THE WAKE VORTEX PREDICTION AND MONITORING SYSTEM WSVBS – PART I: DESIGN

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ABSTRACT

The design of the Wake Vortex Prediction and Monitoring System WSVBS is described with all its components and their interaction. The WSVBS has been developed to tactically increase airport capacity for approach and landing on 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. The prediction tools employ a number of conservative aircraft parameter combinations that represent the aircraft weight categories medium and heavy. Predictions of the time when all approach corridors along the final approach do not overlap with safety areas determine aircraft separations for follower aircraft of categories medium and heavy. As a safety net a LIDAR monitors the correctness of WSVBS predictions in the most critical gates at low altitude.

1. 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. 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 rapid growth scenario within a Eurocontrol study [1] indicates that in the year 2025 sixty European airports could be congested and as a results 3.7 million flights per year could not be met. 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 [10]. This estimation accounts only for cost avoidance based on reductions in arrival delays. Savings due to reduced departure delays, value of passenger time, additional airline revenue, avoidance of runway or airport construction and airline relocation are not considered. A survey on wake-vortex advisory systems and modifications of procedures that are meant to increase airport capacity is available in [19].

DLR has developed the Wake Vortex Prediction and Monitoring System (WirbelSchleppen-Vorhersage- und -BeobachtungsSystem WSVBS [8]) 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 is particularly adapted to the closely spaced parallel runway system of Frankfurt airport. 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 manuscript describes the design of the WSVBS with all its components and their interaction. The elements of the WSVBS are generic and can well be adjusted to other runway systems and airport locations. The promising performance of the WSVBS during a three-month measurement campaign at Frankfurt Airport is described in Part II of this manuscript.

2. SYSTEM OVERVIEW

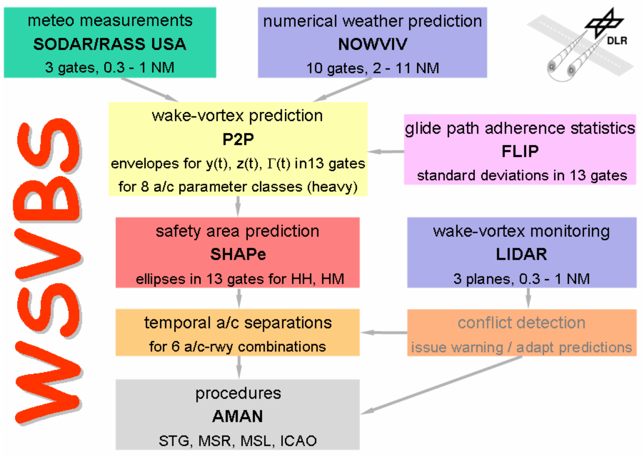

FIG 1. Flowchart of the WSVBS.

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). The instant when these safety areas do not overlap with the flight corridor define temporal aircraft separations that are translated into established procedures by the arrival manager (AMAN). As a safety net the LIDAR monitors the correctness of WSVBS predictions in the most critical gates at low altitude. The components of the WSVBS are described in detail in section 4.

3. TOPOLOGY

The WSBVS requires that all aircraft are established on the glide slope at the final approach fix (FAF) which is situated 11 NM before touchdown. For each runway 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. TAB 1 lists the gates' altitudes and distances from the touchdown zone (TDZ). FIG 2 delineates the parallel runway system 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 spaced by 518 m and axially displaced by 226.5 m.

gate No	x_{gate} [NM]	x_{gate} [m]	z_{gate} [m]
1	-11	-20372	-1077
2	-10	-18520	-979
3	-9	-16668	-880
4	-8	-14816	-781
5	-7	-12964	-683
6	-6	-11112	-584
7	-5	-9260	-486
8	-4	-7408	-387
9	-3	-5556	-289
10	-2	-3704	-191
11	-1	-1852	-94
12	-2/3	-1235	-61
13	-1/3	-617	-29

TAB 1. Gate centre positions along glide path in geodetic coordinates.

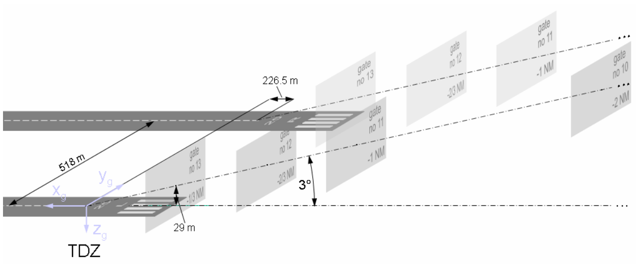

FIG 2. Zoom on gate topology for Frankfurt's closely-spaced parallel runway system.

4. 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.

4.1. 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.

4.1.1. Instrumentation

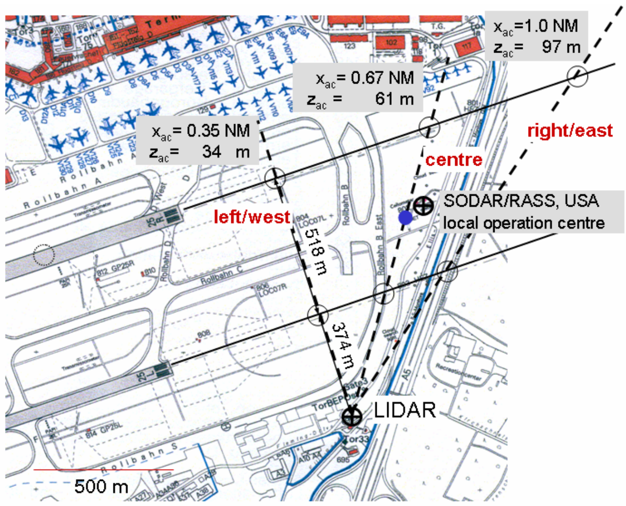

FIG 3. Sketch of instrumentation set-up at Frankfurt Airport. xac, zac denote the distance to touch-down zone and the height of landing aircraft in the three vertical lidar scan planes (dashed lines). Map reprinted by courtesy of Fraport AG.

FIG 3 shows runways 25L and 25R 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 [5]. 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 subrange of the velocity frequency spectrum.

In the LOC a Linux-PC is installed which is connected via ethernet to the SODAR/RASS/USA system and via UMTS to the computers at DLR and to the lidar container. This PC serves as a front-end for the weather and wake forecasts and observations.

4.1.2. Numerical Weather Prediction

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. NOWVIV has been successfully employed for predictions of wake vortex environmental parameters in the field campaigns WakeOP 2001 [13] and WakeTOUL 2002 [14] of projects Wirbelschleppe and C-Wake, in the first flight test campaign 2003 of AWIATOR [14], and in the measurement campaign at Frankfurt airport accomplished in fall 2004 [6], [15]. Detailed descriptions of NOWVIV and its nowcasting skill are available in [7], [8].

Within the forecast system NOWVIV, the mesoscale model MM5 [9] 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 LM (Local Model, [3]) 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 runs twice a day (at 00 and 12 UTC) on a dedicated LINUX cluster at University of Stuttgart. Profiles of meteorological data are extracted at gates 1 through 10 with an output frequency of 10 minutes. The meteorological quantities comprise the three wind components, air density, virtual potential temperature, turbulent kinetic energy, eddy dissipation rate (EDR), and pressure.

FIG 4 shows the favourable comparison of measured and predicted key meteorological quantities for wake vortex prediction collected during a 40 days measurement campaign conducted at Frankfurt airport in 2004 [7].

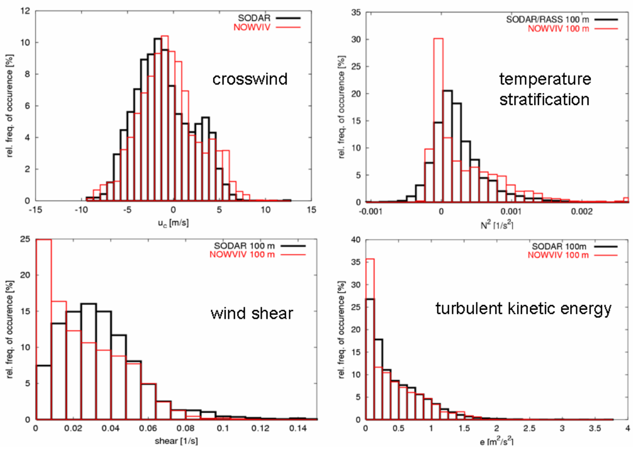

FIG 4. Histograms of measured and predicted crosswind, temperature stratification, wind shear, and turbulent kinetic energy for a 40-day measurement campaign at Frankfurt airport.

4.1.3. Integration of Meteorological Data

For approaches the largest probability to encounter wake vortices prevails at altitudes below 300 ft [2], [16]. 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 [15] the only remaining mechanism that may allow for reduced aircraft separations is lateral transport of wake vortices by crosswind.

FIG 5 evidences that the best wake-vortex prediction skill of lateral transport is achieved employing SODAR wind measurement data. Only if it is assumed that the measured wind would persist for over 70 min (lead time), the lateral vortex transport predicted with NOWVIV input yields superior results. In ground proximity vertical transport and vortex decay is largely independent from meteorological conditions. Consequently, it is also almost independent from the source of the meteorological input data and the lead time.

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 data which yields minor wake prediction skill.

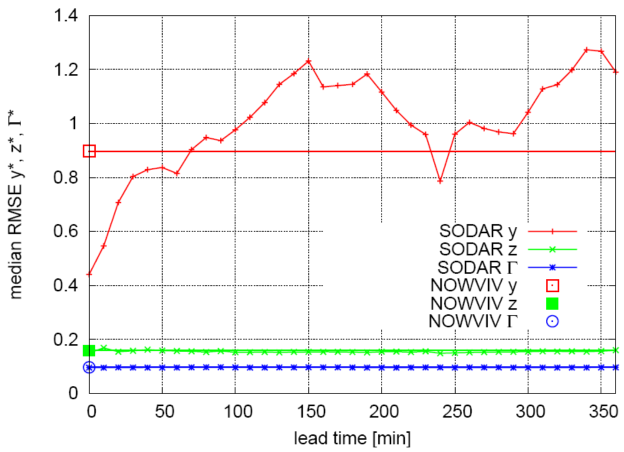

FIG 5. Normalized root-mean square deviations between measured and predicted lateral position, y*, vertical position, z*, and circulation, Γ*, as a function of the source of meteorological data and lead time.

4.2. Approach Corridor Dimensions

For the definition of approach corridor dimensions we employ the glide path adherence statistics of the FLIP study [4], 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 localiser 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 9). 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.

4.3. Representation of Aircraft Weight Classes

In principle, the WSVBS could predict conservative separations for individual aircraft pairings provided that the approaching aircraft types are known. However, in order to keep the system simple as simple as possible and, thus, to minimize additional workload for controllers, the WSVBS only considers aircraft weight class combinations. For Frankfurt airport the relevant combinations are heavy followed by heavy (HH) and heavy followed by medium (HM).

To conservatively represent generator aircraft parameters of the heavy weight category at first fits are established which bound a representative compilation of parameters of existing aircraft as function of the maximum take-off weight (see green lines in FIG 6). For the individual aircraft the circulation of the generated wake vortices is calculated according to

$$\Gamma_0 = \frac{M \cdot g}{\rho \pi / 4 B V} \quad (1)$$

where M is the maximum landing weight, ρ is air density of the standard atmosphere at sea level, $\pi/4\,B$ is the vortex separation for an elliptically loaded wing, and V the final approach speed.

FIG 6 and TAB 2 illustrate the way initial circulations, wing spans, and approach speeds are combined at the weight class boundaries. The B747-400 with a MTOW of 397 t is chosen as upper limit of the heavy weight category. TAB 2 lists the 8 resulting parameter combinations which conservatively represent all possible generator aircraft within the heavy weight category. In FIG 6 and TAB 2 the first u (l) denotes the upper (lower) bound of the weight class and the second u (l) upper (lower) fits at a given weight class boundary. The resulting wide variations of initial vortex descent speed and wake vortex time scales (variations by almost a factor of four) which are employed for any approaching aircraft indicate one of the conservative margins of the WSVBS.

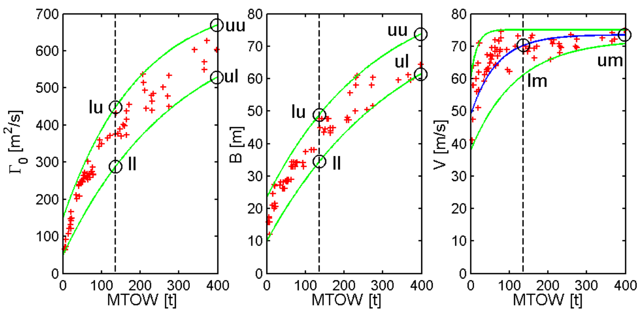

FIG 6. Initial circulation, Γ_0, wing span, B, and flight speed, V, for final approach as function of maximum take-off weight, MTOW, for 73 aircraft types. Green lines border aircraft parameters, circles denote the parameters which are combined to represent the aircraft weight class heavy.

parameter comb.	Γ_0 [m²/s]	b_0 [m]	V [m/s]	char. time scale t_0 [s]	desc. speed w_0 [m/s]
$\Gamma_{0uu}\ b_{0uu}$	669.2	57.9	73.5	31.5	1.84
$\Gamma_{0uu}\ b_{0ul}$	669.2	48.2	73.5	21.8	2.21
$\Gamma_{0ul}\ b_{0uu}$	528.5	57.9	73.5	**39.9**	1.45
$\Gamma_{0ul}\ b_{0ul}$	528.5	48.2	73.5	27.6	1.75
$\Gamma_{0lu}\ b_{0lu}$	448.1	38.4	70.3	20.7	1.86
$\Gamma_{0lu}\ b_{0ll}$	448.1	27.1	70.3	**10.3**	**2.63**
$\Gamma_{0ll}\ b_{0lu}$	288.2	38.4	70.3	32.1	**1.19**
$\Gamma_{0ll}\ b_{0ll}$	288.2	27.1	70.3	16.0	1.69

TAB 2. Aircraft parameter combinations for initial circulation, Γ_0, vortex separation, b_0, and flight speed, V, which represent the aircraft weight class heavy and resulting characteristic time scales and initial descent speeds (maxima and minima in bold).

4.4. Wake-Vortex Prediction

Wake-vortex prediction is conducted with the Probabilistic Two-Phase wake-vortex decay model (P2P) which is described in detail in [12]. Applications, assessments and further developments are reported in [6], [13], [14], and [15]. 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 1,300 cases gathered in two US and four 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 (see FIG 7). FIG 7 illustrates asymmetric vortex rebound characteristics caused by crosswind in ground proximity.

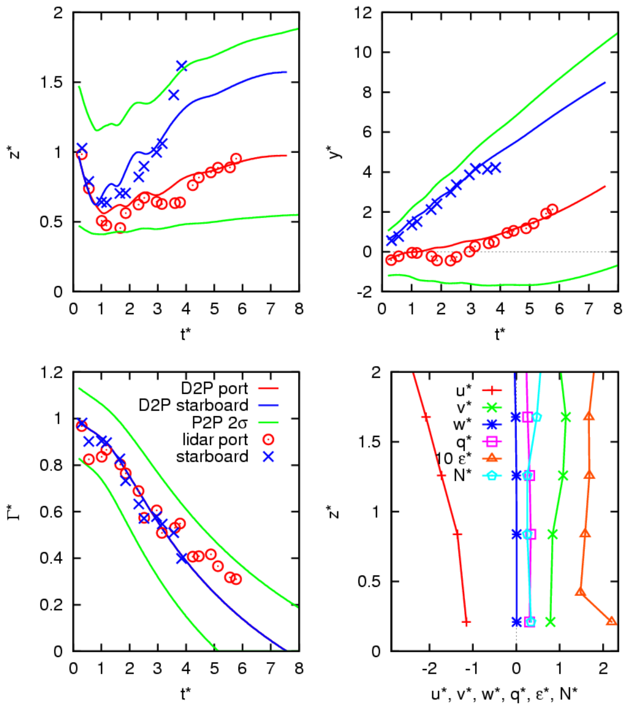

FIG 7. Evolution of normalized vertical and lateral positions and circulation in ground proximity. Measurements by lidar (symbols) and predictions with P2P wake vortex model (lines). Red and blue lines denote deterministic behaviour, green lines are probabilistic envelopes (95.4%). Right below vertical profiles of measured meteorological parameters. Normalizations based on initial values of vortex spacing, circulation, and time needed to descend one vortex spacing.

For the time being, the confidence intervals for y, z, and Γ_0 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 [14]. 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 input.

4.5. 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 [18], [10] 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 roll control input, which is required to compensate the exerted rolling moment, to the maximum available roll control power.

In FIG 8 the red areas with $RCR_{req} > 1$ denote regions where the roll capability of the follower aircraft is exceeded. Full flight simulator investigations yield acceptable results for manual control for a value of $RCR_{req} = 0.2$ [18]. Recent results from real flight tests using DLR's fly-by-wire in-flight simulator ATTAS support this conclusion [17]. In FIG 8 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.

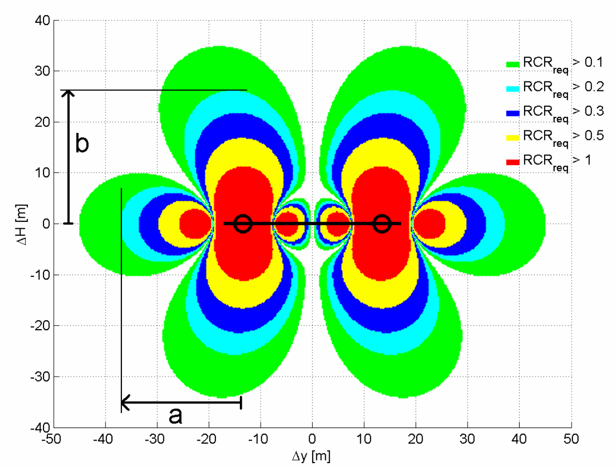

FIG 8. Roll control power required to compensate wake-vortex induced rolling moments. Horizontal and vertical allowances a and b for $RCR_{req} < 0.2$.

Again no individual wake vortex and follower aircraft pairings are considered for the WSVBS (although that would be possible) but wake vortex envelopes which represent the heavy category are 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 in section 4.3 for wake vortex prediction. This method of using MTOW based aircraft parameters for the determination of simplified hazard areas is called SHAPe (Simplified Hazard Area Prediction) [10].

5. SYSTEMS INTEGRATION

This section describes how the above introduced components are combined for the prediction of adapted aircraft separations. Section 5.1 considers components within a single gate, section 5.2 then explains how the minimum temporal aircraft separations are derived from the predictions within all the gates. Finally, section 5.3 sketches the temporal prediction cycle which defines parameters like update rate and prediction horizon.

5.1. Components in Single Gate

FIG 9 illustrates the process seen in flight direction in control gate 11 for the leader aircraft parameter combination Γ_{0uu}, b_{0uu} 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 9 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. Because the lateral vortex position can only be predicted less precise (uncertainty and variability of crosswind) than vertical position (c.f. FIG 5), 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 [15]. Safety area margins for aircraft pairings HH and HM are added to the vortex corridors, resulting in overall safety areas to be avoided.

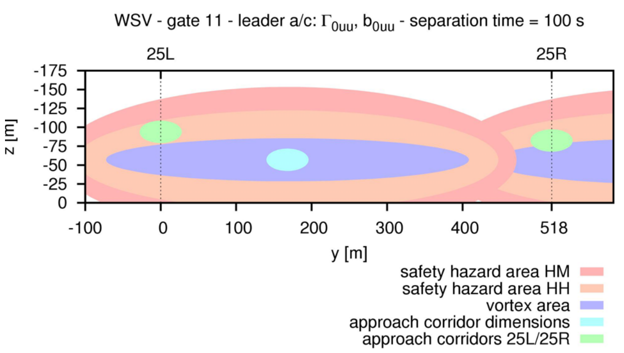

FIG 9. Ellipses denoting approach corridor dimensions, vortex areas, and safety areas in gate 11 for a vortex age of 100 s.

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 a single 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 runway within the prediction horizons. 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 9 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.

5.2. Complete Domain

One prediction sequence comprises 13 gates for each runway, 8 generator aircraft parameter combinations, 3 runway combinations (generator and follower on single runway (25L25L or 25R25R), generator on 25L and follower on 25R (25L25R), and vice versa), and 2 follower weight classes. So in total 1248 cases are considered. From the 1248 cases for each of the 3 runway combinations and 2 follower weight classes the cases with maximum vortex ages with conflicts are identified. These maximum gate obstruction times define minimum aircraft separation times MST. The output of the WSVBS consequently consists of the following matrix.

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

TAB 3. Minimum separation times for different runway and weight category combinations.

Note that the MST in TAB 3 are consistent with the situation displayed in FIG 9. In TAB 3 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). The translation of the separation matrix into procedures and displays which are suitable for air traffic control (ATC) is described in part II of the paper.

The idea is that all corridors used in the process and shown in FIG 9 should be based on identical probability levels, currently, twice the standard deviations (2σ) of respective data. However, the safety area prediction concept on one hand is not probabilistic, i.e. the predicted safety areas are safe without any exception for the investigations conducted so far, and on the other hand it assumes that the wake vortices are situated along the envelopes of the vortex area. A reduction of vortex area allowances to 1.7σ (91.1%) causes that the safety areas are only added to 95.4% of the potential wake vortex positions and herewith implicitly confers a 2σ-confidence level to the safety area module.

Unfortunately, the very question: "Which overall safety is actually achieved by the combination of the various conservative elements of the WSVBS?" can not be answered easily. It is planned to adjust all components to consistent confidence levels once the methodology of a comprehensive risk analysis is established.

5.3. Prediction Cycle

Every 10 minutes new Sodar/RASS and NOWVIV data are available. Then the WSVBS 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.

6. 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 is 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). Once the real-time capability of vortex monitoring is established it is foreseen to integrate a conflict detection module which may issue warnings and/or may adapt the WSVBS predictions (see FIG 1).

7. CONCLUSIONS

The manuscript describes the design of the Wake Vortex Prediction and Monitoring System WSVBS with all its components and their interaction. The WSVBS consists of components that consider meteorological conditions, aircraft glide path adherence, aircraft parameter combinations representing aircraft weight categories, the resulting wake-vortex behaviour, the surrounding safety areas, and wake vortex monitoring. The elements of the WSVBS are generic and can well be adjusted to other runway systems and airport locations.

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. 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 that represent complete aircraft weight categories. 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 within 1248 investigated parameter combinations determines the possible aircraft separations. d) A safety net consisting of 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.

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