

# THE WAKE VORTEX PREDICTION AND MONITORING SYSTEM WSVBS

## DESIGN AND PERFORMANCE AT FRANKFURT AIRPORT

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### Abstract

The 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 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. As a safety net a 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.

**Keywords:** *wake vortex, airport capacity, closely-spaced parallel runways, meteorology, safety*

### 1 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 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 [13]. A survey on wake-vortex advisory systems and modifications of procedures that are meant to increase airport capacity is available in [22].

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. Nevertheless, the elements of the WSVBS are generic and can well be adjusted to other runway systems and airport locations. The system predicts wake vortex transport and decay and the resulting safety areas along the glide slope from final approach fix to threshold.

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. Precursor versions of this paper have been presented before [9], [18].

## 2 System Overview

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).

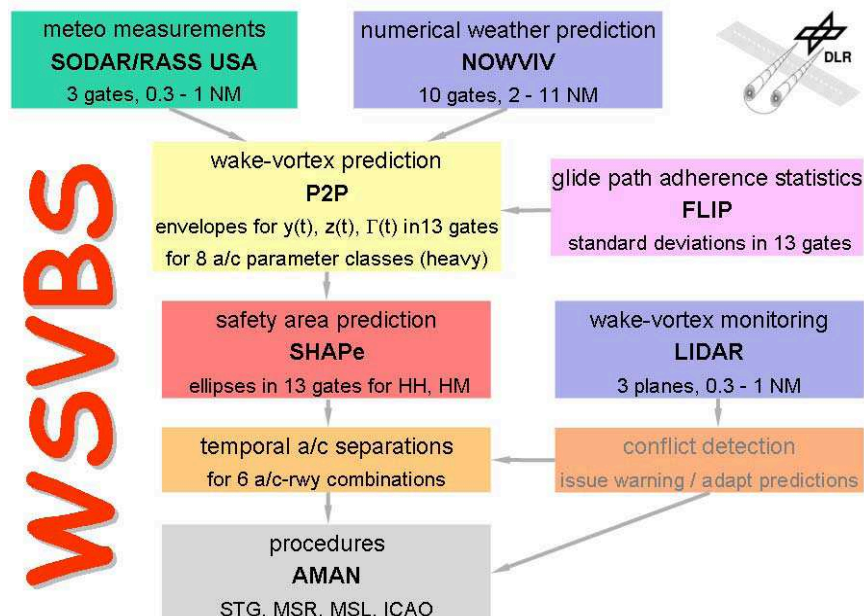


FIG 1. Flowchart of the WSVBS.

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 (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 WSVBS 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). For each runway 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 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.

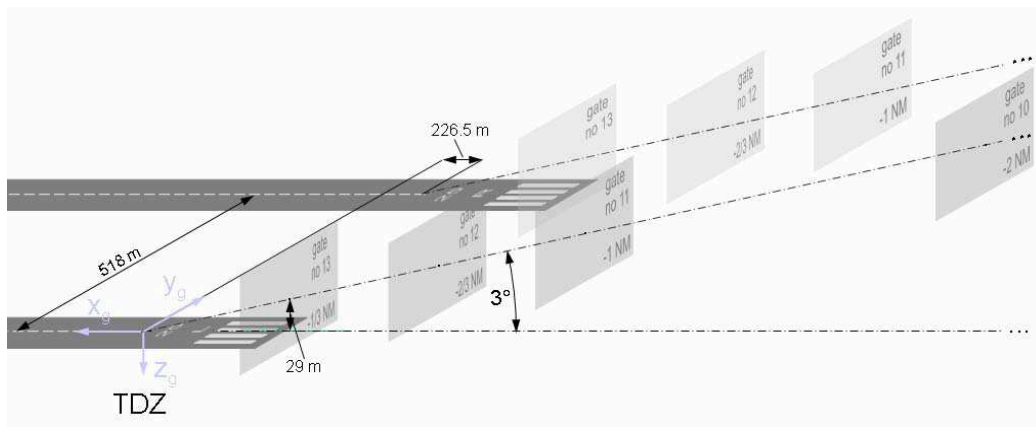


FIG 2. Zoom on gate topology for Frankfurt's closely-spaced parallel runway system.

## 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,  $2\sigma$ , 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.

### Instrumentation

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.

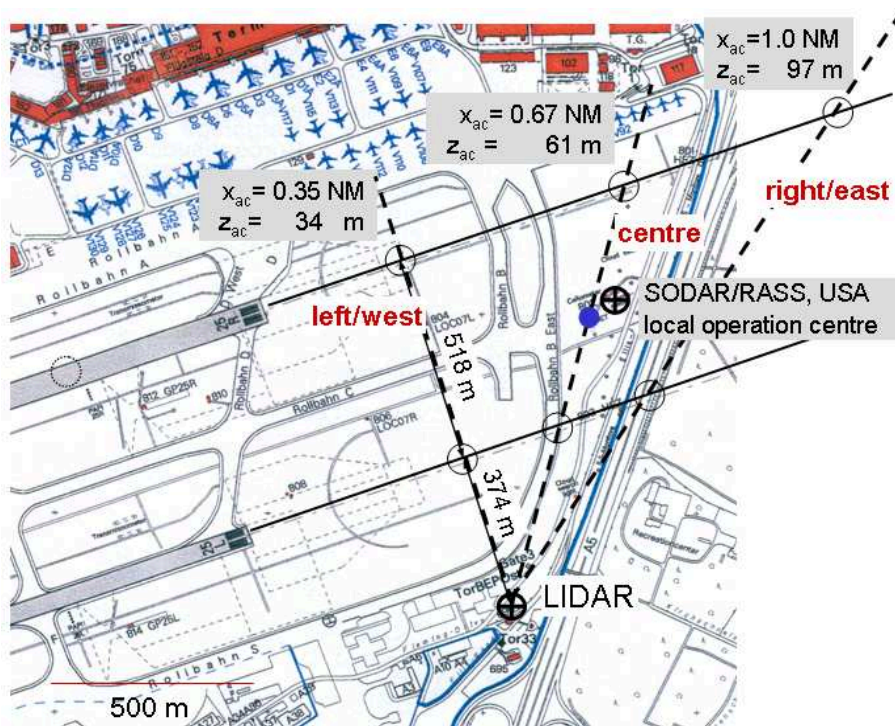


FIG 3. Sketch of instrumentation set-up at Frankfurt Airport.  $x_{ac}$ ,  $z_{ac}$  denote the distance to touch-down zone (TDZ) and the height of landing aircraft in the three vertical LIDAR scan planes (dashed lines). Map reprinted by courtesy of Fraport AG.

### 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 (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 [18]. Detailed descriptions of NOWVIV and its nowcasting skill are available in [6], [7], [8].

Within the forecast system NOWVIV, the mesoscale model MM5 [10] predicts the meteorological conditions for the Frankfurt terminal area in two nested domains with sizes of about 250 x 250 km<sup>2</sup> and about 90 x 90 km<sup>2</sup> 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, [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 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.

### **Integration of Meteorological Data**

For approaches the largest probability to encounter wake vortices prevails at altitudes below 300 ft [2], [19], [22]. 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 [17] the most important mechanism that may allow for reduced aircraft separations is lateral transport of wake vortices by crosswind.

Ref. [6] 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 data which yields minor wake prediction skill.

### **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 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 ( $2\sigma$ ) 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 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 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) 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.

### 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 [14]. Applications, assessments and further developments are reported in [5], [15], [16], and [17]. 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 1,400 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, see FIG 4, 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  $\Gamma$  are adjusted to  $2\sigma$ -probabilities. The respective uncertainty allowances are achieved by a training procedure which employs statistics of measured and predicted wake vortex behaviour [16]. 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.

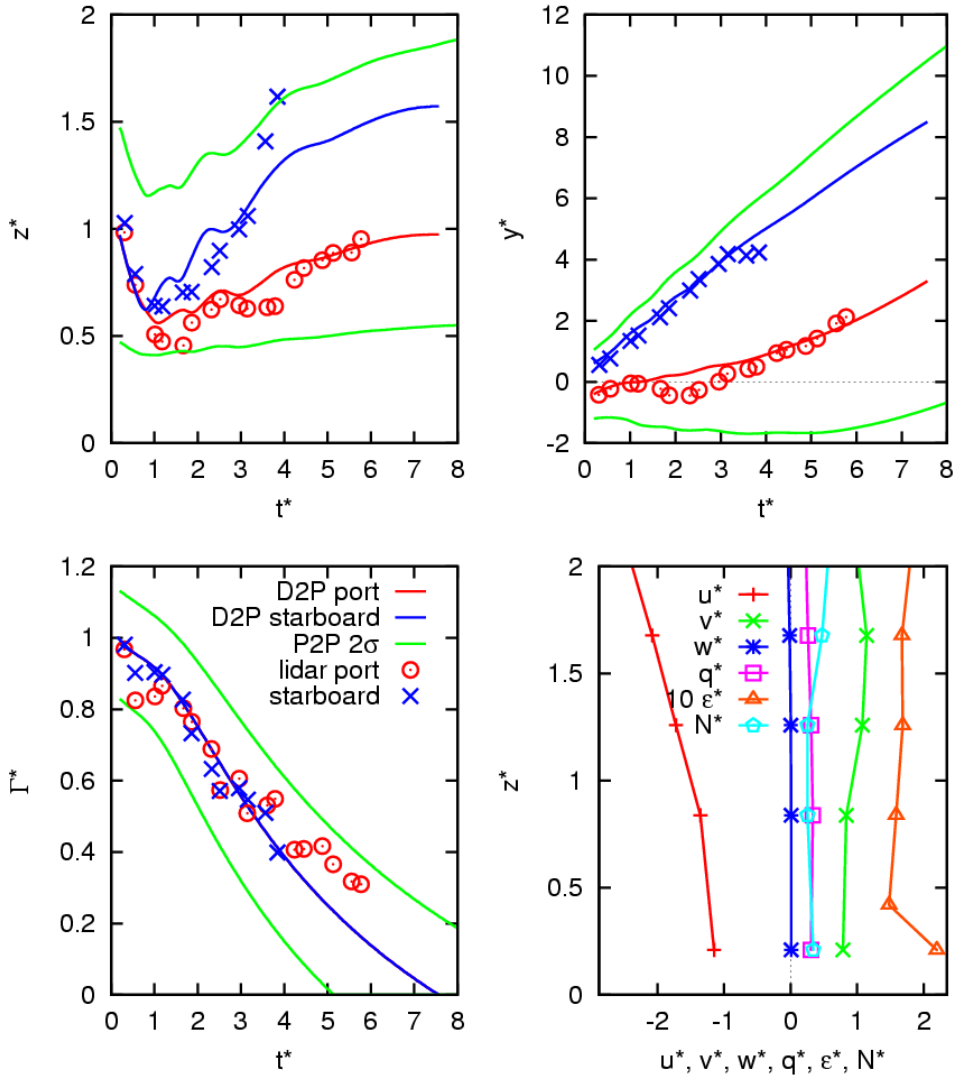


FIG 4. Evolution of normalised vertical and lateral positions and circulation in ground proximity. Measurements by lidar (symbols) and predictions with the P2P wake vortex model (lines). Red and blue lines denote deterministic behaviour; green lines are probabilistic envelopes (95.4%). Right below vertical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

#### 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 [12], [21] 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  $R_{CR_{req}}$  which relates the roll control input, that is required to compensate the exerted rolling moment, to the maximum available roll control power.

In FIG 5 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  $RCR_{req} = 0.2$  [20]. Results from real flight tests, using DLR's fly-by-wire in-flight simulator ATTAS, support this conclusion [19]. In FIG 5 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.

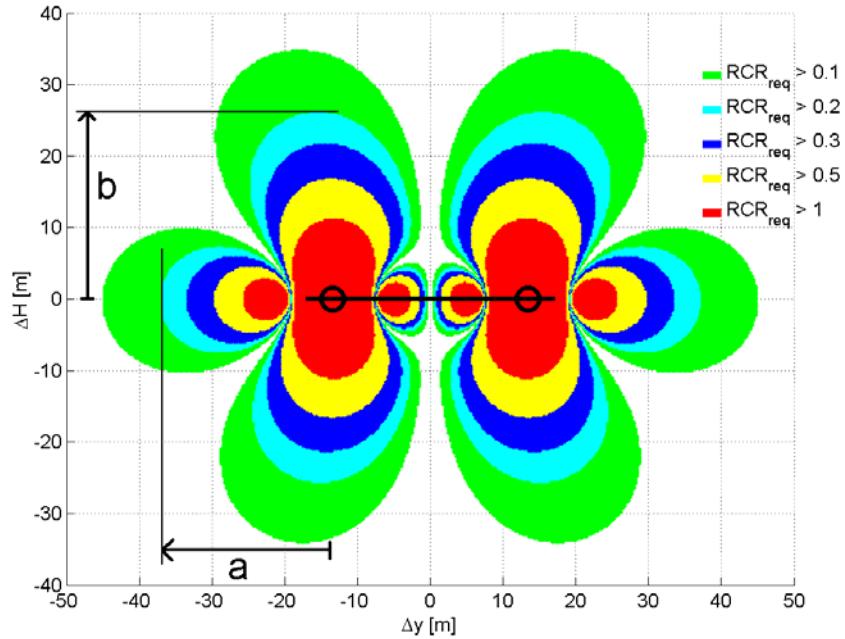


FIG 5. Roll control power required to compensate wake-vortex induced rolling moments. Horizontal and vertical allowances a and b for  $RCR_{req} < 0.2$ .

As for wake vortex prediction 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) [12].

## 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 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.

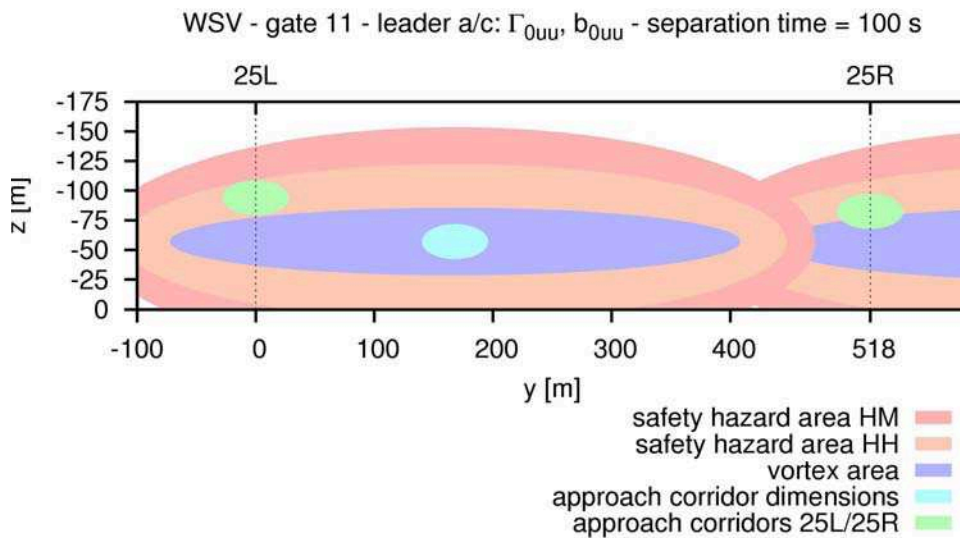


FIG 6. Ellipses denoting approach corridor dimensions, vortex areas, and safety areas in gate 11 for a vortex age of 100 s.

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, 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 [17]. 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.

## 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 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).

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

TAB 1. Minimum separation times for different runway and weight category combinations.

The predicted MST are translated into four modes or concepts of operation for aircraft separation which have been established by the German Air Safety Provider DFS to be applied to the dependent parallel runway system at Frankfurt Airport under instrumented meteorological conditions (IMC) [11]:

- “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.

The idea is that all corridors used in the process and shown in FIG 6 should be based on identical probability levels, currently, twice the standard deviations ( $2\sigma$ ) 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 positioned at the envelopes of the vortex area, which manifests a very conservative element of our prediction. A reduction of the vortex area allowances from  $2\sigma$  to  $1.7\sigma$  (91.1%) causes that the safety areas are only added to 95.4% of the potential wake vortex positions and herewith implicitly confers a  $2\sigma$ -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.

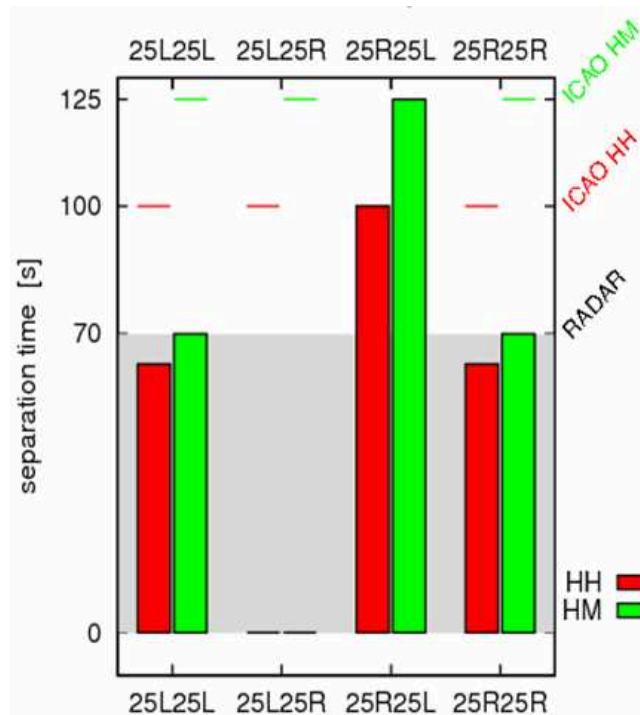


FIG 7. Display of full MST information and derived arrival procedures for Frankfurt Airport on 2007-Jan-25 at 15:10 UTC.

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.

## 6 Wake-Vortex Monitoring

Wake-vortex monitoring is used to identify potential erroneous predictions of the WSVBS. For this purpose DLR's 2  $\mu\text{m}$  pulsed Doppler LIDAR is operated in vertical scan mode with elevations between  $0^\circ$  to  $6^\circ$  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).

FIG 8 shows a quick-look result from 16. January 2007 at 04:17 UTC in the "centre" vertical scan plane. At that time most heavy aircraft landed on runway 25R (the northern runway). The colour-coded area shows the line-of-sight (LOS) wind component. Patterns of wind shear and of a wake vortex pair can be distinguished. The quick-look also indicates roughly the position of the two flight corridors for landing aircraft in the scan plane. Thus, it is possible to check if the predicted minimum separation times are correct: the vortices visible in the LIDAR quick-look should not reside within the flight corridors when the forecast system allows the next aircraft to enter the control gate. The quick-look, however, only allows for a rough estimate of the vortex location. After signal and image (post-) processing, the spatial resolution of the LOS velocity is 3 m and the wake vortex position (and strength) can be deduced with high accuracy.

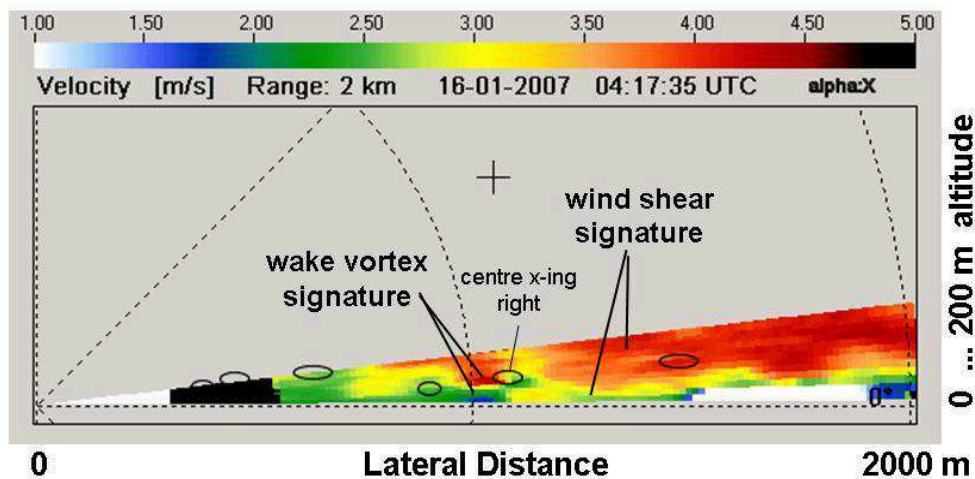


FIG 8. LOS velocity as measured by LIDAR (quick-look after one scan, positive values indicate velocities away from the instrument) with signatures of wind shear and a wake vortex pair. The crossings of the laser beam with the glide paths are indicated by small ellipses; "centre x-ing right" identifies the approximate intersection of the beam in scan plane "centre" with runway 25R at 1070 m distance.

## 7 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. [9]. 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.

FIG 9 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 3%.

FIG 10 summarises the history of DFS operation modes as proposed by the WSVBS during the 66 days of performance at the airport (not considering any traffic mix). In 75% of the time the modes, which allow improving capacity or punctuality of landing aircraft, could have been deployed. The focus on five days (FIG 10 lower panel) indicates that each mode can be deployed throughout a significant fraction of time.

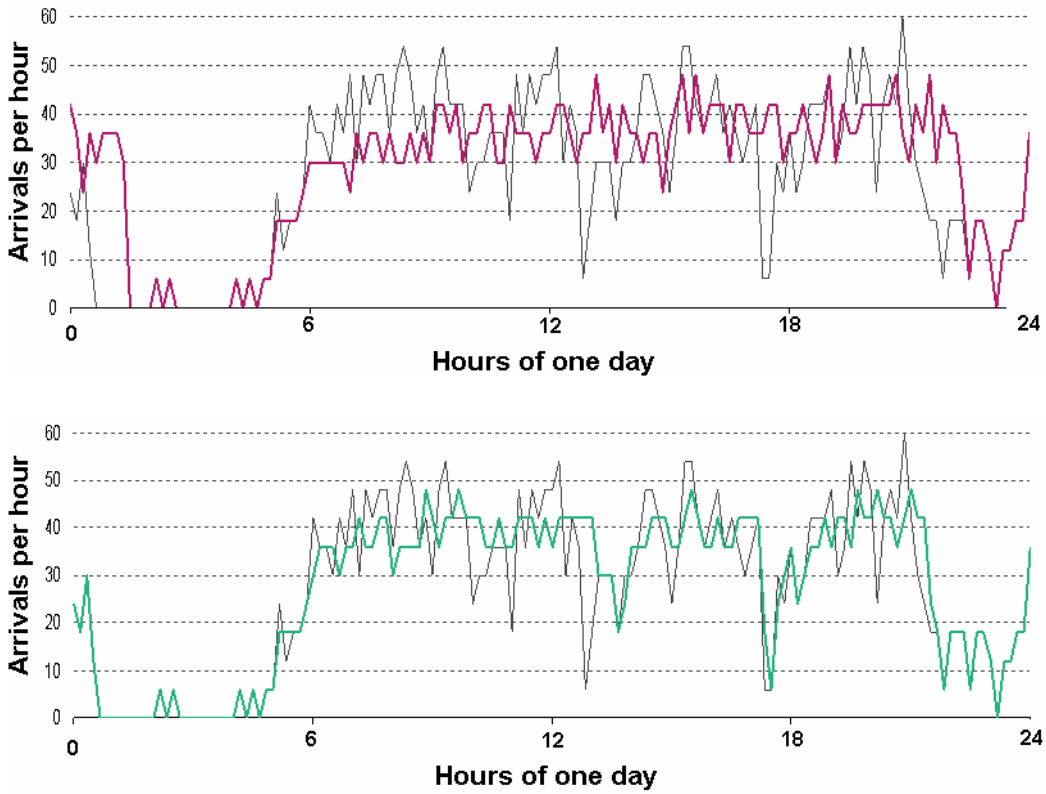


FIG 9. Traffic flow (arrivals per hour) during a day at Frankfurt Airport. Top: demand (grey) vs. ICAO standards (red); bottom: demand vs. WSVBS utilisation (green).

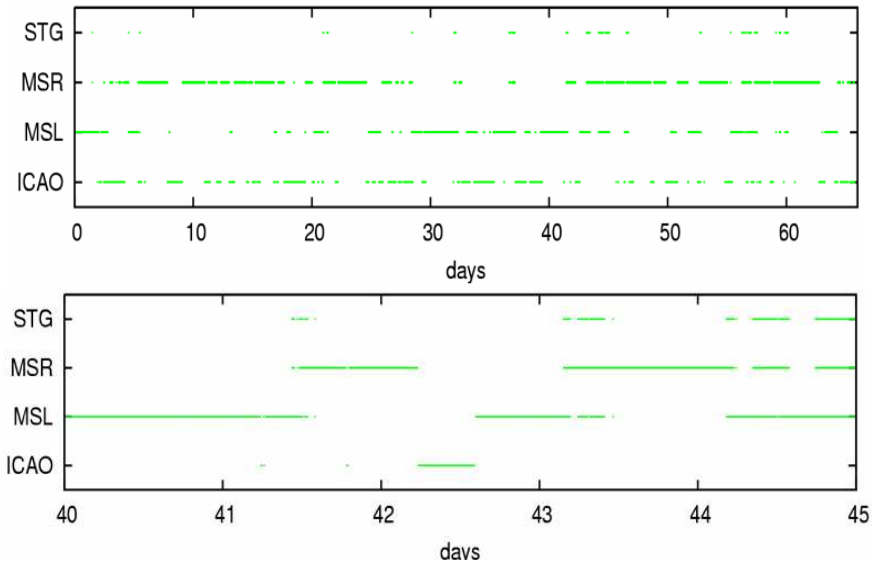


FIG 10. History of usage of the 4 DFS operation modes during the 66 days of the campaign at Frankfurt. Top: full period; bottom: zoom on five days.

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 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 numbers hold for the aircraft pairing HH and somewhat reduced numbers 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).

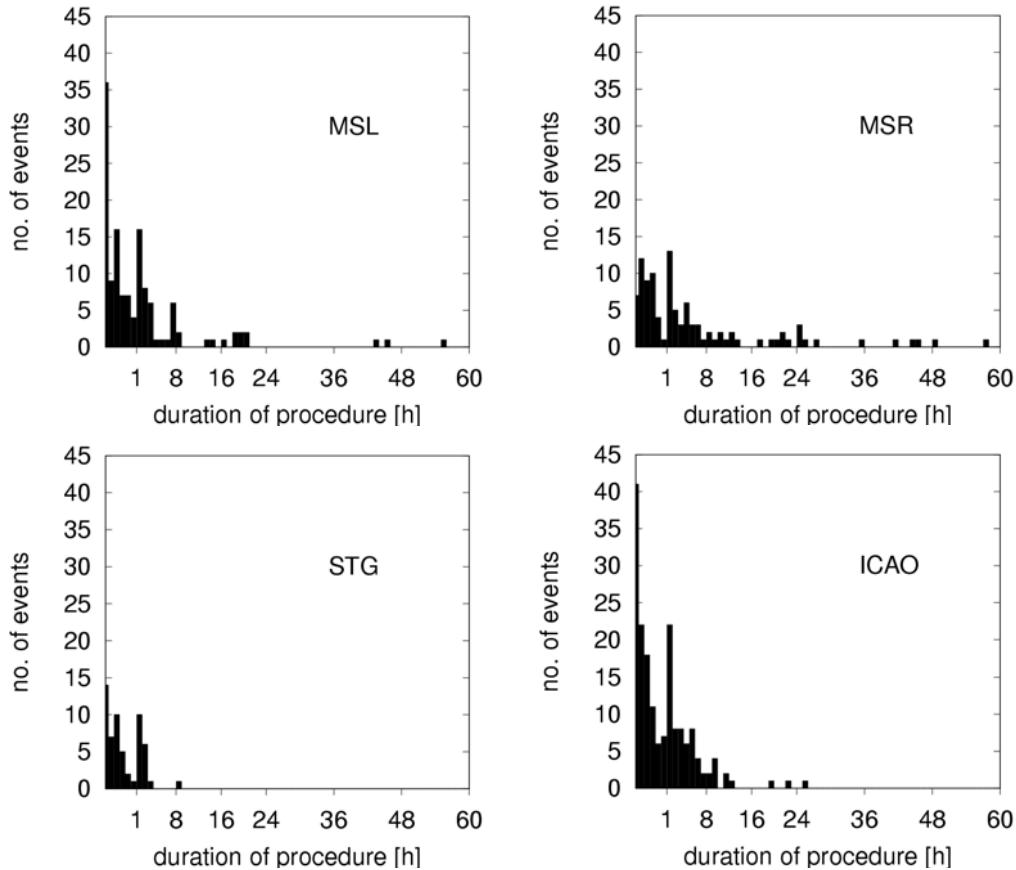


FIG 11. Number of events versus duration of DFS procedures in hours for HM aircraft pairs; a 10 min interval is used in the 1<sup>st</sup> hour, the interval is 1 hour afterwards.

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 the safety net LIDAR in the three scan planes shown in FIG 3. For the 18<sup>th</sup> 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 8<sup>th</sup> 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.

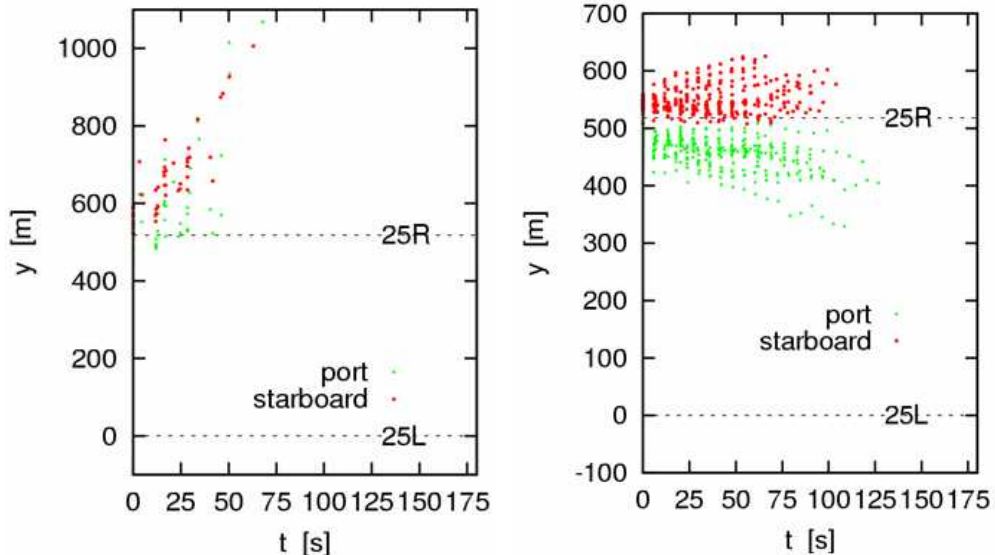


FIG 12. Lateral positions of wake vortices vs. vortex age from 8 and 32 heavy aircraft landing on 25 R on 18<sup>th</sup> Jan. (left) and 8<sup>th</sup> Feb. (right) 2007, respectively, as tracked by the LIDAR in the three scan planes.

## 8 Conclusions

The paper 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, wake vortex monitoring, and the integration of the predictions into the arrival manager. The elements of the WSVBS are generic and can well be adjusted to other runway systems and airport locations. The prediction horizon is larger than 45 min (as required by air traffic controllers) and updated every 10 minutes. It predicts the concepts of operations and procedures established by DFS and it further predicts additional temporal separations 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. 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.

The WSVBS has demonstrated its functionality at Frankfurt airport during 66 days in the period from 18/12/06 until 28/02/07. The performance test indicates that (i) the system ran stable - no forecast breakdowns occurred, (ii) aircraft separations could have been reduced 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 predictions were correct as for about 1100 landings observed during 16 days no warnings occurred from the LIDAR.

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 an increase in capacity to 3% 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".

Before the WSVBS can be handed over for final adaptations to become a customized fully operational system some further steps are planned. DLR will expand the system to include landings on runways 07/L/R. The LIDAR shall be operated automatically and the traced vortex positions shall be used on-line to check for forecast errors and warn the operators in case of an increased risk. Finally, also a risk analysis needs to be pursued to convince all stakeholders of the usefulness and capabilities of our system.

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