Air Traffic Control Quarterly

An International Journal of Engineering and Operations

Volume 17 • Number 4 • 2009

Published by:

Air Traffic Control Association Institute, Inc.

Air Traffic Control Quarterly

An International Journal of Engineering and Operations

Published by the: Air Traffic Control Association Institute, Inc.

PUBLISHER
Air Traffic Control Association Institute, Inc.
1101 King Street, Suite 300
Alexandria, Virginia 22314
Telephone: (703) 299-2430
Fax: (703) 299-2437
E-mail: info@atca.org
Web site: www.atca.org

Air Traffic Control Quarterly (ISSN: 1064-3818) is published quarterly by the Air Traffic Control Association Institute, Inc., 1101 King Street, Suite 300, Alexandria, Virginia 22314.

Subscription price: $200 U.S. and Canada; $250 outside U.S. and Canada; $100 members of the Air Traffic Control Association; $100 students, faculty, and researchers at academic institutions. Claims for undelivered copies will be accepted only after the following issue has been received. Please enclose a copy of the mailing label. Missing copies will be supplied when losses have been sustained in transit and where reserve stock permits. Please allow four weeks for processing a change of address.

Manuscripts should be sent to the editor at the above address.

This paper meets the requirement of ANSI/NISO Z39.48-1992 (Permanence of Paper).

Air Traffic Control Quarterly

An International Journal of Engineering and Operations

Volume 17 • Number 4 • 2009

The Wake Vortex Prediction and Monitoring System WSVBS Part I: Design

Frank Holzäpfel, Thomas Gerz, Michael Frech, Arnold Tafferner, Friedrich Köpp, Igor Smalikho, Stephan Rahm, Klaus-Uwe Hahn, and Carsten Schwarz

The design of the Wake Vortex Prediction and Monitoring System WSVBS is described with all its components and their interaction. The WSVBS was developed to tactically increase airport capacity for approach and landing on closely-spaced parallel runways. The WSVBS supports dynamic adjustment of aircraft wake vortex separations dependent on weather conditions and the resulting wake vortex behavior without compromising safety. Dedicated meteorological instrumentation and short-term numerical terminal weather prediction provide the input to the prediction of wake-vortex behavior and respective safety areas. The prediction tools employ a number of conservative aircraft parameter combinations that represent the medium and heavy aircraft weight categories. Safe aircraft separations correspond to times when the predicted safety areas associated with wake vortices generated by leading heavy aircraft cannot overlap the arrival flight corridor. A LIDAR monitors the correctness of WSVBS predictions in the most critical regions at low altitude.

Frank Holzäpfel, Thomas Gerz, Michael Frech, Arnold Tafferner, Friedrich Köpp, Igor Smalikho, and Stephan Rahm are with Deutsches Zentrum für Luft- und Raumfahrt (DLR), Oberpfaffenhofen, Germany. Klaus-Uwe Hahn, and Carsten Schwarz are with DLR, Braunschweig, Germany.

Received March 23, 2009; accepted August 25, 2009.

Air Traffic Control Quarterly, Vol. 17(4) 301–322 (2009)
 CCC 1064-3818/95/030163-20

INTRODUCTION

Aircraft trailing vortices may pose a potential risk to following aircraft. The empirically motivated wake vortex separation standards that were first introduced in the 1970s still apply. The current aircraft separations standards 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 efficient use of both runways.

The most rapid growth scenario within a EUROCONTROL study [EUROCONTROL, 2004] indicates that in the year 2025 sixty European airports could be congested and up to 3.7 million flights per year could not be accommodated. The introduction of a wake-vortex advisory system could achieve estimated annual savings of direct operating costs of US $ 15 million per year at congested airports that have a closely-spaced parallel runway configuration [Hemm et al., 1999]. This estimate 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 of wake-vortex advisory systems and procedural modifications meant to increase airport capacity is available in [Elsenaar, 2006].

The Deutsche Zentrum für Luft- und Raumfahrt (DLR) has developed the Wake Vortex Prediction and Monitoring System (Wirbel-Schleppen-Vorhersage- und Beobachtungs-System WSVBS [Gerz et al., 2005]) to tactically increase airport capacity for approach and landing. The WSVBS shall support dynamic adjustment of aircraft wake vortex separations dependent on weather conditions and the resulting wake vortex behavior 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 determines the resulting safety areas along the glide slope from final approach fix to threshold. The elements of the WSVBS are generic and can be adjusted to other runway systems and airport locations.

This paper describes the design of the WSVBS with all its components and their interaction. The experimental integration of the WSVBS into air traffic control automation systems and its promising performance during a three-month measurement campaign at Frankfurt Airport are described in Part II of this paper. Precursor versions of these papers have been presented at the CEAS Conference 2007 [Gerz et al., 2007; Holzäpfel et al., 2007].

SYSTEM OVERVIEW

Figure 1 delineates the components of the WSVBS and their interplay. The bottleneck of runway systems occurs near the ground where stalling or rebounding wake vortices may not descend below the arrival flight corridor. Therefore, the best wake prediction performance is required when wakes are in close proximity to the ground. The WSVBS incorporates measurements of meteorological conditions with a SODAR/RASS system and an ultra sonic anemometer (USA) to enhance the prediction of wake vortex behavior near the ground. 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 predictions of wake position and strength 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 a safety area around a vortex that must be avoided by follower aircraft for safe and undisturbed flight (SHAPe). The instant these safety areas do not overlap with the arrival flight corridor defines safe temporal aircraft separations. These temporal separations are translated into dynamic separations based on established procedures by the DLR arrival manager (AMAN). The LIDAR monitors the correctness of WSVBS wake vortex predictions in the most critical gates associated

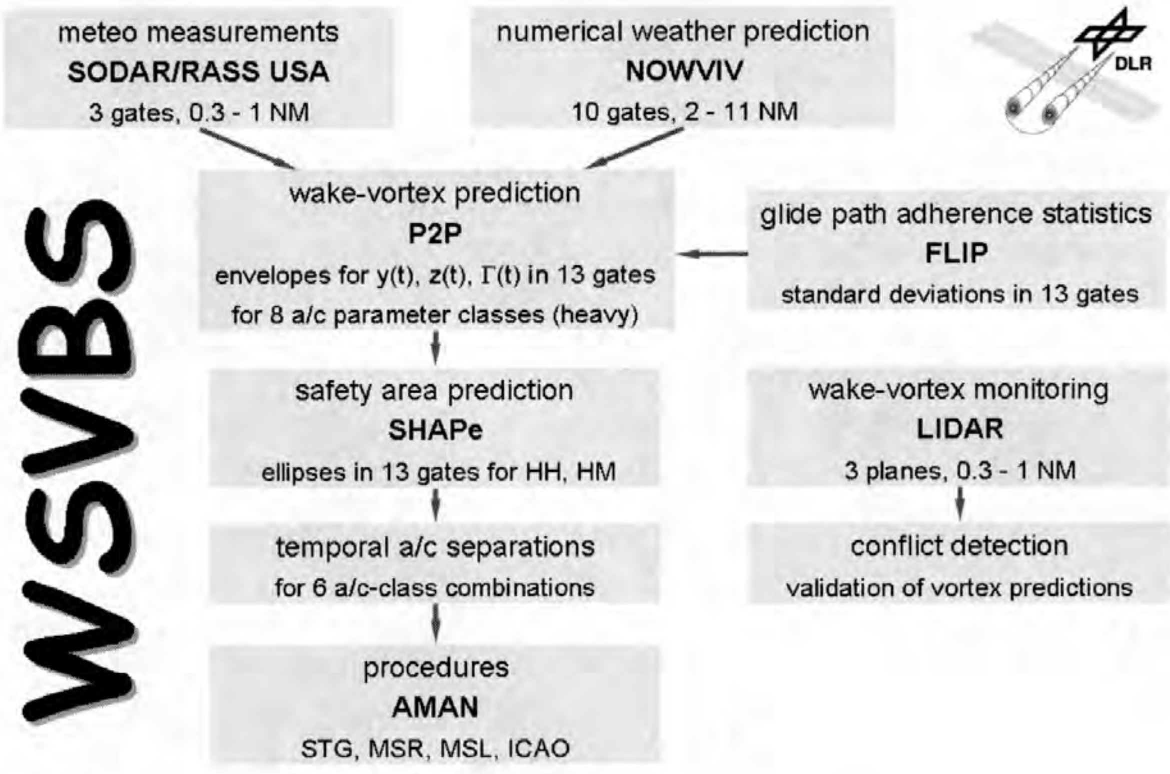

Figure 1. Flowchart of the WSVBS.

with the low altitude portions of the arrival corridor. The components of the WSVBS will be described in detail later, together with their respective references.

RELATED WAKE VORTEX ADVISORY SYSTEMS

The two wake vortex advisory systems that were most influential for the development of the WSVBS are briefly introduced in this section. NASA has been developing the Aircraft Vortex Spacing System (AVOSS) [Hinton et al., 2000] to produce weather dependent, dynamic wake vortex spacing criteria. The AVOSS concept provides for several similar components as those of the WSVBS described in the previous section. In a real-time field demonstration during July 2000 at the Dallas Ft. Worth International Airport, functional elements for meteorological measurements, glide path adherence statistics, wake-vortex prediction, and wake-vortex monitoring (cf. Figure 1) were applied to a single runway system [Rutishauser and O'Connor, 2001]. An increase of runway throughput of 6% was predicted, where less than 1% of the predictions did not yet safely represent the observed wake behavior.

The DFS Deutsche Flugsicherung GmbH has developed the Wake Vortex Warning System (WVWS) [Gurke and Lafferton, 1997] to allow for the suspension of wake vortex separation between subsequent aircraft approaching the closely-spaced parallel runways 25 at Frankfurt airport during favorable meteorological conditions. Based on wind and turbulence measurements of a 15 m anemometer array, the WVWS predicts whether or not wake vortices may reach the parallel runway in ground proximity. As described in Part II of this paper the landing procedures developed for the WVWS were adopted by the WSVBS.

Later the DFS established the so-called glide path extension of the WVWS, which employs a wind-temperature radar with a radio acoustic sounding system (WTR/RASS) to measure wind and temperature up to 5000 ft above ground level [Konopka and Fischer, 2005]. The limited fraction of time when safe approaches with reduced wake turbulence separation can be guaranteed prevents the operational utilization of the system.

A survey on further wake-vortex advisory systems and procedural modifications meant to increase airport capacity is available in [Elsenaar, 2006].

TOPOLOGY

The WSBVS concept requires that all aircraft are established on the glide slope at the final approach fix (FAF), which is situated 11 nmi before touchdown. For each runway, wake-vortex evolution

is predicted within 13 distinct planes, termed gates, perpendicular to the final approach flight path. In ground proximity the nominal gate separation of 1 nmi is reduced to 1/3 nmi to properly resolve the interaction of wake vortices with the ground. Table 1 lists the gates' altitudes and distances from the touchdown zone (TDZ). Figure 2 delineates the parallel runway system with the employed geodetic coordinate system and some of the gates near the ground. The parallel runways and consequently also the gate centers are laterally spaced by 518 m and axially displaced by 226.5 m.

SYSTEM COMPONENTS

The different system components will be adjusted to produce 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

Table 1. Gate Centre Positions Along Glide Path in Geodetic Coordinates

gate No	x_{gate} [nmi]	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

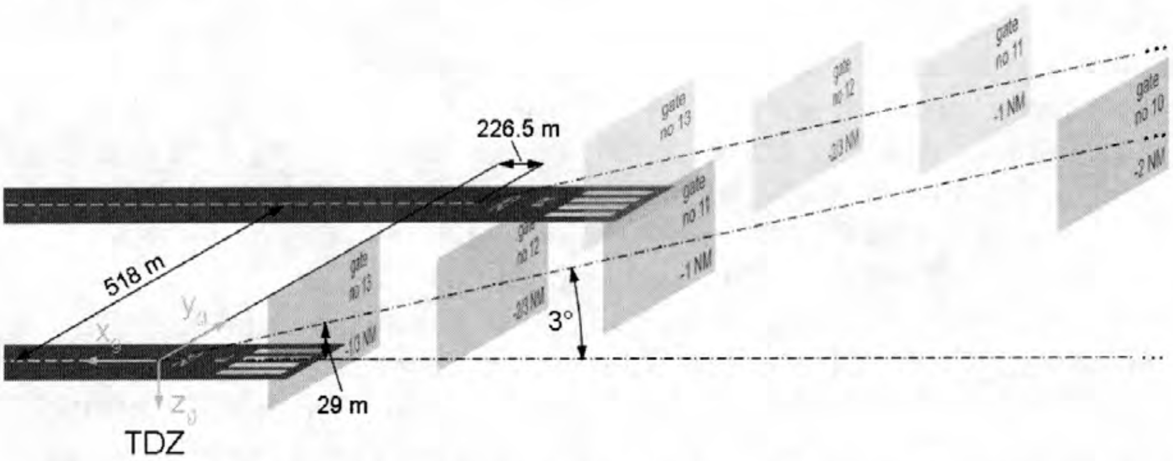

Figure 2. Zoom on gate topology for Frankfurt's closely-spaced parallel runway system.

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 Figure 1 in detail.

Meteorological Data

For prediction of wake-vortex behavior along the final approach path meteorological conditions with good accuracy must be provided for the relevant airspace with a forecast horizon of 1 hour. A combination of measurements (employing the persistence assumption [Frech and Holzäpfel, 2008]) and numerical weather predictions provides for the required temporal and spatial coverage.

Instrumentation. For the three lowest gates at 1/3, 2/3, and 1 nmi from the TDZ a METEK Sodar with a RASS extension provides 10-minute averages of vertical profiles of the three wind components, the 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 the vertical fluctuation velocity and the vertical wind gradient employing a simplified budget equation [Frech, 2004]. A spectral analysis of the longitudinal wind velocity measured by the sonic anemometer is used to estimate EDR by fitting the -5/3 slope in the inertial subrange of the velocity frequency spectrum.

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 that is not covered by measurements (the more remote 10 gates from 2 to 11 nmi). NOWVIV has been successfully employed for predictions of wake vortex environmental parameters in the field campaigns WakeOP 2001 [Holzäpfel and Robins, 2004] and WakeTOUL 2002 [Holzäpfel, 2006] of the Wirbelschleppe and C-Wake projects, respectively. It has also been successfully employed in the first flight test campaign 2003 of AWIATOR [Holzäpfel, 2006], and in the measurement campaign at Frankfurt airport accomplished in fall 2004 [Holzäpfel and Steen, 2007; Frech and Holzäpfel, 2008]. Detailed descriptions of NOWVIV and its nowcasting performance are available in [Frech et al., 2007; Gerz et al., 2005].

Within the forecast system NOWVIV, the mesoscale model MM5 [Grell et al., 2000] predicts the meteorological conditions for the Frankfurt terminal area in two nested domains with sizes of about 250 x 250 km^2 and about 90 x 90 km^2 centered on Frankfurt airport with grid distances of 6.3 km and 2.1 km, respectively. Sixty 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 of NOWVIV are taken from the operational weather prediction model LM (Local Model, [Doms and Schaettler, 1999]) of DWD (German Weather Service). The LM data allow for the best possible initialization and subsequent forcing of NOWVIV, since actual observations (radio soundings, AMDAR (Aircraft Meteorological Data Relay), satellite data, surface observations, etc.) are assimilated into the LM model predictions. Detailed topography, land use and soil type data for the Frankfurt area are also 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 are the three wind components, air density, virtual potential temperature, turbulent kinetic energy, eddy dissipation rate (EDR), and pressure.

Figure 3 shows the correspondence of measured (SODAR) and predicted (NOWVIV) key meteorological quantities for wake vortex

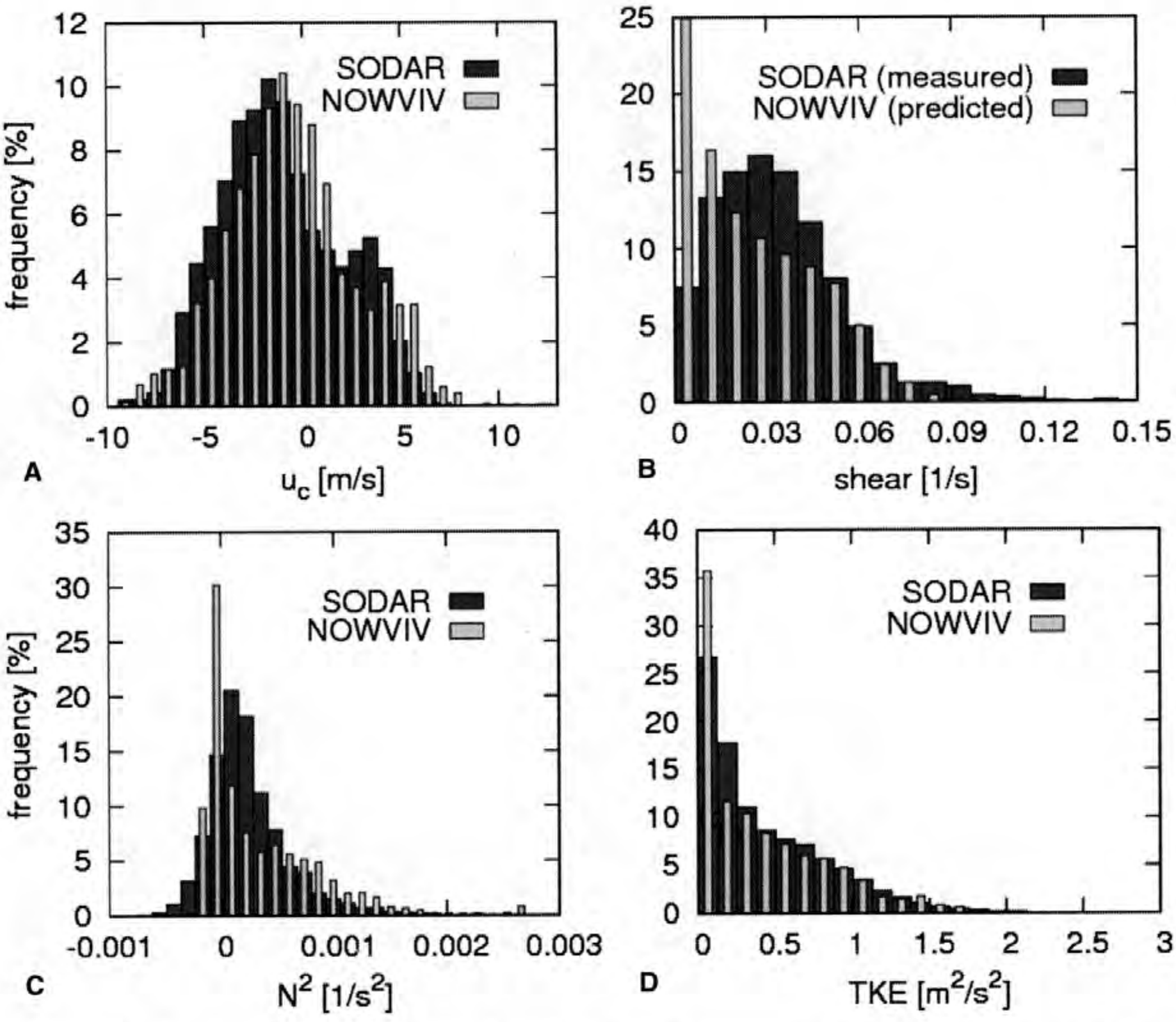

Figure 3. Histograms of measured and predicted crosswind (a), wind shear (b), temperature stratification (c), and turbulent kinetic energy (d) at a height of 100 m above ground for a 40-day measurement campaign at Frankfurt airport [Frech et al., 2007].

prediction collected during a 40 days measurement campaign conducted at Frankfurt airport in 2004 [Frech et al., 2007].

Integration of Meteorological Data. For approaches, the largest probability of encountering wake vortices prevails at altitudes below 300 ft [Critchley and Foot, 1991; Holzäpfel et al., 2009; Elsenaar, 2006]. There stalling or rebounding vortices may not clear the flight corridor vertically and weak crosswinds may be compensated by vortex-induced lateral transport, which may prevent the vortices from exiting the flight corridor laterally. Since vortex decay close to the ground is almost insensitive to meteorological conditions [Holzäpfel and Steen, 2007] the principal mechanism that may allow for reduced aircraft separations is lateral transport of wake vortices by crosswind.

Figure 4 shows that the best wake-vortex prediction performance for 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), would the lateral vortex transport predicted with NOWVIV input yield superior results. In ground proximity, vertical transport and vortex decay is largely independent from meteorological conditions. Consequently, the average deviations between measured and predicted vertical transport and vortex

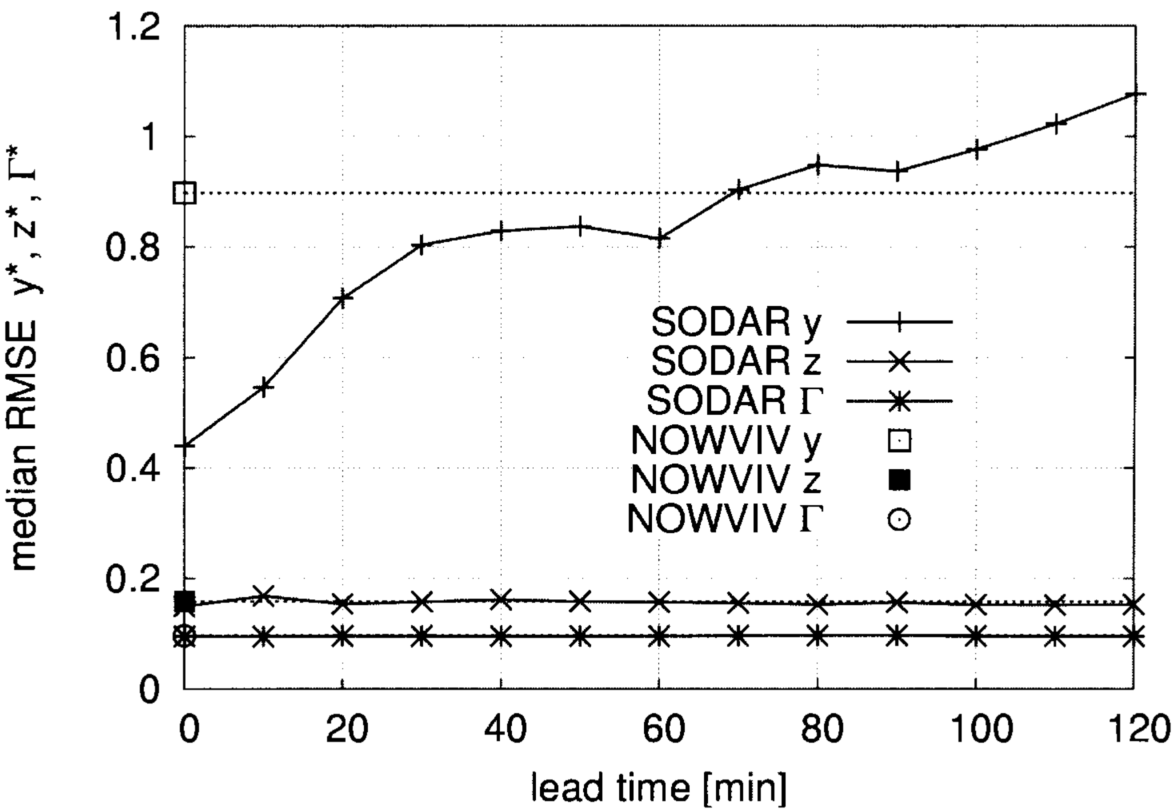

Figure 4. Median of normalized root-mean square deviations between measured and predicted lateral position, y*, vertical position, z*, and circulation, Γ*, as a function of the source of meteorological data and lead time.

decay are 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 region at low altitudes (gates 11 – 13). For the less critical areas aloft, we use NOWVIV data, which yields lesser but still acceptable wake prediction characteristics.

Approach Corridor Dimensions

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

The approach corridors in the different gates consist of ellipses (see Figure 5). Vertical and horizontal semi axes of these ellipses correspond to two standard deviations derived from glide path adherence statistics, respectively. For Gaussian distributions two standard deviations (2σ) correspond to a probability of 95.4% that an aircraft does not leave the corridor in one dimension (either laterally or vertically). For ellipsoidal corridors this probability reduces to 86.5% assuming statistical independence of lateral and vertical positions.

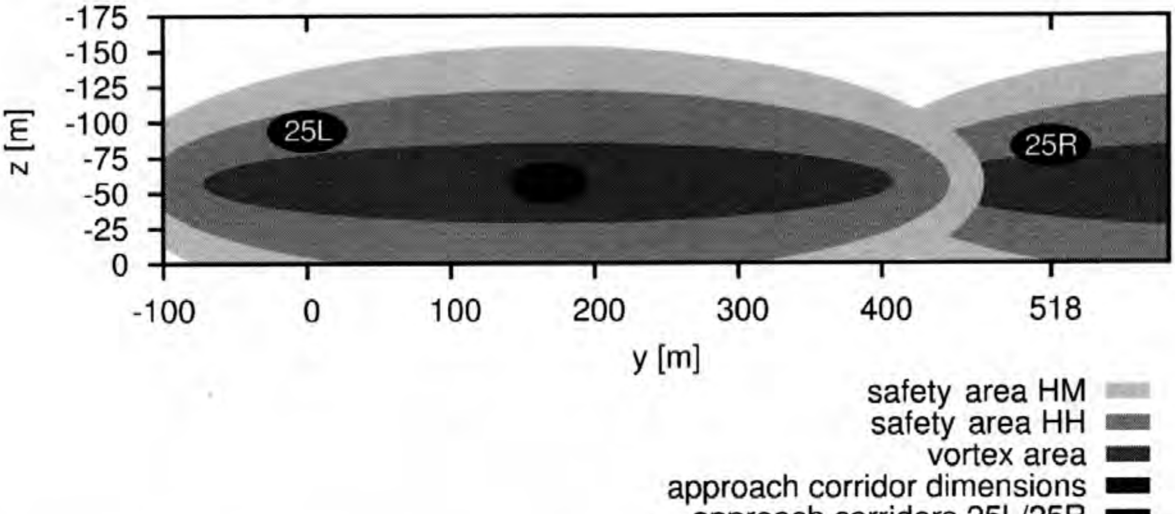

Figure 5. Ellipses denoting approach corridor dimensions, vortex areas, and safety areas in gate 11 for a vortex age of 100 s.

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 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 boundary curves for a representative compilation of parameters of existing aircraft as function of the maximum take-off weight (MTOW) (see solid lines in Figure 6) are established. For the individual aircraft the circulation of the generated wake vortices is calculated according to

$$\Gamma_0 = \frac{M \cdot g}{\rho(\pi/4)BV} \tag{1}$$

where M is the maximum landing weight (MLW), ρ is the air density of the standard atmosphere at sea level, B is the wing span, and V the final approach speed. Note that Figure 6 employs MTOW to characterize the various aircraft types because ICAO weight classes are based on MTOW. Nevertheless, the plotted and used circulation values are derived from MLW.

Figure 6 and Table 2 illustrate the way initial circulations, wing spans, and approach speeds are combined at the weight class

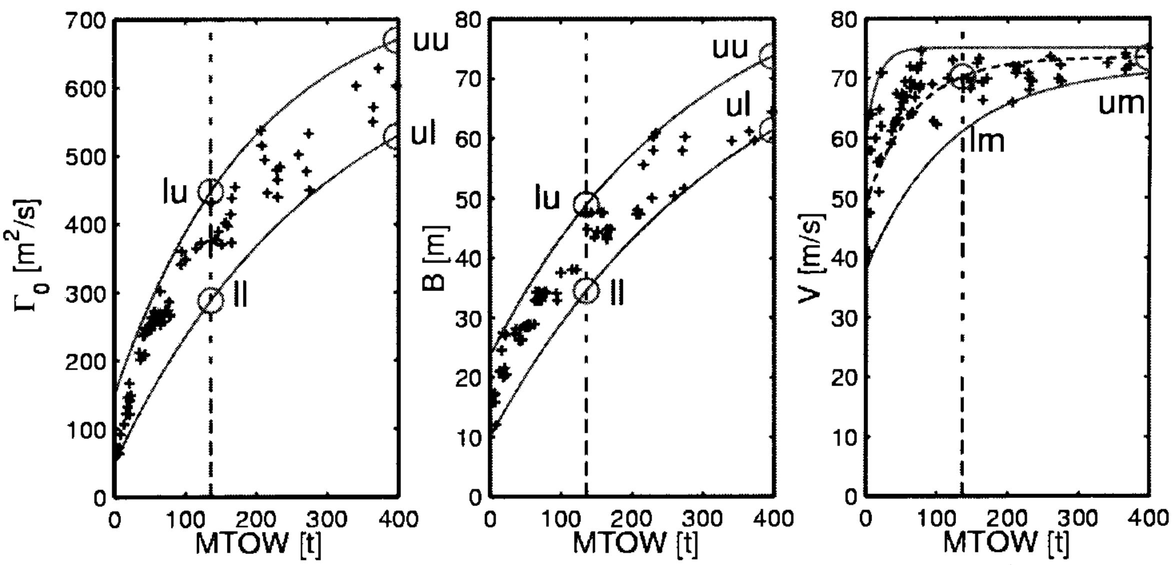

Figure 6. Initial circulation, Γ_0, wing span, B, and flight speed, V, for final approach as function of maximum take-off weight, MTOW, for 73 aircraft types. Solid lines border aircraft parameters, circles denote the parameters which are combined to represent the aircraft weight class heavy.

Table 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)

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

boundaries. In Table 2 $b_0 = \pi/4\ B$ corresponds to the vortex separation for an elliptically loaded wing. The B747-400 with a MTOW of 397 t is chosen as upper limit of the heavy weight category. Table 2 lists the 8 resulting parameter combinations that conservatively represent all possible generator aircraft within the heavy weight category. In Figure 6 and Table 2 the first u (l) denotes the upper (lower) bound of the weight class and the second u (l) upper (lower) fits at a weight class boundary. The resulting wide variations of initial vortex descent speed, w_0, and wake vortex time scales, $t_0 = w_0/b_0$, (variations by almost a factor of four) that are employed for any approaching aircraft indicate one of the conservative margins of the WSVBS.

Wake-Vortex Prediction

Wake-vortex prediction is conducted with the Probabilistic Two-Phase wake-vortex decay model (P2P), which is described in detail in [Holzäpfel, 2003]. Applications, assessments and further developments are reported in [Frech and Holzäpfel, 2008; Holzäpfel and Robins, 2004; Holzäpfel, 2006; Holzäpfel and Steen, 2007]. P2P considers all effects of the leading order impact parameters: aircraft configuration (span, weight, velocity, and trajectory), wind (cross and head components), wind shear, turbulence, temperature stratification, and ground proximity. P2P has been validated against data of over 10,000 cases gathered in two US and six European measurement campaigns (parts of this work have been documented in the above last four references).

Precise deterministic wake vortex predictions are not feasible operationally. Primarily, it is the nature of atmospheric 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 solid lines in Figure 7). The measured (symbols) and predicted (dashed and dotted lines) evolution of vertical (top left) and lateral (top right) wake vortex trajectories in Figure 7 illustrate asymmetric vortex rebound characteristics caused by crosswind in ground proximity [Holzäpfel and Steen, 2007].

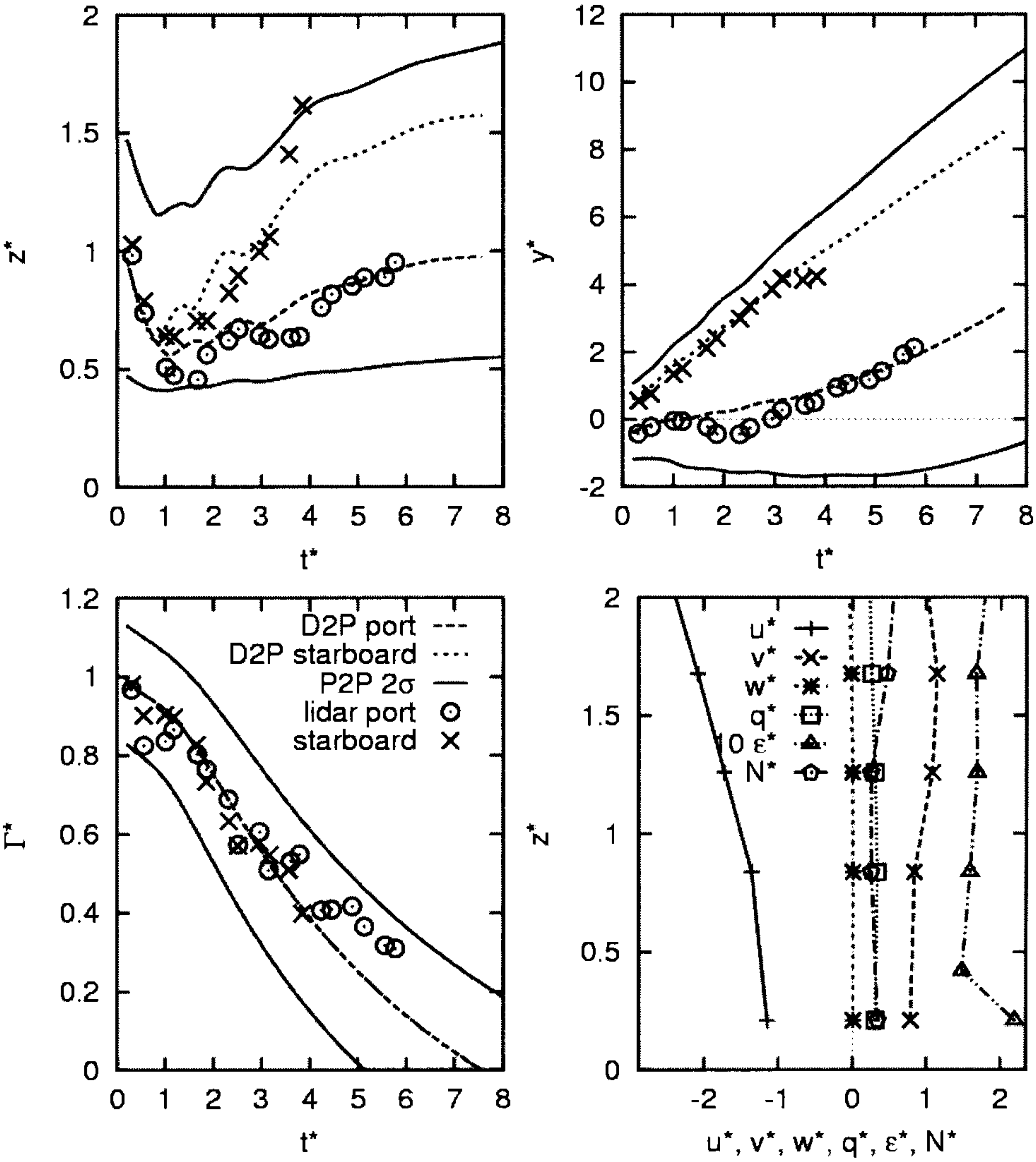

Figure 7. Evolution of normalized vertical (z*) and lateral positions (y*) and circulation (Γ*) in ground proximity. Measurements by lidar (symbols) and predictions with P2P wake vortex model (lines). Dashed and dotted lines denote deterministic behavior, solid lines are probabilistic envelopes (95.4%). The bottom right panel shows vertical profiles of measured meteorological parameters. Normalizations are based on initial values of vortex spacing, circulation, and the time needed to descend one vortex spacing.

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 that employs statistics of measured and predicted wake vortex behavior [Holzäpfel, 2006]. Note that the training procedure implicitly considers the quality of the meteorological input data. As a consequence, uncertainty allowances of wake-vortex predictions based on the high-quality SODAR/RASS measurements in the lowest three gates are smaller than uncertainty allowances applied to wake-predictions at higher altitudes, which are based on NOWVIV input.

Safety-Area Prediction

Once the potential positions of the wake vortices at each gate are known, safe distances between wake vortex core positions and the follower aircraft need to be assigned. The Simplified Hazard Area (SHA) concept [Hahn et al., 2004; Schwarz and Hahn, 2006] predicts distances that allow for safe and undisturbed operations.

The SHA-concept assumes that for encounters during approach and landing the vortex induced rolling moment constitutes the dominant effect [de Bruin, 2003; Hallock and Eberle, 1977; Schwarz and Hahn, 2006] 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 that is required to compensate the exerted rolling moment to the maximum available roll control power.

In Figure 8 the innermost 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 at a value of $RCR_{req} = 0.2$ [Schwarz and Hahn, 2006]. Results from real flight tests using DLR's fly-by-wire in-flight simulator, ATTAS, support this conclusion [Schwarz and Hahn, 2005]. In Figure 8 the lines a and b denote the resulting distances between vortex centers and follower aircraft for $RCR_{req} < 0.2$, which are added to the wake vortex envelopes.

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 that represent the heavy category are combined with the follower categories medium or heavy. In order to conservatively represent these follower aircraft weight classes, all relevant aircraft parameters (wing span, wing area, airspeed, lift coefficient, 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 a function of MTOW, as described in the section on Representation of Aircraft

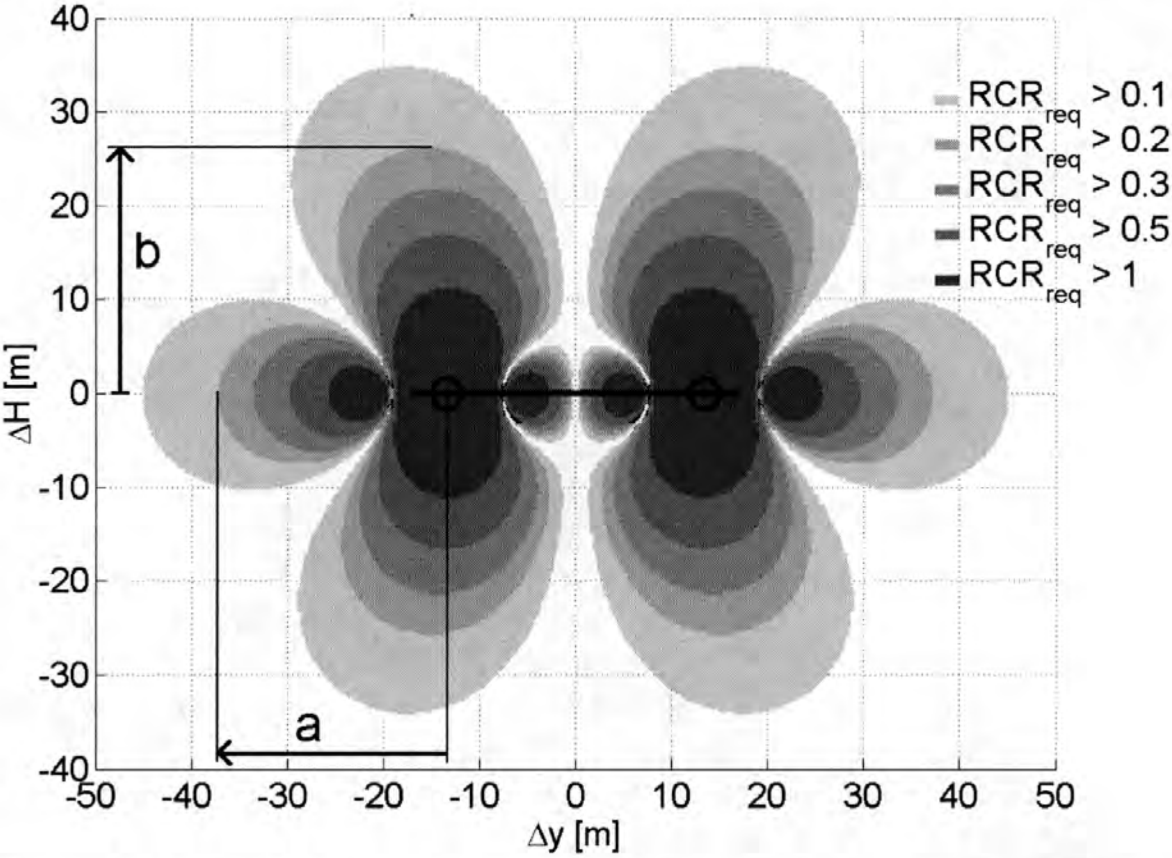

Figure 8. Roll control power required to compensate wake-vortex induced rolling moments. Horizontal and vertical allowances a and b for $RCR_{req} < 0.2$.

Weight Classes 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) [Hahn et al., 2004].

SYSTEMS INTEGRATION

This section describes how the above introduced components are combined for the prediction of adapted aircraft separations. The first part considers components within a single gate. The second part then explains how the minimum temporal aircraft separations are derived from the predictions within all the gates. Finally, the third part sketches the temporal prediction cycle, which defines parameters such as update rate and prediction horizon.

Components in Single Gate

Figure 5 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, the vortex area prediction, and the

safety area prediction. Note that horizontal and vertical dimensions in Figure 5 are in scale.

The corridor of possible vortex positions (vortex area) indicates that superimposed with vortex descent a southerly cross-wind advects the wake from runway 25L to 25R. Because the lateral vortex positions are predicted less precisely (uncertainty and variability of crosswind) than vertical position (cf. Figure 4), the aspect ratio of the vortex area ellipse exceeds a value of eight. Out of ground effect where uncertainties regarding vortex descent are increased [Holzäpfel and Steen, 2007] this aspect ratio is much smaller. 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. Rather, they move depending on wake transport, 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 no longer overlaps the approach corridor (gate obstruction time) determines the minimum temporal separation for that gate. However, for the parallel runway system, the question is whether the safety areas reach the neighboring 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).

The example in Figure 5 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 the glide path corridor for 25R. However, at 125 s the HM envelope will reach the glide path corridor for 25R. Therefore, reduced separations for 25R can only be assigned to heavy aircraft. Safety areas from 25R in turn will not reach the corridor 25L, so for aircraft approaching 25L reduced separations can be applied to both follower weight categories.

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 and potential wake encounter conflicts are identified. These maximum

Table 3. 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

gate obstruction times define minimum aircraft separation times MST. The output of the WSVBS consequently consists of the matrix shown in Table 3.

Note that the MST in Table 3 are consistent with the situation displayed in Figure 5. In the matrix 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 practice the aircraft separations can then be reduced to radar separation (for example 70 s). The translation of the separation matrix into procedures and displays that are suitable for air traffic control (ATC) is described in Part II of this paper.

The idea is that all corridors used in the process, such as those depicted in Figure 5, should be based on identical probability levels, currently, twice the standard deviations (2σ) of respective data. However, the safety area prediction concept is not probabilistic, i.e. the predicted safety areas are safe without any exception for the investigations conducted so far. It however, assumes that the wake vortices are situated along the envelopes of the vortex area, which is a very conservative assumption. A 2σ probabilistic confidence level on the safety module may be introduced by adding the safety areas only to 95.4% of the 2σ wake vortex areas. With this effective reduction of the vortex areas to 1.7σ (91.1%) a consistent probabilistic level of 95.4% is also achieved for the safety area module.

Unfortunately, the very question: "What 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. This analysis will also have to consider risks occurring outside the area controlled by the WSVBS.

Prediction Cycle

Every 10 minutes new Sodar/RASS and NOWVIV data are available. After receipt of these data the WSVBS predicts MST matrices for a 60 min horizon with 10 min-increments. This guarantees availability of predictions for at least 45 min in advance as required by ATC for planning purposes.

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 Part II of this paper). Once the real-time capability of vortex monitoring is established, it would be possible to integrate a conflict detection module, which may issue warnings and/or may adapt the WSVBS predictions.

CONCLUSIONS

This 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, multiple aircraft parameter combinations characterizing various aircraft weight categories, the resulting wake-vortex behavior, the surrounding safety areas, and wake vortex monitoring. The elements of the WSVBS are generic and can 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 of encountering wake vortices is highest, the wake predictor employs measured environmental parameters that yield superior prediction results. For the less critical aloft portions of the approach, which cannot be monitored completely by instrumentation, the meteorological parameters are taken from dedicated numerical terminal weather predictions. The P2P wake vortex model predicts envelopes for vortex position and strength that implicitly consider the quality of the meteorological input data. This feature is achieved by a training procedure that employs statistics of measured and predicted meteorological parameters and the resulting wake vortex behavior.

The WSVBS combines various conservative elements that presumably lead to a very high overall safety level of the WSVBS. a) Wake vortex prediction as well as safety area prediction employ worst case combinations of aircraft parameters that span complete aircraft weight categories. b) The wake vortex model assumes that the aircraft are situated at the limits of the approach corridor envelopes. (The probability that this assumption actually occurs is extremely small.) Likewise, the safety area model assumes that the wake vortices are situated at the limits of the wake vortex envelopes. As a consequence the probability to actually encounter wake vortices at

the edges of the safety areas is extremely small. c) The most critical cases within the 1248 investigated parameter combinations determine the possible aircraft separations. d) A LIDAR scans the most critical gates at low altitude in order to verify the correctness of the suggested aircraft separations. The combination of these conservative measures leads to a very high but currently not quantified overall safety level. Once the methodology for a comprehensive risk analysis is established, it is planned to adjust all components to appropriate and consistent confidence levels.

ACKNOWLEDGEMENTS

We thank four anonymous reviewers and the editors for their thoughtful comments and suggestions. Special thanks go to one of the reviewers who spared no effort to enhance the manuscripts with high expertise in wording and technical knowledge. The work presented here was funded by the DLR project *Wirbelschleppe* and benefited from the EU projects *ATC-Wake* (IST-2001-34729), *FAR-Wake* (AST4-CT-2005-012238), *FLYSAFE* (AIP4-CT-2005-516 167), and the European Thematic Network *WakeNet2-Europe* (G4RT-CT-2002-05115). We greatly appreciate the excellent support of the teams from DFS Deutsche Flugsicherung GmbH, DWD Deutscher Wetterdienst, Fraport AG, and METEK GmbH.

ACRONYMS

AMDAR	Aircraft Meteorological Data Relay
AMAN	Arrival Manager
ATC	Air Traffic Control
ATTAS	Advanced Technologies Testing Aircraft System
AVOSS	Aircraft Vortex Spacing System
AWIATOR	Aircraft Wing with Advanced Technology Operation
CSPR	Closely-Spaced Parallel Runways
DFS	Deutsche Flugsicherung GmbH
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DWD	Deutscher Wetterdienst
EDR	Eddy Dissipation Rate
FAF	Final Approach Fix
FLIP	Flight Performance Using Frankfurt ILS
HH	Heavy Followed by Heavy
HM	Heavy Followed by Medium
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System
LIDAR	Light Detection and Ranging
LM	Local Model
MST	Minimum Aircraft Separation Time

NASA	National Aeronautics and Space Administration
NOWVIV	Nowcasting Wake Vortex Impact Variables
MM5	Mesoscale Meteorology Model 5
MLW	Maximum Landing Weight
MTOW	Maximum Take-Off Weight
P2P	Probabilistic Two-Phase Wake Vortex Model
RASS	Radio Acoustic Sounding System
RCR	Roll Control Ratio
SHA	Simplified Hazard Area Concept
SHAPe	Simplified Hazard Area Prediction
SODAR	Sound Detection and Ranging
TDZ	Touchdown Zone
USA	Ultra Sonic Anemometer
UTC	Universal Time Coordinated
WSVBS	Wake Vortex Prediction and Monitoring System
WTR	Wind Temperature Radar
WVWS	Wake Vortex Warning System

REFERENCES

Critchley, J.B. and Foot, P.B. (1991), *UK CAA Wake Vortex Database: Analysis of Incidents Reported Between 1982 and 1990*, Civil Aviation Authority, CAA Paper 91015.

de Bruin, A. (2003), S-wake assessment of wake vortex safety, Publishable Summary Report, National Aerospace Laboratory, NLR-TP-2003-243, Amsterdam, The Netherlands.

Doms, G. and Schaettler, U. (1999), *The nonhydrostatic Limited Area Model LM (Lokal Modell) of DWD. Part I: Scientific Documentation*, Deutscher Wetterdienst, Offenbach, Germany.

Elsenaar, B. (2006), *Wake Vortex Research Needs for "Improved Wake Vortex Separation Ruling" and "Reduced Wake Signatures"*, Final Report of the Thematic Network 'WakeNet2-Europe', 6th Framework Programme, National Aerospace Laboratory, NLR-CR-2006-171, Amsterdam, The Netherlands.

EUROCONTROL (2004), *Challenges to Growth 2004 Report*, Brussels, Belgium.

Frauenkron, H., Maiss, M., Nalpanis, P. (2001), *FLIP - Flight Performance using Frankfurt ILS*, DFS German Air Navigation Services, Air Traffic Management Division, Version 2.0.

Frech, M. (2004), "A simple method to estimate the eddy dissipation rate from SODAR/RASS measurements," *16th Symposium on Boundary Layers and Turbulence*, AMS, Portland.

Frech, M. and Holzäpfel, F. (2008), "Skill of an Aircraft Wake-Vortex Model using Weather Prediction and Observation," *Journal of Aircraft*, 45 (2).

Frech, M., Holzäpfel, F., Tafferner, A., Gerz, T. (2007), "High-Resolution Weather Data Base for the Terminal Area of Frankfurt Airport," Journal of Applied Meteorology and Climatology 46.

Gerz, T., Holzäpfel, F., Bryant, W., Köpp, F., Frech, M., Tafferner, A., Winckelmans, G. (2005), "Research towards a wake-vortex advisory system for optimal aircraft spacing," Comptes Rendus Physique +6.

Gerz, T., Holzäpfel, F., Gerling, W., Scharnweber, A., Frech, M., Wiegele, A., Kober, K., Dengler, K., Rahm, S. (2007), "The Wake Vortex Prediction and Monitoring System WSVBS - Part II: Performance and ATC Integration at Frankfurt Airport," *1st European Air and Space Conference (CEAS 2007) / Deutscher Luft- und Raumfahrtkongress 2007*, Berlin, Germany, September.

Grell, G.A., Emeis, S., Stockwell, W.R., Schoenemeyer, T., Forkel, T., Michalakes, J., Knoche, R., Seidl, W. (2000), "Application of a multiscale, coupled MM5/chemistry model to the complex terrain of the VOTALP valley campaign," *Atmospheric Environment* 34.

Gurke, T., Lafferton, H. (1997), "The development of the wake vortex warning system for Frankfurt Airport: Theory and implementation," *Air Traffic Control Quarterly*, 5.

Hahn, K.-U., Schwarz, C., Friehmelt, H. (2004), "A Simplified Hazard Area Prediction (SHAPe) Model for Wake Vortex Encounter Avoidance," *24th International Congress of Aeronautical Sciences*, Yokohama, Japan.

Hallock, J.N., Eberle, W.R. (1977), "Aircraft wake vortices: a state-of-the-art review of the United States R&D program," US Department of Transportation (DOT), Federal Aviation Administration (FAA), Report No. FAA-RD-77-23.

Hemm, R., Shapiro, G., Lee, D.A., Gribko, J., Glaser, B. (1999), "Benefit Estimates of Terminal Area Productivity Program Technologies," NASA/CR-1999-208989.

Hinton, D.A., Charnock, J.K., Bagwell, D.R. (2000), "Design of an Aircraft Vortex Spacing System for Airport Capacity Improvement," AIAA Paper 2000-0622, *38th AIAA Aerospace Sciences Meeting & Exhibit*, Reno, NV, January.

Holzäpfel, F. (2003), "Probabilistic Two-Phase Wake Vortex Decay and Transport Model," *Journal of Aircraft* 40.

Holzäpfel, F., Robins, R.E. (2004), "Probabilistic Two-Phase Aircraft Wake-Vortex Model: Application and Assessment," *Journal of Aircraft* 41.

Holzäpfel, F. (2006), "Probabilistic Two-Phase Aircraft Wake-Vortex Model: Further Development and Assessment," *Journal of Aircraft* 43.

Holzäpfel, F. and Steen, M. (2007), "Aircraft Wake-Vortex Evolution in Ground Proximity: Analysis and Parameterization," *AIAA Journal* 45.

Holzäpfel, F., Gerz, T., Frech, M., Tafferner, A., Köpp, F., Smalikho, I., Rahm, S., Hahn, K.-U., Schwarz, C. (2007), "The Wake Vortex Prediction and Monitoring System WSVBS - Part I: Design," *1st European Air and Space Conference (CEAS 2007) / Deutscher Luft- und Raumfahrtkongress 2007*, Berlin, Germany, September.

Holzäpfel, F., Frech, M., Gerz, T., Tafferner, A., Hahn, K.-U., Schwarz, C., Joos, H.-D., Korn, B., Lenz, H., Luckner, and R., Höhne, G. (2009), "Aircraft Wake Vortex Scenarios Simulation Package - WakeScene," *Aerospace Science and Technology*, 13 (1).

Konopka, J. and Fischer, H. (2005), "The Wake Vortex Warning System at Frankfurt Airport," 24th Digital Avionics Systems Conference, Washington, DC, October.

Rutishauser, D.K. and O'Connor, C.J. (2001), *Aircraft Wake Vortex Spacing System (AVOSS) Performance Update and Validation Study*, NASA/TM-2001-211240, Langley Research Center, Hampton, VA.

Schwarz, C., Hahn, K.-U. (2005), "Simplified Hazard Area for Wake Vortex Encounter Avoidance," AIAA Paper 2005-5903, *AIAA Atmospheric Flight Mechanics Conference*, San Francisco, CA, August.

Schwarz, C.W., Hahn, K.-U. (2006), "Full-flight simulator study for wake vortex hazard area investigation," *Aerospace Science and Technology*, 10.

BIOGRAPHIES

Frank Holzäpfel graduated as a mechanical engineer from the University of Karlsruhe (TH) in 1990. He then specialized in multi-hot-wire measurement techniques and turbulence modeling in turbulent swirling flows at the Engler Bunte Institut of the University Karlsruhe, where he obtained his Dr.-Ing. in 1996. In 1997 he became a Research Scientist at the Institute of Atmospheric Physics, DLR in

Oberpfaffenhofen, where he concentrates on wake vortex research, which includes large eddy simulation, real-time model development, wake vortex systems and risk analysis. In 2005 he obtained his Habilitation in Fluid Dynamics at the Faculty of Mechanical Engineering of the Technical University Munich where he is an associate lecturer since 2007. E-mail: frank.holzäpfel@dlr.de

Thomas Gerz graduated as a meteorologist with a diploma degree in 1984 and obtained a Dr. rer. nat. in 1988, both from Ludwigs-Maximilians-Universität in München (Munich). He works as a scientist and research manager at the Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center) DLR – Institut für Physik der Atmosphäre (Institute of Atmospheric Physics) in Oberpfaffenhofen, Germany. He managed the DLR project Wirbelschleppe (Wake Vortex) from 1998 to 2007 and since 2008 he is head of the DLR project Wetter & Fliegen (Weather & Flying).

Michael Frech received a Masters degree in Atmospheric Sciences from Oregon State University in 1994. In that year he joined the German Aerospace Research Center in Oberpfaffenhofen pursuing research on turbulence exchange processes in the atmospheric boundary layer. In 1998 he received his Phd from the Ludwig-Maximilian-University in Munich. In the following years he worked on designing operational wake vortex prediction and monitoring systems. There the prime focus was to monitor and predict relevant atmospheric variables to predict and characterize wake vortex evolution. Since 2007 he is working for the German Meteorological Service where he works on the introduction of the new German operational radar network.

Arnold Tafferner meteorologist, got his doctoral degree in 1988 in natural sciences after a one year stay at the Rosenstiel School of Marine and Atmospheric Science in Miami (USA). Holding a research position at the Meteorologisches Institut der Universität München, he specialized in numerical weather forecasting on regional and local scales. Since 1997 he works at the Institut für Physik der Atmosphäre at DLR, where his main focus is on designing and operationally installing systems for detection and forecasting atmospheric conditions that pose hazards to aircraft, e.g. aircraft icing, wake vortices, thunderstorms and winter conditions.

Friedrich Köpp Physics studies at the Technical University of Munich plus several years of investigations of radiation transfer in the atmosphere at the LM-University of Munich. Employment as research scientist in the DLR Laser Technology Group until the retirement end of 2005. There, the main task was the development of operational Doppler lidar systems and their application for investigation of atmospheric flows. Since the early 1980s, this work was focused on the measurement of wake vortices both by ground-based and airborne lidars. The great experience gathered during this period has been introduced in many national and international wake-vortex projects.

Igor Smalikho graduated from the Tomsk State University (TSU) in 1983 with a diploma in optics and radiophysics. From 1983 to 2001 he worked as a research scientist in the Institute of Atmospheric Optics (IAO) of the Siberian Branch of the Russian Academy of Sciences, where he concentrated on research of optical wave propagation in the atmosphere, including effects of refractive turbulence, scattering and thermal blooming on laser radiation. In 1989 he received his Ph.D. from TSU. From 2001 to 2008 he worked as a research scientist in the Institute of Atmospheric Physics of DLR in Oberpfaffenhofen, where he developed methods of coherent Doppler lidar measurements of wind, atmospheric turbulence and aircraft wake vortices and processed experimental data. Since 2008 he works in the IAO.

Stephan Rahm graduated as an electrical engineer from the University of Munich in 1988. He then specialized in optical amplifiers and coherent Doppler lidar at the DLR in Oberpfaffenhofen, where he obtained his Dr.-Ing. in 1993. Then he became a research scientist at the Institute of Atmospheric Physics, DLR in Oberpfaffenhofen, where he concentrates on coherent Doppler lidar measurements on wind and wake vortex phenomena with ground based as well as airborne systems.

Klaus-Uwe Hahn graduated as a mechanical engineer from the College Wolfenbüttel in 1975 and received his diploma in aerospace sciences at TU Braunschweig in 1981. He became a scientist in the Institute of Flight Guidance (1981) and joined the long term research group "Flight Safety" at TU Braunschweig (1983-1989) where he received his Dr.-Ing. in1988. Since 1989 he is a scientist at the German Aerospace Center where he became deputy head of department "Flight Dynamics and Simulation" in 1999 and head in 2006. Since 1994 he is associate lecturer at the TU Hamburg-Harburg where he became Professor in 2008. Main research activities focus on flying in a disturbed atmosphere.

Carsten W. Schwarz graduated with an aeronautical engineering diploma from the Technical University Braunschweig in 2002. Since then he is a research engineer at the German Aerospace Center DLR – Institute of Flight Systems working in the area of wake vortex encounter simulation and severity assessment.

The Wake Vortex Prediction and Monitoring System WSVBS Part II: Performance and ATC Integration at Frankfurt Airport

Thomas Gerz, Frank Holzäpfel, Wilfried Gerling, Alexander Scharnweber, Michael Frech, Kirstin Kober, Klaus Dengler, and Stephan Rahm

The performance and the ATC test integration of DLR's wake vortex advisory system, WSVBS, for the dependent parallel runways 25L and 25R at Frankfurt Airport are described. WSVBS has components to forecast and monitor the local weather and to predict and monitor wake transport and decay along the glide paths. Integration with the DLR's arrival manager AMAN has also been demonstrated. Every 10 minutes the WSVBS delivers minimum safe aircraft separation times for the next hour, which are translated into operational modes for runways 25L/R aiming at tactically improving capacity to reduce delays. During a performance test described herein the system was stable and the predicted minimum separation times were confirmed by measurements. Capacity-improving wake-vortex separation concepts of operation could have been used in 75% of the time and continuously applied for at least several tens of minutes.

Thomas Gerz, Frank Holzäpfel, Michael Frech, Kirstin Kober, Klaus Dengler, and Stephan Rahm are with Deutsches Zentrum für Luft- und Raumfahrt (DLR), Oberpfaffenhofen, Germany. Wilfried Gerling and Alexander Scharnweber are with DLR, Braunschweig, Germany.

Received March 23, 2009; accepted August 25, 2009.

Air Traffic Control Quarterly, Vol. 17(4) 323–346 (2009)
 CCC 1064-3818/95/030163-20

From fast-time simulations the (strategic) capacity gain for Frankfurt was estimated to be 3%, taking into account the real traffic mix and operational constraints.

INTRODUCTION

Since aircraft trailing vortices may pose a potential risk to following aircraft, vortex separation standards between consecutive aircraft had been introduced as early as in the 1970s. These empirically motivated separation standards still apply, are often overly conservative, and limit the capacity of congested airports in a rapidly growing aeronautical environment. Capacity limitations are especially drastic and unacceptable at airports like in Frankfurt (Germany) with two closely spaced parallel runways (CSPR) where the possible transport of wakes from one runway to the adjacent one by crosswinds impedes an independent use of both runways.

To increase airport capacity for landing aircraft, DLR has developed a wake vortex advisory system named WSVBS, German for Wake Vortex Prediction and Monitoring System [Gerz et al., 2005]. The WSVBS is intended to dynamically adjust aircraft wake vortex separations dependent on weather conditions and the resulting wake vortex behaviour without compromising safety. The system is particularly designed for the closely spaced parallel runway system of Frankfurt Airport (Figure 1) but can be adapted to any other airport. It predicts wake vortex transport and decay and determines the resulting wake vortex safety areas along the glide slope, from the final approach fix to the threshold. The design of the WSVBS is described in Part I [Holzäpfel et al., 2009b]. In this paper we describe its performance during a test campaign at Frankfurt Airport and indicate possible gains in capacity, if the WSVBS were installed there and used by air traffic control (ATC) authorities.

INSTALLATION AT FRANKFURT AIRPORT

The WSVBS with its components (*tools*)

- weather forecast (*NOWVIV*),
- wake vortex predictor (*P2P*),
- safety area predictor (*SHAPe*),
- weather profiler (*SODAR / RASS / USA*), and
- wake detector (*LIDAR*)

was evaluated at Frankfurt Airport in the period of December 2006 until February 2007. The system used forecast and measured meteorological parameters along the glide path to predict temporal wake vortex separations of aircraft landing on the parallel runway

Figure 1. Frankfurt Airport with the two parallel runways 25L and 25R, spaced by 518 m (1727 ft).

system 25L/R. The system also translated the required separation between two aircraft into approach procedures that could have been employed by air traffic control ATC. At the same time, the actual transport of the wake vortices was monitored by the wake detector component (LIDAR) in 3 different control gates. All components of the WSVBS are described in detail in [Holzäpfel et al., 2009b]. Here we note some specific features of the set-up at Frankfurt Airport.

Figure 2 sketches the instrumentation layout at Frankfurt Airport. It depicts runways 25L and 25R with the locations of the employed sensors and the local operation centre (LOC) which is located in the observer house of the German Meteorological Service (DWD). Close to the LOC, midway between the glide paths, a 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 up to 300 m AGL. The SODAR/RASS system is complemented by an ultrasonic anemometer (USA) mounted on a 10 m mast which measured wind and temperature with a frequency of 20 Hz. Eddy dissipation rate (EDR) profiles are derived from the vertical fluctuation velocity and the vertical wind gradient employing a simplified budget equation [Frech, 2007]. A spectral analysis of the longitudinal wind velocity measured by the

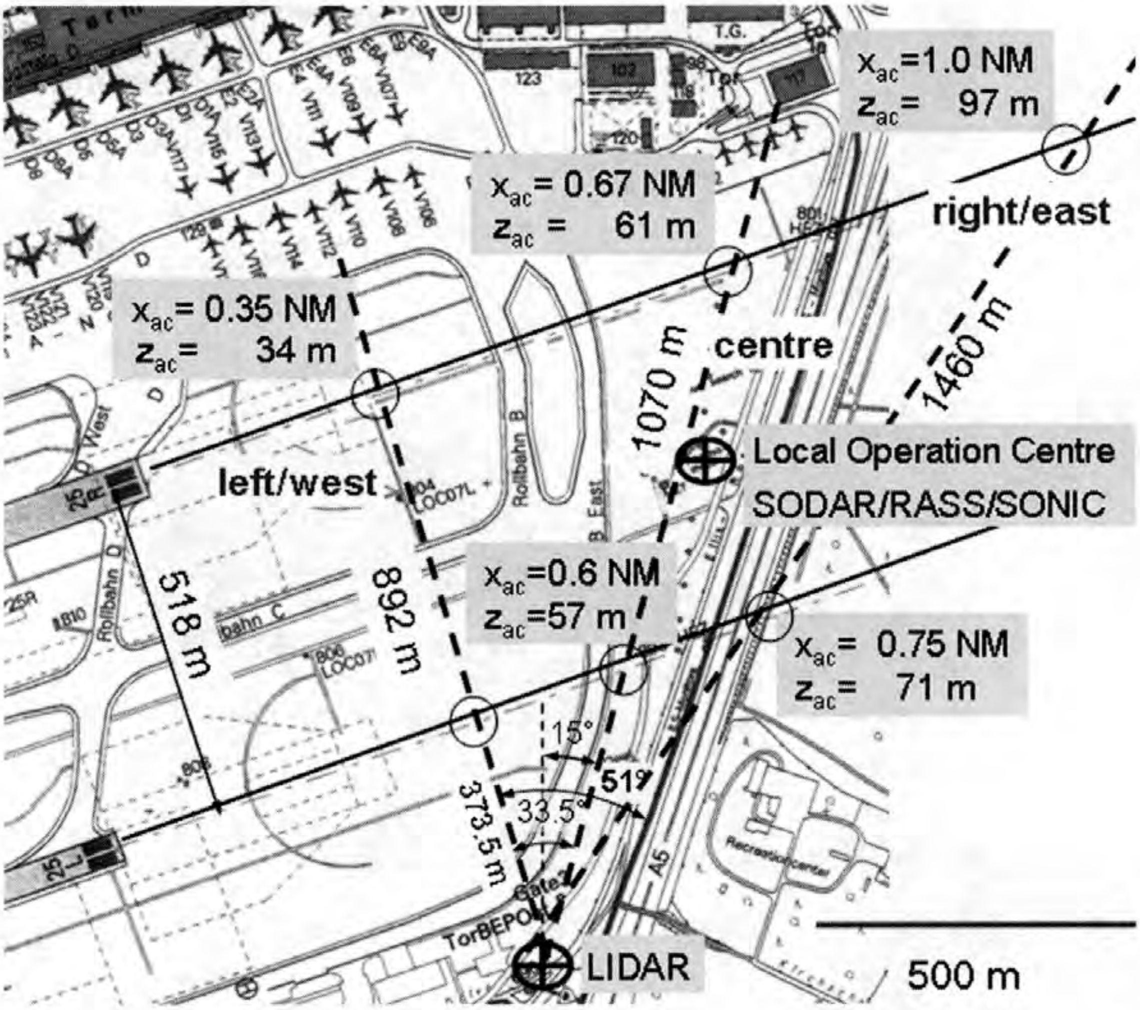

Figure 2. The instrumentation layout at Frankfurt Airport; x_{ac}, z_{ac} denote the distance to touch-down zone and the height of landing aircraft in the three vertical scan planes of the LIDAR (dashed lines); LOC and the meteorological profiler were situated between both extended runway centrelines. Map reprinted by courtesy of Fraport AG.

sonic anemometer is used to estimate EDR by fitting the -5/3 slope in the inertial sub-range of the velocity frequency spectrum. Due to the position of the SODAR/RASS/USA between the extended centrelines of both runways these data are considered representative of the area where aircraft and vortices are in ground proximity. In the LOC, a Linux-PC is installed which is connected via ethernet to the SODAR/RASS/USA system and via UMTS (Universal Mobile Telecommunications System) 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.

The weather forecast model NOWVIV [Gerz et al., 2005; Frech et al., 2007; Frech and Holzäpfel, 2008] ran twice a day on a massively parallel Linux cluster at University Stuttgart. It predicted the meteorological conditions for the Frankfurt Airport Terminal Area. The forecast output was sent via UMTS to the Linux-PC in the Local Operation Centre (LOC) to be used by the real-time wake predictor, P2P (Figure 3).

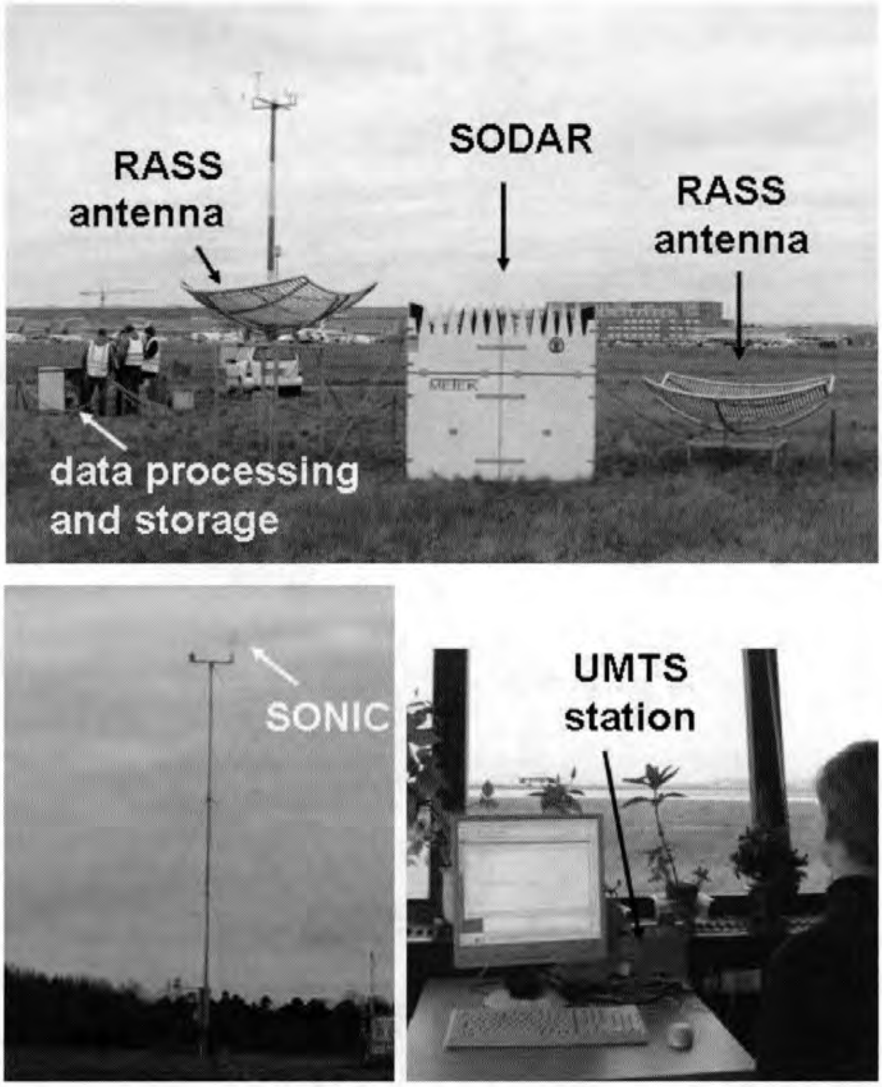

Figure 3. Meteorological instruments at Frankfurt Airport. Top & lower left: SODAR/RASS and USA by Fa. Metek; lower right: the LOC with Linux-PC & UMTS station in the DWD observer house.

Figure 4 shows two examples of diurnal variations of horizontal wind profiles, a weak wind condition on 15th of January and a stronger wind case on the following day. The height range covered by the SODAR/RASS measurements depends on the backscatter properties and ambient noise level in the boundary layer which vary during the day. The NOWVIV forecasts are only plotted in the range where observations were available. Also indicated are the differences between observed and predicted cross-wind u_c. On the calm day the deviation between observation and prediction was about ± 1.5 m/s on average but considerably larger in the early morning hours between 2 and 5 UTC. This was due to a south-westerly low level jet which developed and vanished earlier than anticipated by the NOWVIV forecast. The temporal deviations produced the dark and light grey coloured u_c-deviation dipole shown in Figure 4. Hence, the phenomenon – a low level jet – was predicted but with a delay of about 2 hours. A similar phenomenon was observed on the next morning but, in this

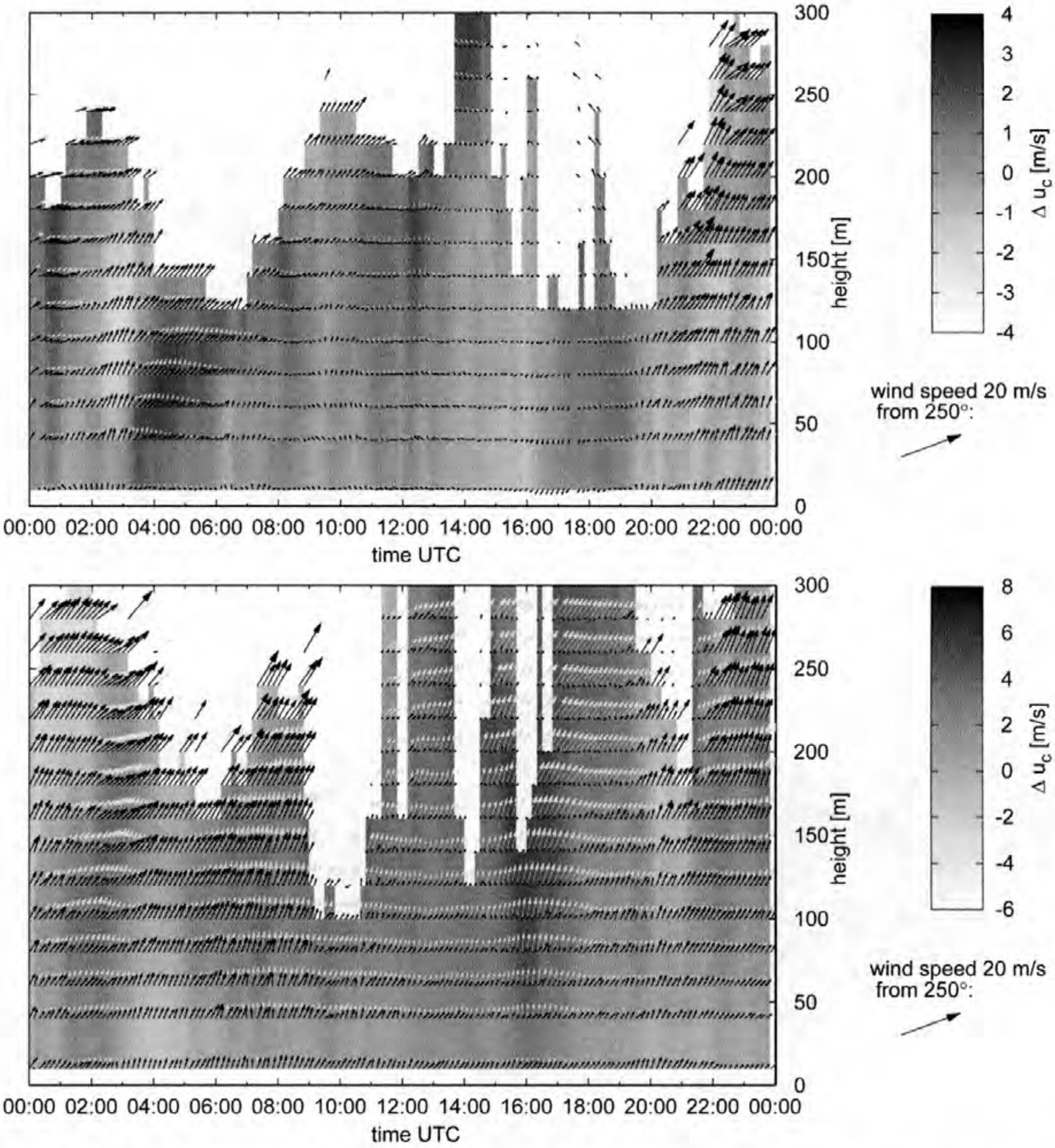

Figure 4. Diurnal variations of the wind velocity profile measured by SODAR/RASS (black arrows) and predicted by NOWVIV (grey arrows) on 15.01.07 (top) and 16.01.07 (bottom). Deviations in cross-wind u_c between observation and prediction are coded in grey-scale. White areas indicate no measurements.

case, the jet developed later than predicted. The generally higher winds on the 16^{th} of January also indicate that the weather was dominated by advection processes (large scale weather patterns). Under these conditions the initial and boundary conditions for NOWVIV have a larger impact on the forecast quality than on the 15^{th} where the weather was driven by local orographic and land-use features.

The real-time probabilistic two-phase wake vortex decay and transport model P2P [Holzäpfel, 2003; Holzäpfel and Robins, 2004; Holzäpfel, 2006; Holzäpfel and Steen, 2007; Frech and Holzäpfel, 2008; Holzäpfel et al., 2009a] received the measured and forecast meteorological profiles as inputs. It computed envelopes of probable

decay and location of the wake vortices of aircraft from the HEAVY (H) aircraft category in thirteen gates along the glide path to runways 25L/R. The Linux-PC in the LOC performed the P2P wake model calculations. The Simplified Hazard Area Prediction (SHAPe) model [Hahn et al., 2004, Schwarz and Hahn, 2005, 2006, Holzäpfel et al., 2009b] then computed safety zones around the area of the probable vortex locations.

DLR's 2 μm pulsed Doppler LIDAR was used to monitor the correctness of the predictions of the WSVBS at Frankfurt Airport. It operated in vertical scan-plane mode with elevations between 0° to 6° to detect and track the vortices alternately in the three lowest and most critical planes (Figure 2). The line-of-sight (LOS) velocity in a scanned plane is immediately visible in the so-called "quick-look". These quick-look files were transmitted via UMTS to the LOC computer and were also accessible via internet. Figure 5 shows a quick-look result from 16 January 2007 at 04:17 UTC in the "centre" vertical scan plane.

In that hour, most heavy aircraft landed on runway 25R (the northern runway). The Figure 5 quick-look results show the 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 WSVBS predicts that it is safe for the next aircraft to enter the control gate. The quick-

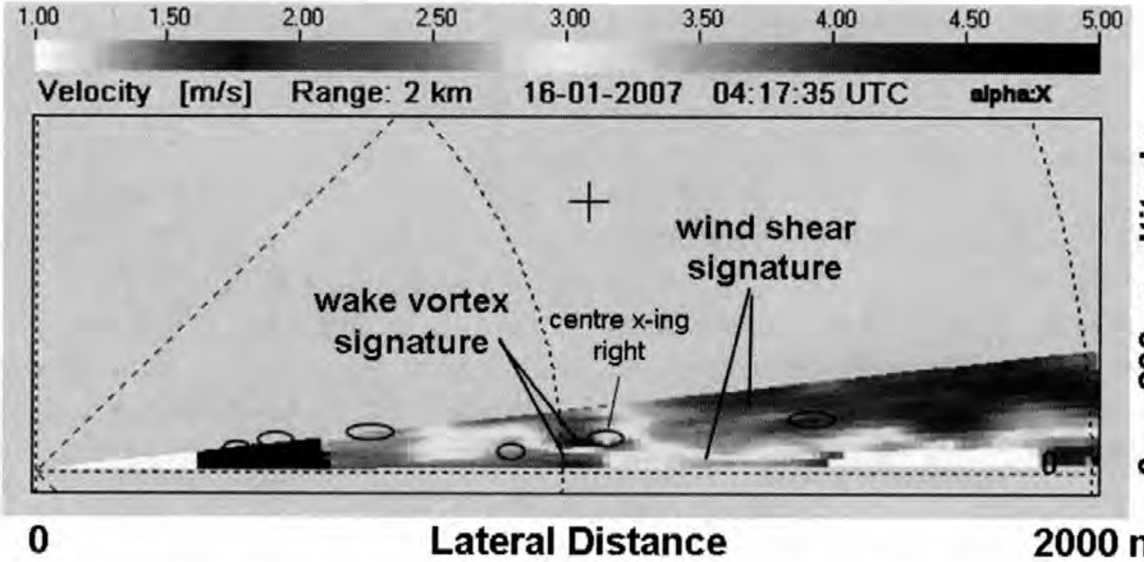

Figure 5. LOS velocity as measured by LIDAR (quick-look after one scan, positive values indicate velocities away from the instrument) with signatures of wind shear and a wake vortex pair. The crossings of the laser beam with the glide path gates in Figure 2 are indicated by small ellipses; "centre x-ing right" identifies the approximate intersection of the beam in scan plane "centre" with runway 25R at 1070 m distance.

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.

INTEGRATION INTO ATC PROCEDURES

The Concepts of Operation

The German Air Safety Provider, DFS, has established four modes, or concepts of operation, for aircraft separation to be applied for the dependent parallel runway system at Frankfurt Airport under instrumented meteorological conditions (IMC) [Gurke and Lafferton, 1997], see Figure 6:

- "ICAO" – standard procedure under IMC with 4 nmi for a HH aircraft pair and 5 nmi 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 nmi;
- "Modified Staggered Left" (MSL) – aircraft on right (windward) runway keep 2.5 nmi separated from aircraft of left (lee) runway;
- "Modified Staggered Right" (MSR) – aircraft on left (windward) runway keep 2.5 nmi separated from aircraft of right (lee) runway.

Note that in all modes, all aircraft in-trail (approaching the same runway) remain separated according to ICAO standards. The modes STG, MSL, MSR can only be applied in favorable weather conditions (especially favorable cross-wind) and require the use of a wake vortex advisory system as DLR's WSVBS or DFS' wake vortex warning system, WVWS [Gurke and Lafferton, 1997]. These modes are not used operationally today.

Table 1 translates the operationally applied separation distances for HH, HM and radar separation into separation times which must be followed in each concept of operation and for each runway combination. For 5 and 4 nmi separation we applied an approach speed of 74 m/s (144 kn) to all aircraft, following the conservative parameter setting in DLR's Arrival Manager, AMAN. For the minimum (radar) separation we took a conservative 70 s (instead of 62.5 s).

The Prediction Cycle

The installation of the WSVBS at Frankfurt Airport was accomplished on the 19th of December, 2006. It then delivered data for 66 days until the 28th of February, 2007. The wake predictive chain started with the forecast of the local weather twice a day at 0 and 12 UTC. The SODAR/RASS/USA operated continuously 24 hours a

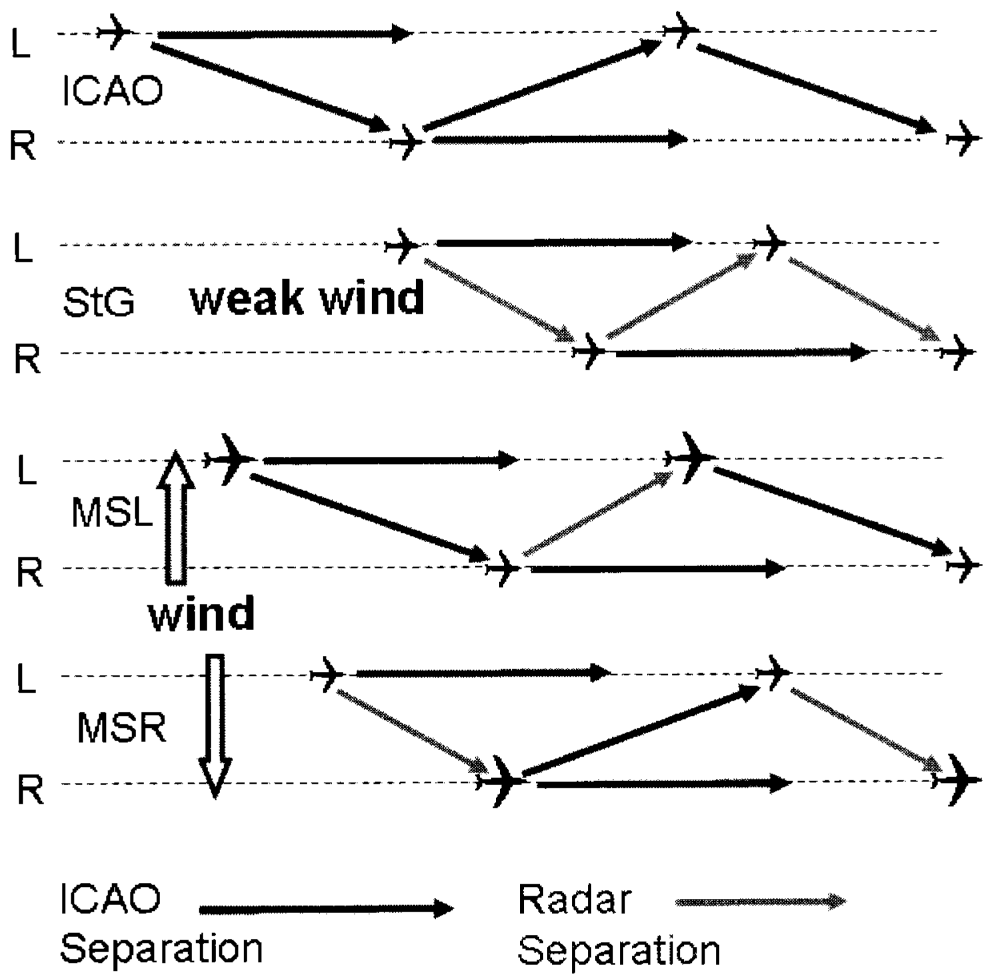

Figure 6. The concepts of operation under IMC for the dependent parallel runway system at Frankfurt Airport.

day and delivered measured weather profiles every 10 min. With these weather data, the areas of possible vortex locations and the surrounding safety areas were computed by P2P and SHAPe. The forecast of minimum safe wake separations was made every 10 min for both runways at all 13 gates with a forecast horizon of 60 min.

Table 1. Aircraft Separation Times for the Four DFS Concepts of Operation ICAO, STG, MSL, MSR and the Four Runway Combinations of Leader and Follower Aircraft (e.g., RL = leader on 25R, follower on 25L runway)

ICAO	H-H	H-M	*STG*	H-H	H-M
LL	100 s	125 s	LL	100 s	125 s
LR	100 s	125 s	LR	70 s	70 s
RL	100 s	125 s	RL	70 s	70 s
RR	100 s	125 s	RR	100 s	125 s
MSR	H-H	H-M	*MSL*	H-H	H-M
LL	100 s	125 s	LL	100 s	125 s
LR	100 s	125 s	LR	70 s	70 s
RL	70 s	70 s	RL	100 s	125 s
RR	100 s	125 s	RR	100 s	125 s

After consultation with controllers, it was assumed that they require at least 45 min lookahead time to utilize the WSVBS system. The *minimum separation time (MST)* between two aircraft landing on the same or the adjacent parallel runway is determined by the maximum time that the predicted wake safety area overlaps the approach corridor. The time is computed in all gates for the respective aircraft weight class combinations.

Based on the MST, landing procedures were eventually recommended and displayed on the PC in the Local Operation Centre as shown in Figure 7 and Figure 8; they were also accessible remotely via the Internet. Figure 7 is updated every ten minutes and adjusted for the progression of time each minute. The figure shows that for most of the forecast time the operational procedure MSL can be used with a short period where the (northerly) wind is so weak that the runways can be used independently (STG). After 50 minutes the WSVBS system anticipates a change that requires a return to the standard separations (ICAO).

Figure 8 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 also allows surveying possible reduced separations for aircraft flying in-trail and it further distinguishes HH and HM aircraft pairs. The sketched example indicates that the DFS procedure MSL can be used (no wake-vortex separation required for runway combination 25L25R but full ICAO separation for 25R25L), and, in addition, 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.

The Human-machine Interfaces

The proposed operational procedures for up to one hour were also displayed on simulated controller screens for the real-time

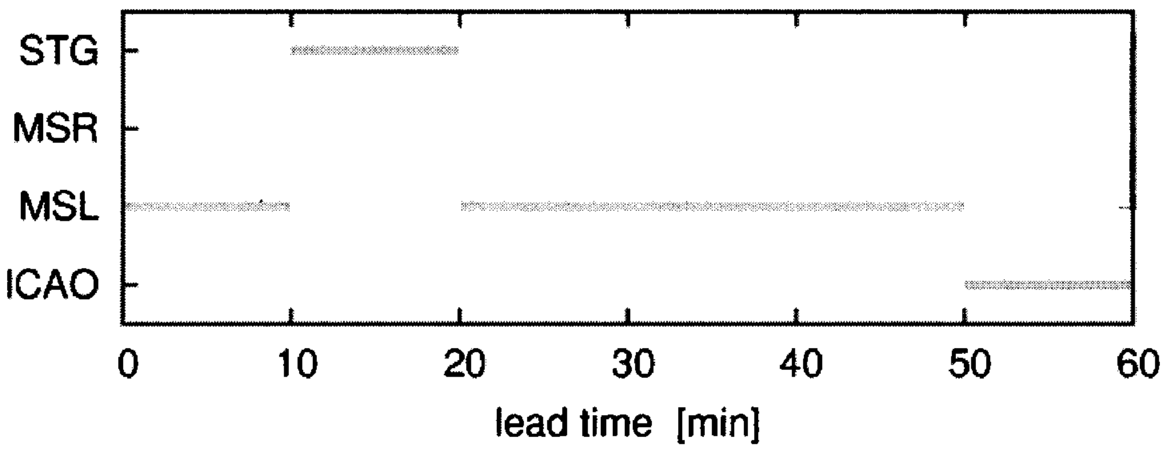

Figure 7. Indicated use of DFS approach procedures within the next hour.

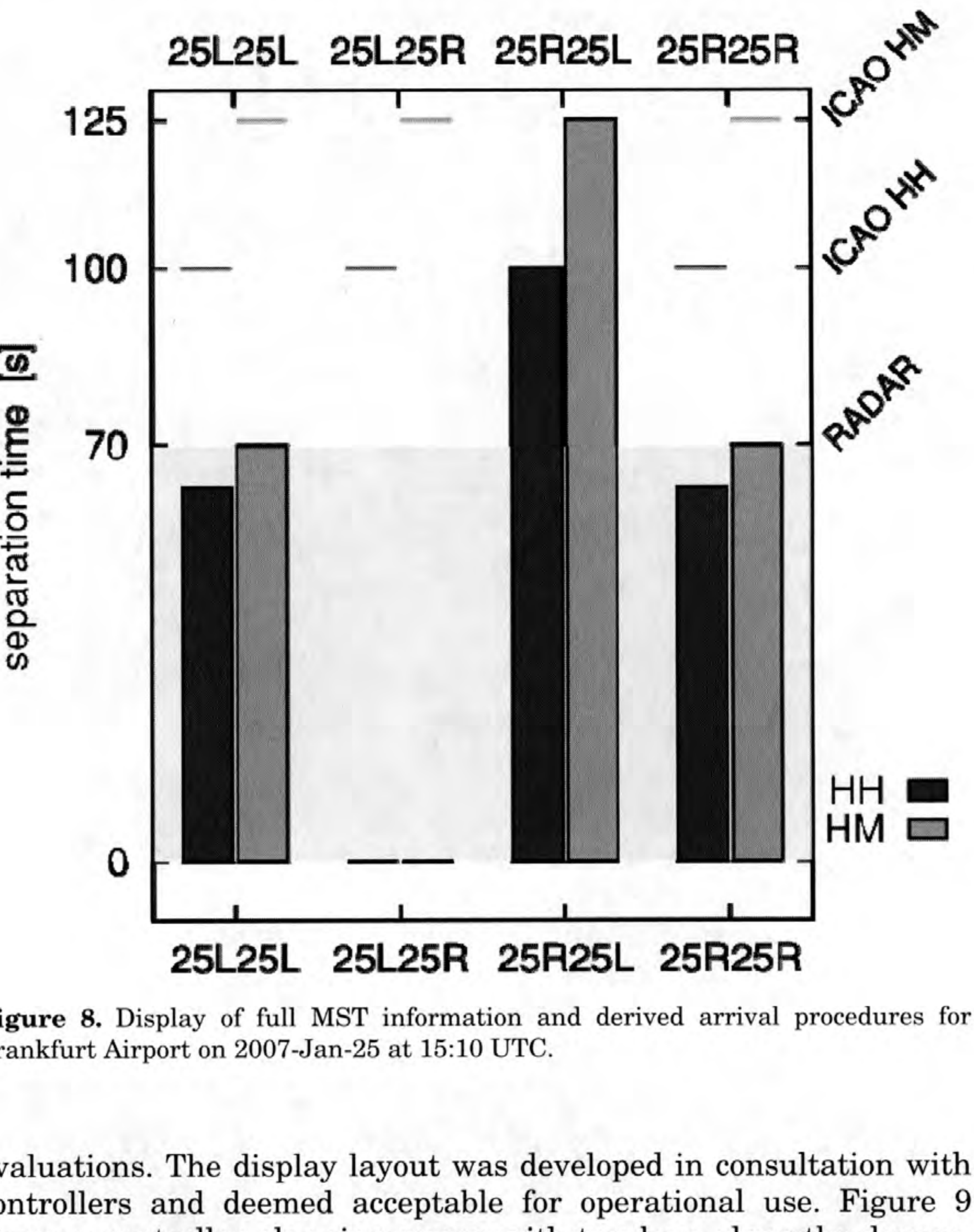

Figure 8. Display of full MST information and derived arrival procedures for Frankfurt Airport on 2007-Jan-25 at 15:10 UTC.

evaluations. The display layout was developed in consultation with controllers and deemed acceptable for operational use. Figure 9 shows a controller planning screen with two bars along the dynamic time scale up to 37 min indicating mode MSL for the period 07:06 until 07:29 and mode STG afterwards. Upon request from controllers the forecast wind direction and speed at heights FL 70 and 4000 feet and at ground level were also displayed. Another situation is depicted on a controller radar screen shown in Figure 10, where the parallel runways can be seen by two tiny lines (see arrow). The final approach path of the northern runway is indicated by the time ladder. The thick bright lines parallel to it have a 12 min time horizon and appear when aircraft may be separated by 2.5 nmi. Hence, the situation displayed allows mode STG for the next 10 min, followed by mode MSL afterwards.

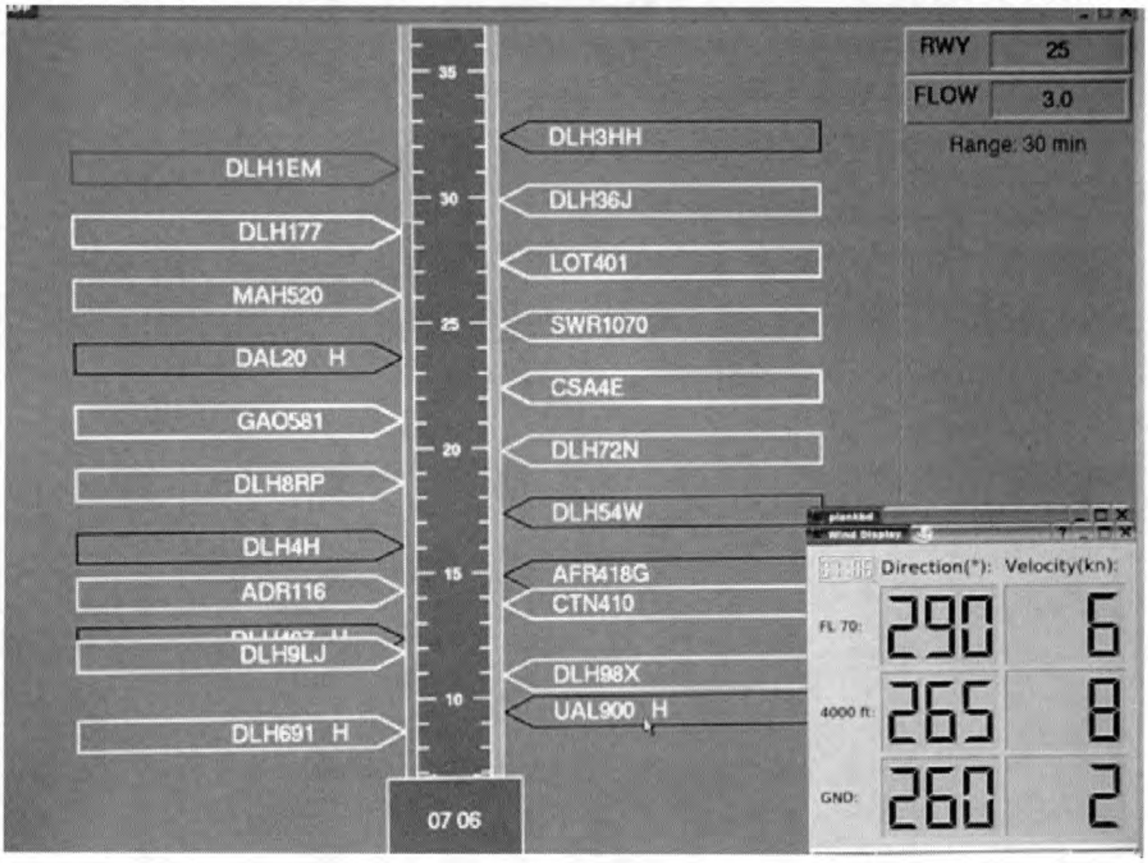

Figure 9. Controller's planning screen with dynamic time scale and wind information.

PERFORMANCE AND IMPROVED CAPACITY

We performed real-time and fast-time simulations, employing the Air Traffic Management and Operations Simulator (ATMOS II) and the SIMMOD tool of DLR. During a one-week period real-time

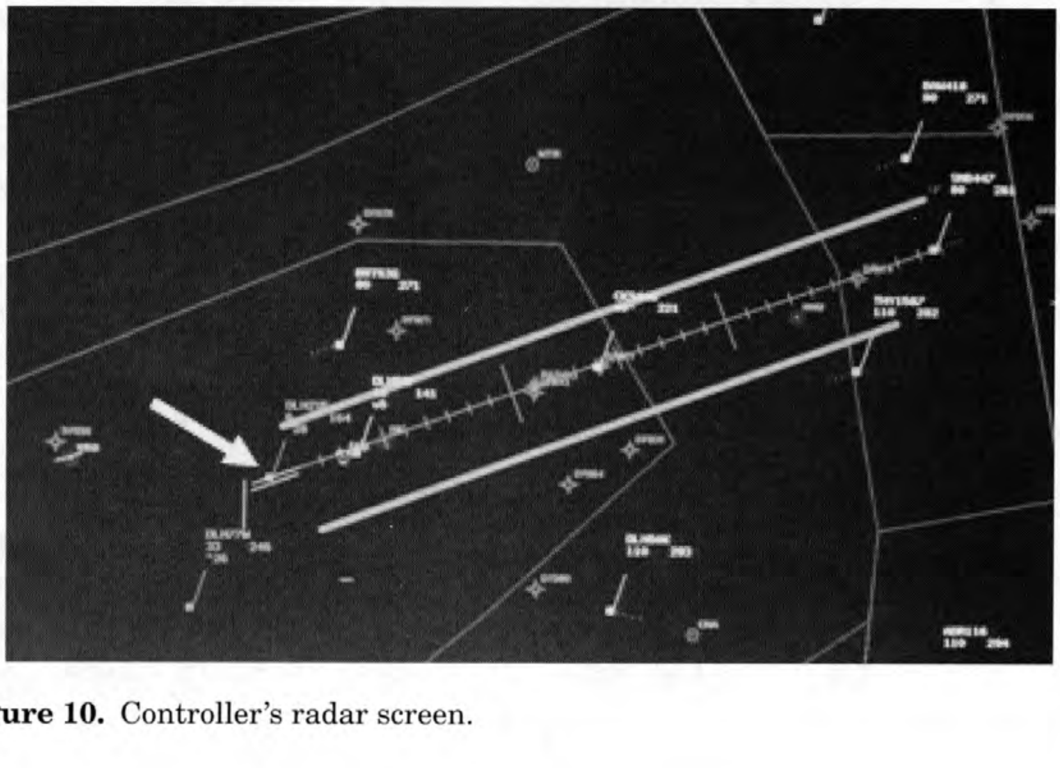

Figure 10. Controller's radar screen.

simulations were carried out at the simulator ATMOS II under the assistance of five air traffic controllers from the DFS. The investigation was aimed at determining the behaviour and efficiency of the WSVBS at a simulated real-time controller working position, and obtaining controller evaluations of the system.

By means of a questionnaire the controllers from DFS were interviewed with respect to aspects such as:

- acceptance of the simulation environment,
- acceptance of the WSVBS,
- procedural regulations and human interface,
- operational applicability.

The participating controllers generally found the WSVBS system and associated procedures acceptable. In particular, the system was judged not to interfere with their normal working procedures (Gerling et al., 2007).

We also performed fast-time simulations to obtain capacity figures for the different concepts of operation utilized 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 (Figure 11). The simulations included actual aircraft types and flight

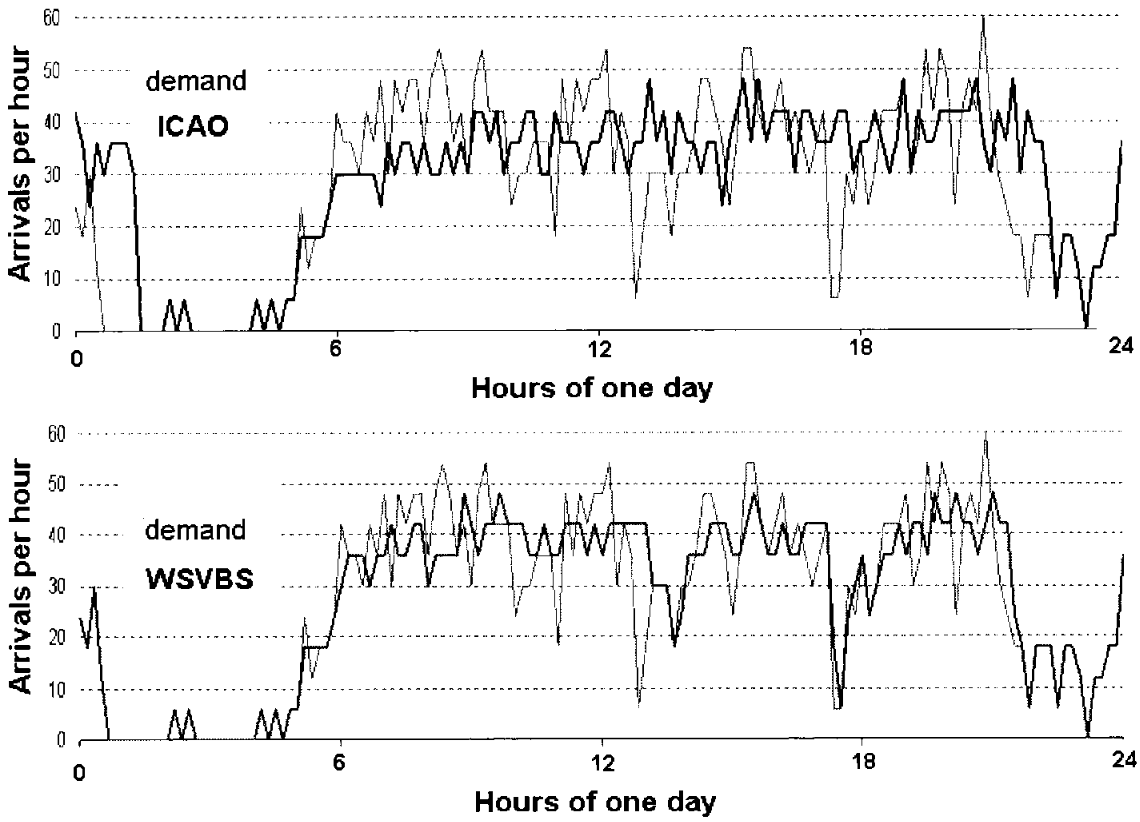

Figure 11. Traffic flow (arrivals per hour) during a day at Frankfurt Airport. Top: demand (grey) vs. ICAO standards (black); bottom: demand (grey) vs. WSVBS utilisation (black).

characteristics spanning a realistic distribution of wake vortex categories, demand peaks throughout the day, weather data, and the WSVBS proposed minimum wake vortex separations. The fast-time simulations covered a period of one month.

Figure 11 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 resolved in the late evening hours.

Improved capacity at an airport offers a variety of options for future aircraft operations which range from an entirely tactical scenario (increase punctuality of flights while keeping number of landings constant) to an entirely strategic scenario (increase the average traffic flow at the expense of higher average delays). Figure 12 shows the theoretical capacity gain for the different concepts of operation. A SIMMOD model of the parallel runways at Frankfurt Airport was developed assuming a constant flow of arrivals and a traffic mix of 27, 67 and 6% of heavy, medium and light aircraft, respectively. For each average number of arrivals per hour ten iterations of the SIMMOD model were executed with randomized computed flight paths. The figure reveals that 2 to 5 more aircraft can land per hour when changing from ICAO mode to MSL/R or STG mode, respectively, if an average delay of 4 minutes is accepted. Or, vice versa, the average

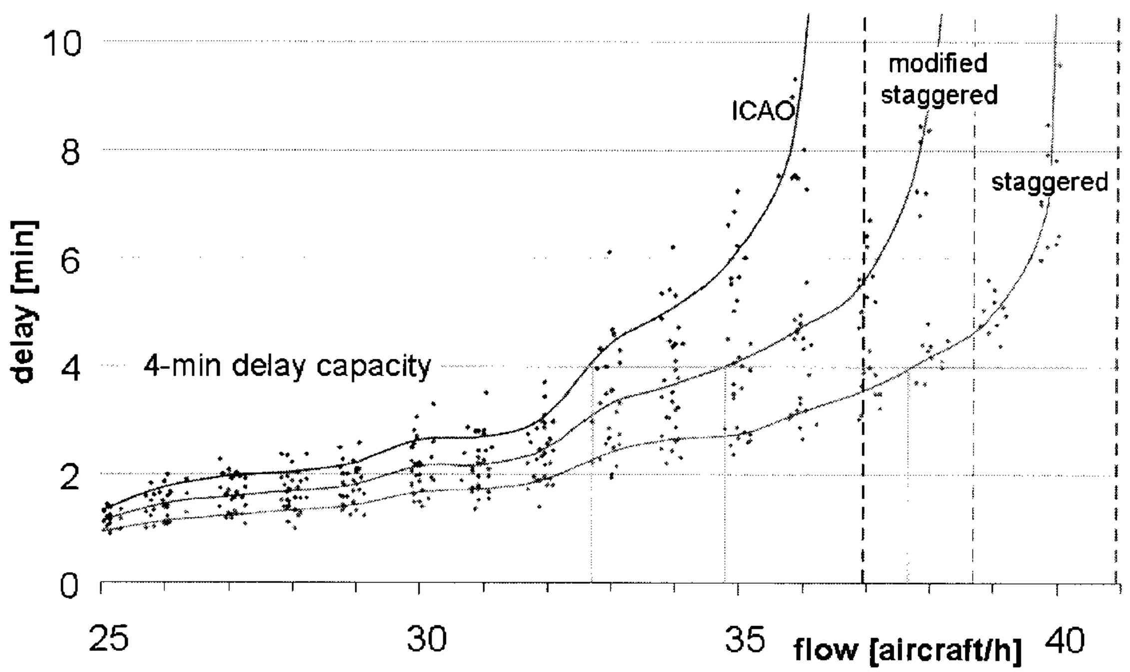

Figure 12. Average delay versus traffic flow (for a mix of H/M/L aircraft of 27/67/6%) for the concepts of operation ICAO, MSL/R, and STG from fast-time simulations; the "4-min delay" capacity is indicated by thin vertical lines.

delay of 4 minutes (ICAO) would drop down to a bit more than 2 minutes (STG) when keeping the arrival rate at almost 33 aircraft per hour. The figure also points out that a further increase of capacity beyond 39 arrivals per hour for mode STG would rapidly increase delays, since the system runs into its saturation point. When taking into account the real traffic mix and operational constraints in the one month period simulated we received a net capacity gain of slightly larger than 3%.

Figure 13 summarizes the history of potential usage of DFS-developed operation modes as proposed by WSVBS during the 66 days evaluation at the Frankfurt airport. It is evident that in the majority of time the proposed modes could have been deployed to improve capacity or punctuality of landing aircraft. A closer look at five specific days indicates that each mode can be deployed throughout a significant fraction of time (see also Figure 14).

Table 2 lists the use of all operation modes as predicted by WSVBS during the 66 day evaluation for the fraction of time in which radar separation of 2.5 nmi (70 s) was suggested. Thus, the table also includes reduced in-trail separation and differentiates between HH and HM aircraft pairs (cf. Figure 8). From the meteorological conditions which prevailed during that winter period, heavy aircraft could have landed behind heavy aircraft in-trail on R or L runway in 2.6% of the time with an average MST of 60 s (but *de facto* separated by 70 s). In another example, 47.9% of the time a medium aircraft could have landed 2.5 nmi behind the preceding heavy aircraft landing on R.

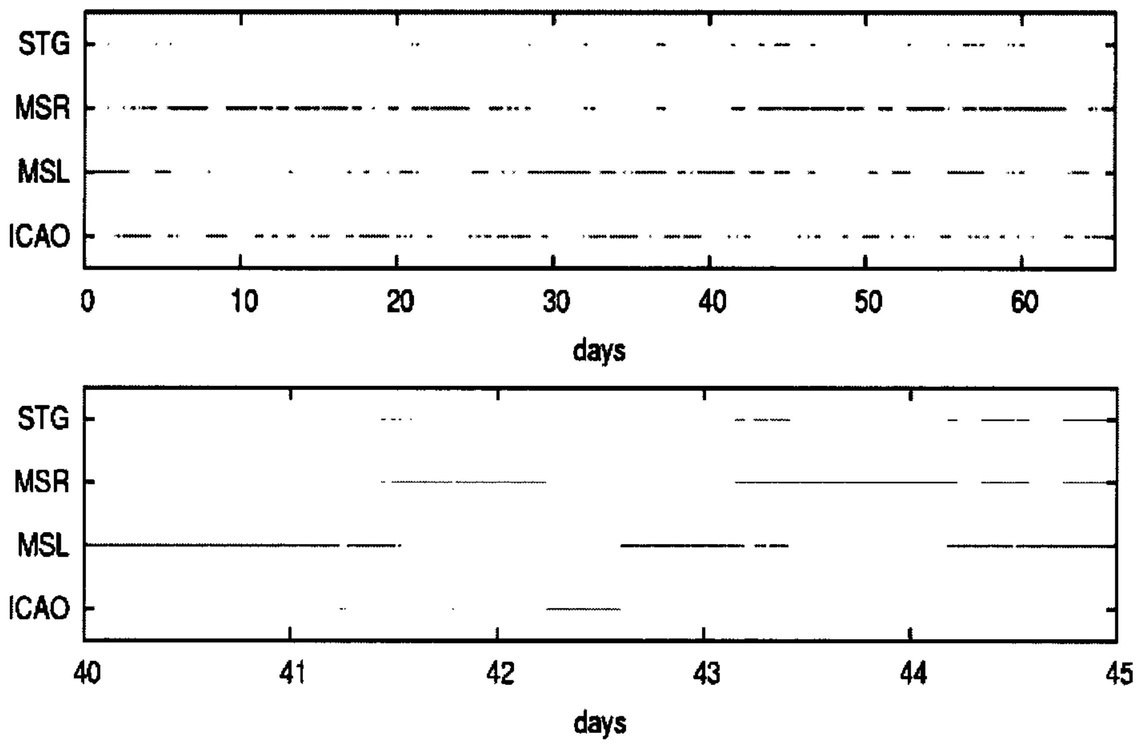

Figure 13. History of potential usage of the 4 DFS operation modes during the 66 days of the campaign at Frankfurt. Top: full period; bottom: zoom on five days.

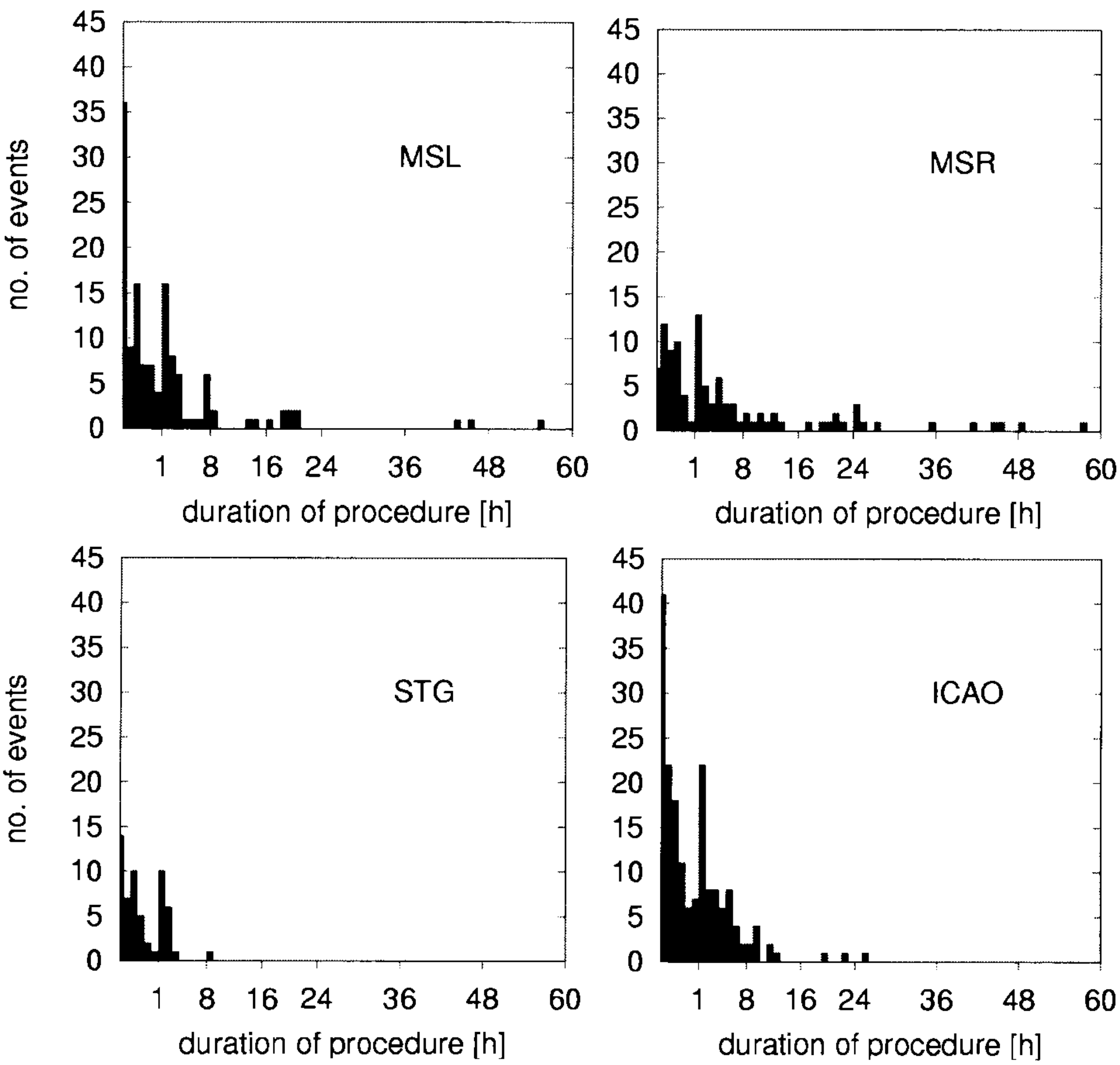

Figure 14. Number of events versus duration of potential DFS wake avoidance procedures in hours for HM aircraft pairs; a 10 min interval is used in the 1st hour, the interval is 1 hour afterwards. The median durations of the procedures amount to 40 min for MSL, 90 min for MSR, 30 min for STG and 40 min for ICAO, respectively.

Table 2. Average Minimum Separation Time and Frequency for HH and HM Aircraft Pairs Landing In-trail (LL, RR) or Across (LR, RL) for the Fraction of Time in which Radar Separation was Suggested

Landing procedure	Average MST [s]	Frequency of use [%]
LL HH	60.0	2.6
LL HM	61.9	1.5
LR HH	0	40.3
LR HM = MSL	0	30.7
RL HH	0	54.3
RL HM = MSR	0	47.9
RR HH	60.0	2.6
RR HM	61.9	1.5
STG HH	0	10.0
STG HM	0	3.6
ICAO		25.0

The cases where DFS-mode STG could have been used for HH (HM) pairings summed up to 10% (3.6%). For the DFS operation modes, the ICAO separation mode was required in only 25% of the time.

Table 3 displays similar information as Table 2 including the assumption that all separation times between 0 and 100 s (125 s) for HH (HM) pairs could be used. In particular, the use of reduced in-trail separations increases strongly by factors 2.5 (6) although at the expense of larger average MST. The staggered procedures are almost unchanged compared to Table 2 since these values depend predominantly on whether or not a vortex reaches the parallel runway.

The frequencies of use listed in Tables 2 and 3 are predominantly related to wake vortex transport by crosswind. If the predicted vortex descent (or descent and decay) is not used, the periods of ICAO separations increase from 25% to 30.4%, i.e. by 21.6% (or from 25% to 31.9%, i.e. by 27.6%). Accordingly, the frequency of use for "modified staggered" procedures is reduced on average by 9.3% (11.5%). For the procedure "staggered" the reduction amounts to 58% (64%) but this mode is seldom used. A pure crosswind based prediction of lateral transport would cause further reductions in potential benefits. In order to achieve the same level of safety, the uncertainty allowances of such a simple scheme would exceed those of the P2P which incorporates the wake removal mechanisms of lateral transport and effects related to vortex descent and decay.

Questions concerning how long the DFS ConOps MSL, MSR, STG or no one of them (ICAO) separations could be continuously used and how often this happened during the campaign is answered in Figure 14 for pairs of Heavy/Medium aircraft. In the 66 days, the procedures MSL/MSR/STG could have been used 36/7/14 times for only 10 minutes. 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 2/2/1 times, respectively. Somewhat higher numbers hold for the aircraft pairing HH and somewhat

Table 3. As for Table 2 but all Separation Times Between 0 and 100/125 s are used

Landing procedure	Average MST [s]	Frequency of use [%]
LL HH	75.7	6.6
LL HM	93.5	9.0
LR HH	0.1	40.3
LR HM = MSL	1.2	31.0
RL HH	0.5	54.6
RL HM = MSR	1.6	48.6
RR HH	75.7	6.6
RR HM	93.5	9.0

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 for one period lasting almost 4 days (93 hours). The median durations of the procedures amount to 40 min for MSL, 90 min for MSR, 30 min for STG and 40 min for ICAO, respectively. Hence, for mode STG, for example, the median number of transitions from STG to another mode is two per hour.

For the interested reader a further analysis reveals which gates impede reduced aircraft separations. This analysis indicated that gate 13 (the one closest to the runway threshold where aircraft fly at 29 m above ground) hinders WSVBS operations for single runway approaches in 51% out of 6042 cases. This is further evidence for the bottleneck close to the ground. Interestingly though, gate 1 (the farthest-out gate at 1077 m height) blocks reduced separations in almost 31% of the cases. This is attributed to the fact that the first approach corridor features the largest dimensions. For staggered and modified staggered approaches, gate 13 is no longer an issue but gate 10 impedes reduced separations 26 to 48% of the time. At this gate two effects appear decisive. First, it is the lowest gate employing numerical cross-wind predictions, which lead to larger uncertainty allowances of vortex position compared with predictions using actual wind measurements. Second, the aircraft vortices are shed at 190 m height where ground effect still contributes to the lateral wake vortex transport for the aircraft parameter combinations with the largest wing spans [Holzäpfel et al., 2009b]. Similar as for the single runway approaches, the first gate with the largest approach corridor dimensions blocks reduced separations for approaches towards the parallel runway system in 10 to 45% of the cases.

Figure 15 shows two examples of traces of the port and starboard vortices of heavy aircraft landing on runway 25R as measured by the LIDAR in the three scan planes shown in Figure 2. 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 prevented the vortices from reaching runway 25L (hence, MSR). The wind became so strong later in the day that a reduced separation in-trail could have been operated. For the 8th of February, WSVBS recommended use of the STG operation 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.

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 (Figure 2). In all these cases it was found that the recommended

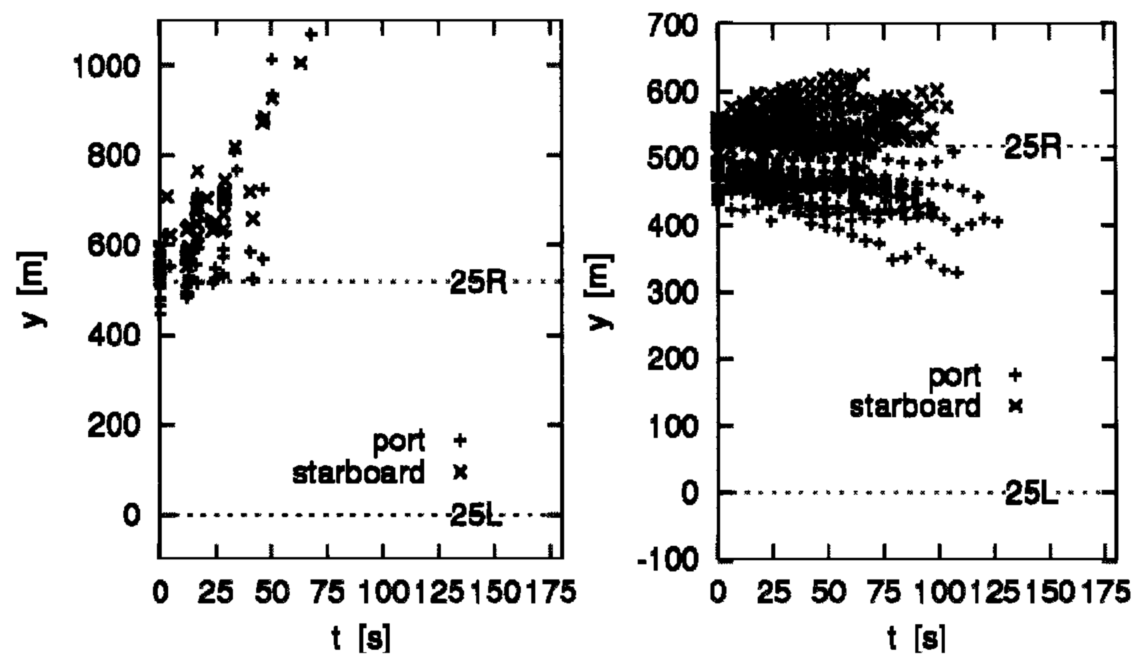

Figure 15. Lateral positions of wake vortices vs. vortex age from 8, 32 heavy aircraft landing on 25 R on 18th Jan. (left) and 8th Feb. (right) 2007, respectively, as traced by the LIDAR in the three scan planes.

operation mode was well predicted — no vortices were detected in the flight corridor after the predicted minimum separation time.

CONCLUSIONS

DLR has developed a wake vortex advisory system for airports and air traffic control, the *Wirbelschleppen-Vorhersage- und -Beobachtungs-system*, named WSVBS. It has the components SODAR, RASS, USA and NOWVIV for monitoring and forecasting the local weather around the airport in Frankfurt (or any other airport). The components P2P and SHAPe are used to predict wake transport and decay and required safety areas. A LIDAR is employed to survey the lower most-critical heights along the glide path for wake vortices. WSVBS is integrated in the arrival manager AMAN of DLR. The WSVBS prediction horizon is larger than 45 min (as required by air traffic controllers) and updates every 10 minutes. It predicts which of the DFS concepts of operation for wake avoidance and associated procedures may be utilized and it further predicts additional temporal separations for in-trail traffic.

The WSVBS demonstrated its functionality at Frankfurt airport during a 66 day evaluation period from 18/12/06 until 28/02/07. It covered the glide paths of runways 25L and R from the final approach fix (11 nmi) to the threshold. It combined measured and forecast meteorological data for wake prediction. From the 66 days of performance testing at Frankfurt we found that [Gerz et al., 2007]:

- the system was stable — no breakdowns of the forecasts occurred,
- aircraft separations could have been reduced 75% of the time compared with ICAO standards,
- reduced separation procedures could have been continuously applied for at least several tens of minutes routinely and up to several hours occasionally,
- the predictions were correct for the 1100 landings observed during 16 days of LIDAR measurement.

We acknowledge that the period of 66 days is rather short to draw final conclusions on the performance of the WSVBS. However, the performance of the system has also been elaborated by using a numerical database (Frech et al., 2007) consisting of one full year of meteorological data along the glide paths of the Frankfurt Airport. These results show similar statistics in the possible use of the operational concepts as reported here from the 66 days field campaign.

Fast-time simulations revealed that the concepts of operation introduced by DFS (i.e. MSL, MSR, STG with 2.5 nmi or 70 s as the minimum separation) and utilized by WSVBS for the Frankfurt Airport, yield significant reductions in delay and/or a 3% increase in capacity, taking into account the real traffic mix and operational constraints. 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 by minimising holding patterns. After experience has been gained over some years of operation (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" probably depending on the time of the day or the season of the year.

From scientific and technological perspectives, the WSVBS has reached a mature and useful state. However, before the system can be handed over to users to become a customized and fully operational system, further steps are necessary. A risk analysis will be pursued and other field campaigns are planned in the context of forthcoming national and international campaigns, like in DLR's follow-on project *Weather & Flying* and within the SESAR Joint Undertaking.

ACKNOWLEDGEMENTS

We highly acknowledge the support and help from the Fraport AG, Frankfurt, in setting up and running the field trial at their airport. We also thank the German Meteorological Service, DWD, in Offenbach, for hosting our Local Operation Centre in their observer house

at the airport and supplying the model output data of their routine weather forecasts. The German air traffic safety provider DFS, Langen, is acknowledged for their support. We thank Fa. Metek, Elmshorn, for renting their very reliable and robust meteorological profiler system to us and Dr. Andreas Wiegele for his support in performing and evaluating the LIDAR measurement campaigns. The work presented here was funded by the DLR project *Wirbelschleppe* and did benefit from the EU projects *ATC-Wake* (IST-2001-34729), *FAR-Wake* (FP6–012238), *FLYSAFE* (AIP4-CT-2005-516 167), and the European Thematic Network *WakeNet2-Europe* (G4RT-CT-2002-05115). We finally thank four anonymous reviewers and the editors for their thoughtful comments and suggestions. Special thanks go to one of the reviewers who spared no effort to enhance the manuscripts with high expertise in wording and technical knowledge.

ACRONYMS

AMAN	Arrival Manager
ATC	Air Traffic Control
ATMOS II	Air Traffic Management and Operations Simulator
CSPR	Closely-Spaced Parallel Runways
DFS	Deutsche Flugsicherung GmbH
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DWD	Deutscher Wetterdienst
EDR	Eddy Dissipation Rate
HH	Heavy aircraft followed by Heavy aircraft
HM	Heavy aircraft followed by Medium aircraft
ICAO	International Civil Aviation Organization
IMC	Instrumented Meteorological Conditions
LIDAR	Light Detection and Ranging
LM	Lokal Modell
LOC	Local Operation Centre
MSL	Modified Staggered Left
MSR	Modified Staggered Right
MST	Minimum Aircraft Separation Time
NOWVIV	Nowcasting Wake Vortex Impact Variables
MM5	Mesoscale Meteorology Model 5
P2P	Probabilistic Two-Phase Wake Vortex Model
PC	Personal Computer
RASS	Radio Acoustic Sounding System
SHAPe	Simplified Hazard Area Prediction
SIMMOD	discrete-event simulation model
SODAR	Sound Detection and Ranging
STG	Staggered
UMTS	Universal Mobile Telecommunications System
USA	Ultra Sonic Anemometer
UTC	Universal Time Coordinated
WSVBS	Wake Vortex Prediction and Monitoring System
WVWS	Wake Vortex Warning System

REFERENCES

Frech M. 2007: Estimating the turbulent energy dissipation rate in an airport environment. *Boundary-layer Meterol.* **123**, 385-393.

Frech M., Holzäpfel F., Tafferner A., Gerz T. 2007: High-Resolution Weather Data base for the Terminal Area of Frankfurt Airport. *J. Appl. Meteor. Climat.* **46**, 1913-1932.

Frech M., Holzäpfel F. 2008: Skill of an Aircraft Wake-Vortex Model Using Weather Prediction and Observation. *J. Aircraft* **45**, 461-470.

Gerling W., Schick F.F., Klostermann E., Keck B., Ehr H. 2007: DLR-Projekt Wirbelschleppe II - Echtzeitsimulationen mit Wirbelschleppenvorhersage. DLR-IB 112-2007/18, 39 pp.

Gerz T., Holzäpfel F., Bryant W., Köpp F., Frech M., Tafferner A., Winckelmans G. 2005: Research towards a wake-vortex advisory system for optimal aircraft spacing, *Comptes Rendus Physique*, Académie des Sciences, Paris, **6**, No. 4-5, 501-523.

Gerz, T., Holzäpfel, F., Gerling, W., Scharnweber, A., Frech, M., Wiegele, A., Kober, K., Dengler, K., Rahm, S. (2007), "The Wake Vortex Prediction and Monitoring System WSVBS - Part II: Performance and ATC Integration at Frankfurt Airport," 1st European Air and Space Conference (CEAS 2007) / Deutscher Luft- und Raumfahrtkongress 2007, Berlin, Germany, September.

Gurke T., Lafferton H. 1997: The development of the wake vortex warning system for Frankfurt Airport: Theory and implementation, *Air Traffic Control Quarterly* **5**, 3-29.

Hahn K.-U., Schwarz C., Friehmelt H. 2004: A simplified hazard area prediction (SHAPe) model for wake vortex encounter avoidance, in: Proc. 24th International Congress of Aeronautical Sciences, Yokohama, Japan.

Holzäpfel F. 2003: Probabilistic two-phase wake vortex decay and transport model, *Journal of Aircraft* **40**, No. 2, 323-331.

Holzäpfel F., Robins R.E. 2004: Probabilistic two-phase aircraft wake-vortex model: application and assessment, *Journal of Aircraft* **41**, No. 5, 1117-1126.

Holzäpfel F. 2006: Two-Phase Aircraft Wake Vortex Model: Further development and Assessment, *J. Aircraft* **43**, 3, 700-708.

Holzäpfel F., Steen M. 2007: Aircraft wake-vortex evolution in ground proximity: Analysis and parameterization. *AIAA J.* **45**, No.1, 218-227.

Holzäpfel F., Frech M., Gerz T., Tafferner A., Hahn K.U., Schwarz C., Joos H.-D., Korn B., Lenz H., Luckner R., Höhne G. 2009a: Aircraft wake vortex scenarios simulation package – WakeScene. *Aerospace Science and Technology* **13**, 1-11.

Holzäpfel F., Gerz T., Frech M., Tafferner A., Köpp F., Smalikho I., Rahm S., Hahn K.-U. & Schwarz C. 2009b: The wake vortex prediction and mointoring system WSVBS. Part I: Design. *Air Traffic Control Quarterly*, this issue.

Schwarz C., Hahn K.-U. 2005: Simplified hazard areas for wake vortex encounter avoidance. AIAA Atmospheric Flight Mechanics Conference and Exhibits, San Francisco, California, USA.

Schwarz C., Hahn K.-U. 2006: Full-flight simulator study for wake vortex hazard area investigation, *Aerospace Science and Technology* **10**, 136–143.

BIOGRAPHIES

Thomas Gerz graduated as a meteorologist with a diploma degree in 1984 and obtained a Dr. rer. nat. in 1988, both from Ludwigs-Maximilians-Universität in München (Munich). He works as a scientist and research manager at the Deutsches

Zentrum für Luft- und Raumfahrt (German Aerospace Center) DLR – Institut für Physik der Atmosphäre (Institute of Atmospheric Physics) in Oberpfaffenhofen, Germany. He managed the DLR project Wirbelschleppe (Wake Vortex) from 1998 to 2007 and since 2008 he is head of the DLR project Wetter & Fliegen (Weather & Flying). E-mail: thomas.gerz@dlr.de

Frank Holzäpfel graduated as a mechanical engineer from the University of Karlsruhe (TH) in 1990. He then specialized in multi-hot-wire measurement techniques and turbulence modeling in turbulent swirling flows at the Engler Bunte Institut of the University Karlsruhe, where he obtained his Dr.-Ing. in 1996. In 1997 he became a Research Scientist at the Institute of Atmospheric Physics, DLR in Oberpfaffenhofen, where he concentrates on wake vortex research, which includes large eddy simulation, real-time model development, wake vortex systems and risk analysis. In 2005 he obtained his Habilitation in Fluid Dynamics at the Faculty of Mechanical Engineering of the Technical University Munich where he is an associate lecturer since 2007.

Wilfried Gerling graduated as an electrical engineer from the University of Braunschweig (TU) in 1978. He then became a Research Scientist at the Institute of Flight Guidance, DLR in Braunschweig, where he concentrated on flight measurement and Air Traffic Control (ATC). He specialized in conflict recognition and obtained his Dr.-Ing. in 1994 from the Technical University of Berlin. Since 2004 he works on wake vortex research with the emphasis on integrating advanced prediction techniques into ATC procedures and controller's workplace.

Alexander Scharnweber graduated from the Technical University Braunschweig in 2005 with a diploma (Dipl.-Ing.) in mechanical engineering. In 2006 he joined the DLR Institute of Flight Guidance in Braunschweig as a Research Scientist in the Air Transportation Department. His areas of expertise include the design and analysis of fast-time simulations for airport airside environments, as well as design and implementation of software tools for simulation analysis.

Michael Frech received a Masters degree in Atmospheric Sciences from Oregon State University in 1994. In that year he joined the German Aerospace Research Center in Oberpfaffenhofen pursuing research on turbulence exchange processes in the atmospheric boundary layer. In 1998 he received his Phd from the Ludwig-Maximilian-University in Munich. In the following years he worked on designing operational wake vortex prediction and monitoring systems. There the prime focus was to monitor and predict relevant atmospheric variables to predict and characterize wake vortex evolution. Since 2007 he is working for the German Meteorological Service where he works on the introduction of the new German operational radar network.

Kirstin Kober graduated in meteorology at the Ludwig-Maximilians-University of Munich in 2006. Since 2007 she is doing her PhD about 'Probabilistic forecasting of thunderstorms through combining nowcasting methods and numerical weather prediction' at the Institute of Atmospheric Physics at DLR, Oberpfaffenhofen.

Klaus Dengler graduated in atmospheric sciences at the University of Munich in 1993. Working on numerical simulations of tropical cyclones he obtained his Dr. rer. nat. in 1997. In 1998 he returned from a Posdoc position at the State University of New York to work in private industry for several years specializing on automatic nowcasting systems for road weather information systems. In 2007 he became a

research scientist at the Institute of Atmospheric Physics, DLR in Oberpfaffenhofen where he works on short time forecasting of parameters relevant for wake vortex prediction.

Stephan Rahm graduated as an electrical engineer from the University of Munich in 1988. He then specialized in optical amplifiers and coherent Doppler lidar at the DLR in Oberpfaffenhofen, where he obtained his Dr.-Ing. in 1993. Then he became a research scientist at the Institute of Atmospheric Physics, DLR in Oberpfaffenhofen, where he concentrates on coherent Doppler lidar measurements on wind and wake vortex phenomena with ground based as well as airborne systems.

Air Traffic Control Quarterly

An International Journal of Engineering and Operations

AUTHOR'S GUIDELINES FOR PUBLICATION

OBJECTIVES AND SCOPE

The *Air Traffic Control Quarterly* is an international peer-reviewed journal dedicated to the advancement and dissemination of research in the science and practice of air traffic control. Its scope includes papers related to experimental, theoretical, and operational results in the areas of operations, standards and procedures, surveillance, navigation, communication, automation, operations research, human factors, meteorology, avionics, safety, aeronautics, management, training, certification, etc.

SUBMISSIONS

Manuscripts are invited to be considered for publication. Please submit to the Managing Editor, Air Traffic Control Association Institute (see front flyleaf), supplying contact information—name, address, affiliation, telephone, fax, and e-mail. Manuscripts must be in English, are typically less than 10,000 words, and have less than 10 figures (each figure is counted as the equivalent of 250 of the 10,000 words). Submissions are preferred as e-mail attachments using a standard word processing program (Microsoft Word preferred). Please do not use PostScript files or page layout programs (such as Pagemaker or Quark Express). Please number all pages. Specific questions or problems should be discussed with the Managing Editor.

Include an abstract of up to 150 words, a section of references at the end, and, if appropriate, a table of acronyms and one of symbols (these may be combined if there are not many symbols), and a brief biography (less than 100 words) of each author. Sections are distinguished by typography rather than numerically.

Figures: While figures may be included with the text, they should also be submitted as separate electronic files—high-resolution, readable in Illustrator, PhotoShop, or Excel. If in doubt, EPS or TIFF formats are satisfactory. Text within the figures should be in Helvetica or similar non-serif font. Unless special arrangements are made, figures will be printed in black-and-white at a maximum width of 4-3/4 inches (12 cm). Identify all figures.

Formulas should be integrated within the text, important ones being numbered consecutively at the right side of the page. For the most part, they will be re-keyed by hand, so a clear original is important. The formula capability of the word processor, or some similar program (e.g. MathType), is recommended. Where the derivation has been abbreviated, it is a help to the reviewers if the full derivation is presented on a separate sheet (not to be published).

Footnotes should be kept to a minimum and be numbered consecutively throughout the text with superscript Arabic numerals. Acknowledgments and information on grants received can be given in a first footnote, which should not be included in the consecutive numbering, or it can be given at the end before the References.

References should be made by the in-text form of citation. For example: [Braff et al., 1993]. Only publicly available material may be referenced. The reference list should be organized alphabetically, formats are as follows:

Article:
Braff, R., Till, R., and Wullschleger, V. (1993), "GPS for Precision Approaches: Flight Test Results," Air *Traffic Control Quarterly*, 1 (2).

Paper at conference:
Pomeret, J.M. and Mahlich, S. (1997), "Piloting ATM through Performance," *Proceedings of the First USA/Europe Air Traffic Management R&D Seminar,* Saclay, France, June.

Report:
den Braven, W. (1992), *Design and Evaluation of an Advanced Air-Ground Data-Link System for Air Traffic Control,* NASA TM 103899, NASA Ames, Moffett Field, CA.

Book:
Nolan, M.S. (1990), *Fundamentals of Air Traffic Control,* Wadsworth, Inc., Belmont, CA.

The editor will transmit to the coresponding author the anonymous reviewers' comments, together with other information necessary for acceptance of the manuscript for publication. When the author submits the final paper (as e-mail attachment), it should be acompanied by an explanation of any key changes, together with points relative to the reviewers' comments. After acceptance, the editorial staff will conduct a final editorial review, make any necesary corrections, and submit the paper to the printer for typesetting. Proofs of the paper will be express mailed to the corresponding author with an expected two-day turn-around to make any minial necessary corrections.

The authors will receive, gratis, an issue of the ATC Quarterly in which the paper has appeared. Any arrangements for reprints, subscriptions, or other special requests can be made prior to publication through the Air Traffic Control Association Institute.

Only original works will be accepted. Authors are responsible for obtaining all clearances, releases, and authorizations, including written permission to reproduce mateial that has appeared in another publication or other media. No manuscript can be accepted unless accompanied by transfer of copyright or by irrevocable license granting the Air Traffic Control Institute, Inc. permission to publish the paper.

Formats for commonly-used units:

Unit	Symbol	Comment
foot	ft	(no period)
gravity accel.	g	(not G)
hour	h	(not hr)
knot	kn	(not kt)
meter	m	
minute	min	(no period)
nautical mile	nmi	(not NM)
second	s	(not sec)