations for landings on single runways could have been reduced either below ICAO separation (125 s) or radar separation (70 s). The fraction of time for radar separations is increased 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 reduced dynamic pairwise separations could have been applied only in 4.0% of the time. This comparison indicates that the Frankfurt trial benefited from the strong wind periods occurring during January and February 2007.

The question how long the DFS ConOps MSL, MSR, STG or no one of them (ICAO) could continuously be used and how often this happened during the Frankfurt campaign is answered in Fig. 11 for pairs of Heavy/Medium aircraft. In the 66 days the procedures MSL/MSR/STG could have been used 36/7/14 times for 10 minutes only. However, a continuous use of these ConOps for 1 hour would have been possible 16/13/10 times, respectively. Even a usage as long as 8 hours would have been feasible still 2/2/1 times. Somewhat higher (lower) numbers hold for the aircraft pairing HH (for single runway approaches) (not shown). Due to the strong wind conditions in January it would even have been possible to use MSR for HH pairings once throughout almost 4 days (93 hours).

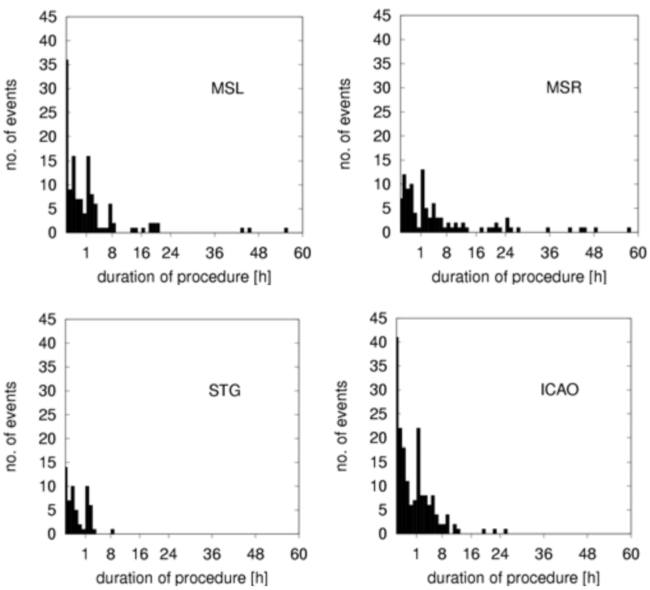

Figure 11. Number of events versus duration of DFS procedures in hours for HM aircraft pairs; a 10 min interval is used in the 1st hour, the interval is 1 hour afterwards.

The (manned) LIDAR did not measure continuously throughout the campaign. It was operated on 16 days where it tracked the wake vortices of about 1100 landing heavy aircraft in the three most critical control gates (Fig. 3). In all these cases it was found that the recommended operation mode was well predicted – no vortices were detected in the flight corridor after the predicted minimum separation time. Fig. 12 shows two examples of traces of the port and starboard vortices of heavy aircraft landing on runway 25R as measured by LIDAR in the three scan planes shown in Fig. 3. For the 18th of January, the WSVBS predicted the modes MSR followed by reduced in-trail separation. The plot, which shows vortex positions of 8 landing heavy aircraft, corroborates both scenarios as the southerly cross-wind hindered the vortices to reach runway 25L (hence, MSR) and the wind became obviously so strong later that also a reduced separation in-trail could have been operated. For the 8th of February, WSVBS recommended to use operations STG followed by MSR. Again, the LIDAR data, now from 32 landing heavy aircraft, confirm the predictions; the wind is very weak and does not transport the vortices to the adjacent runway.

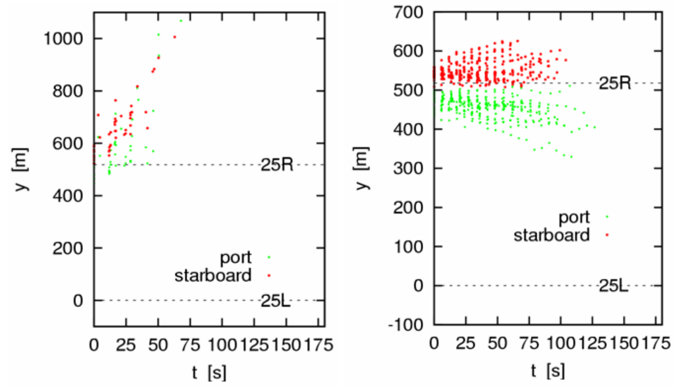

Figure 12. Lateral positions of wake vortices vs. vortex age from 8 and 32 heavy aircraft landing on 25 R on 18th Jan. (left) and 8th Feb. (right) 2007, respectively, as tracked by the LIDAR in the three scan planes.

VII. 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 behaviour, 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 time-based ensemble prediction 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 behaviour.

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. (The probability that this assumption actually occurs is extremely small.) 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.

Fast-time simulations reveal that the concepts of operation, which were introduced by DFS (i.e. MSL, MSR, STG and keeping 2.5 NM or 70 s as the minimum separation) and utilised by WSVBS for Frankfurt Airport, yield significant reductions in delay and/or a 3% increase in capacity taking into account the real traffic mix and operational constraints in the period of one month. Relaxing the DFS constraints and allowing more operation modes would further increase capacity.

We consider these capacity gains as tactical. “Tactical” means that the system aims at increasing the punctuality of flight operations as of today by avoiding holding patterns. After experience has gained over some years of application (including diurnal and seasonal statistics of meteorological quantities along the glide path) the system may also allow increasing the number of flight operations at the airport, i.e. gain capacity “strategically”.

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

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