THE WAKE VORTEX PREDICTION AND MONITORING SYSTEM WSVBS
PART II: PERFORMANCE AND ATC INTEGRATION AT FRANKFURT AIRPORT

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OVERVIEW

The performance and ATC integration of DLR's wake vortex advisory system "WSVBS" (*Wirbelschleppen-Vorhersage- und -Beobachtungssystem*) for the dependent parallel runway system 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. WSVBS is integrated in the arrival manager AMAN of DLR. Each 10 minutes it delivers minimum safe aircraft separation times for the next hour to air traffic control. These times are translated into operational modes for runways 25L/R aiming at improving the capacity. From 66 days of a performance test at Frankfurt it was found that the system ran stable, the predicted minimum separation times were safe and the capacity improving concepts of operation could be used in 75% of the time. From fast-time simulations the eventual capacity gain for Frankfurt was estimated to be 3% taking into account the real traffic mix and operational constraints in the period of one month.

1. INTRODUCTION

Aircraft trailing vortices may pose a potential risk to following aircraft. The empirically motivated separation standards between consecutive aircraft which were introduced in the 1970s still apply. These aircraft separations limit the capacity of congested airports in a rapidly growing aeronautical environment. Capacity limitations are especially drastic and excruciating 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 cross-winds 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 *Wirbelschleppen-Vorhersage- und -Beobachtungssystem* [6]. The WSVBS is intended to dynamically adjust aircraft separations dependent on weather conditions and the resulting wake vortex behaviour without compromising safety. The system is particularly designed for the closely spaced parallel way system of Frankfurt Airport (FIG 1) but can be adapted to any other airport. It predicts wake vortex transport and decay and the resulting safety areas along the glide slope from final approach fix to threshold. The design of the WSVBS is described in Part I. Here we particularise its performance at Frankfurt Airport and indicate possible gains in capacity if WSVBS should be installed at Frankfurt and used by air traffic control (ATC) authorities.

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

2. INSTALLATION AT FRANKFURT AIRPORT

The WSVBS with its components (*tools*)

- weather forecast (*NOWVIV*),
- wake predictor (*P2P*),
- safety area predictor (*SHAPe*),
- weather profiler (*SODAR*/*RASS*/*SONIC*), and
- wake detector (*LIDAR*) as a safety net

has been employed at Frankfurt Airport in the period of December 2006 until February 2007. The system used forecasted and measured meteorological parameters along the glide path to predict temporal separations of aircraft landing on the parallel runway system 25L/R and translated the required separation between two a/c into approach procedures. At the same time, the transport of the wake vortices was monitored by the wake detector component (LIDAR) in different control gates. FIG 2 sketches the instrumentation layout at Frankfurt.

2.1. Weather forecast by NOWVIV

NOWVIV [2,4,5] ran on a massively parallel LINUX cluster at University Stuttgart where it predicted the meteorological conditions for the Frankfurt terminal area. For details see Part I of that study. The output was sent via UMTS to a LINUX-PC in the Local Operation Centre (LOC) (situated in the observer house of DWD) to be used by the real-time wake predictor P2P (FIG 3).

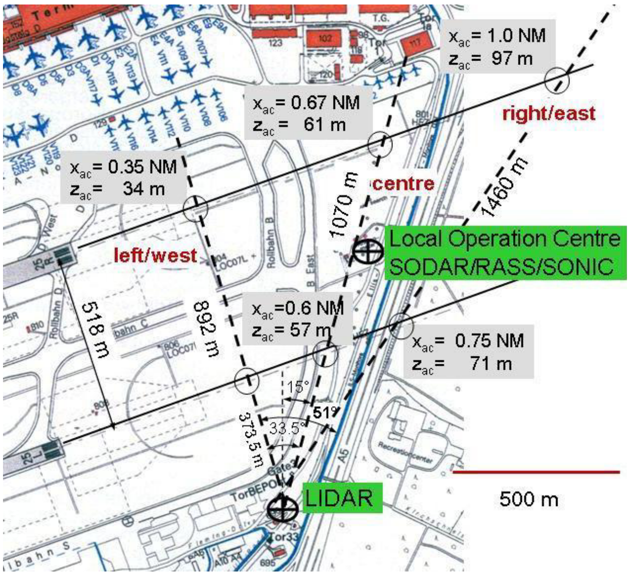

FIG 2. The instrumentation layout at Frankfurt Airport; x_{ac}, z_{ac} denote the distance to touch-down zone and the height of landing aircraft in the three vertical scan planes of the LIDAR; LOC and the meteorological profiler were situated between both extended runway centrelines.

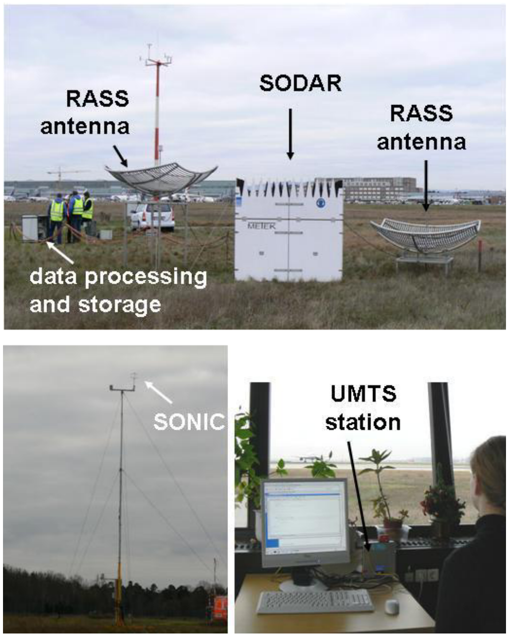

FIG 3. Instruments at Frankfurt Airport. Top & lower left: SODAR/RASS and SONIC by Fa. Metek; lower right: the LOC with LINUX-PC & UMTS station in the DWD observer house.

2.2. Weather monitoring by SODAR/RASS

The meteorological measurement equipment SODAR/RASS/SONIC serves to monitor the local weather at and above the airfield. The SODAR (sound detection and ranging) emits an (audible) acoustic pulse into the atmosphere and receives a back scattered signal caused by atmospheric turbulence. The received signal is shifted in frequency (Doppler Shift) from the emitted signal which allows determining the velocity of the air mass. The SODAR uses 5 beams with one beam pointing vertically and with the other beams tilted by about 5 to 10° and different by 90° in azimuth to obtain the three orthogonal components of the wind vector. The RASS (radio acoustic sounding system) technique relies on RADAR waves which are back scattered on artificially generated sound waves (e.g. by a SODAR); the propagation speed of sound is measured from which the virtual temperature can be inferred. The SODAR/RASS provided 10 min averages of wind and temperature profiles with a vertical resolution of 10 m and up to 300 m AGL. On a 10 m mast a SONIC (ultrasonic anemometer) measured wind with a frequency of 20 Hz. Turbulence kinetic energy and dissipation rate are computed from the velocity variance spectra [3]. Due to the position of the SODAR/RASS/ SONIC between the extended centrelines of both runways these data are considered representative for the area where aircraft and vortices are in ground proximity. All data are sent via ethernet to the LINUX-PC at the Local Operation Centre where they serve as input for the P2P calculations.

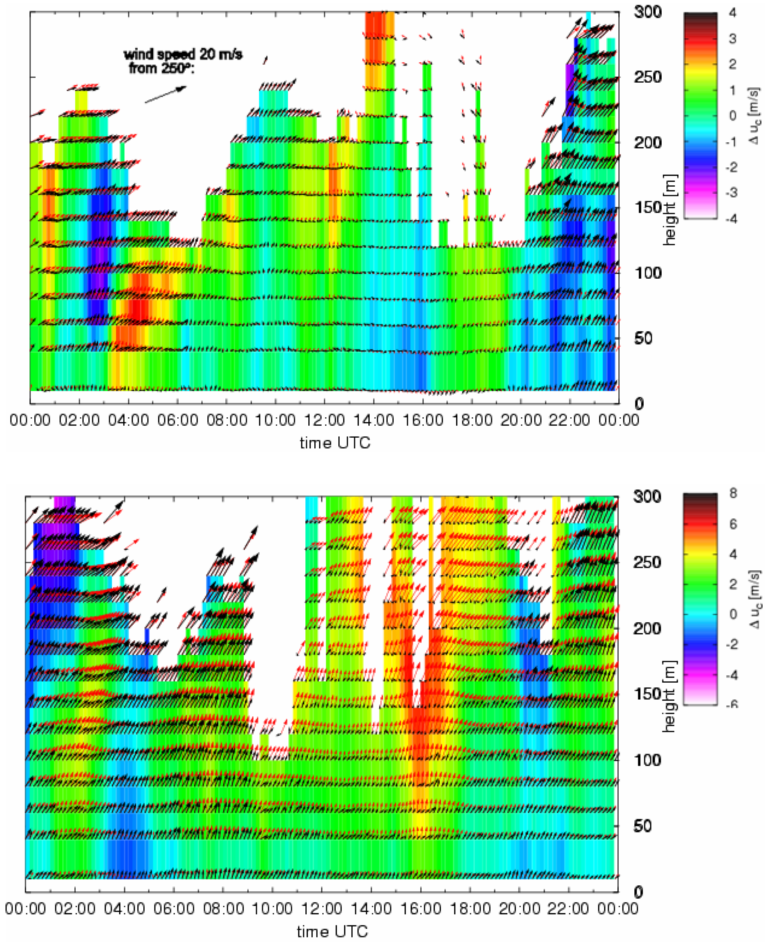

FIG 4. Diurnal variations of the wind velocity profile measured by SODAR/RASS (black) and predicted by NOWVIV (red) on 15.01.07 (top) and 16.01.07 (bottom). Deviations in cross-wind u_c between observation and prediction are colour coded.

FIG 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 forecast yielding to the blue and red u_c-deviation dipole. So, the phenomenon – the low level jet – was predicted but with a delay of about 2 hours. A similar phenomenon was observed on the next morning but now the jet developed later than predicted. The generally higher winds on the 16th of January also indicate that the weather was dominated by advection processes (large scale weather patterns) where initial and boundary conditions for NOWVIV have a larger impact than on the 15th where the weather was driven by local orographic and land-use features.

2.3. Wake prediction by P2P

The real-time probabilistic two-phase wake vortex decay and transport model P2P [9,10,11,12, part I] considers all effects of the leading order impact parameters. At Frankfurt, P2P predicted envelopes of the wake behaviour of aircraft from class HEAVY (H) in 13 gates along the glide path to runways 25L/R at the PC in the LOC). For the three lowest gates at 1/3, 2/3 and 1 NM from the threshold, P2P used the meteorological profiles measured by the profiler system; for larger heights (the more remote 10 gates at 2 to 11 NM), it availed itself of profiles predicted by NOWVIV. This combined use of measured and predicted parameters accounts for the fact that most of the wake encounters occur in the lowest 100 m before touchdown and, hence, require utmost accuracy in prediction.

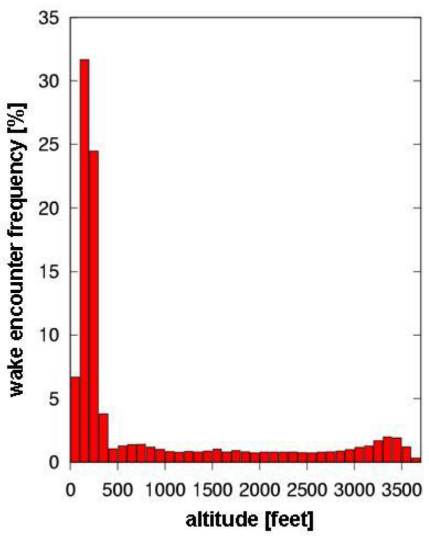

FIG 5. Frequency of wake encounters versus altitude of 100,000 aircraft approaching the runway threshold (WakeScene simulation).

This was one of the findings in the European *S-Wake* project [1] and is corroborated in FIG 5 where the result of 100,000 simulated aircraft approaches to an airport are depicted, applying the Aircraft Wake Vortex Scenarios Simulation Package *WakeScene* [13]. The reason for that drastic increase of encounters close to the ground is attributed to the fact that vortices often stay there in the flight corridor as (i) they cannot descent further, (ii) their lateral drift is often hindered by light cross-wind, and (iii) they may rebound as a consequence of their interaction with ground or detached wind shear.

2.4. Safety area prediction by SHAPe

Once the possible positions of the wake vortices at each gate (the so-called vortex habitation corridors) are known, an envelope around each vortex position needs to be assigned which discriminates a potentially hazardous area around a vortex from definitely non-hazardous regions. This is done by the Simplified Hazard Area Prediction (SHAPe) model [8,14,15, part I]. For the Frankfurt campaign, SHAPe computed safety corridors for aircraft pairings heavy after heavy aircraft (HH) and medium after heavy aircraft (HM) which were added to the vortex habitation corridor, resulting in the “envelope of the safety area to be avoided”. The time between the instant when the a/c has crossed a gate and the instant when this safety area does no longer overlap with the flight corridor determines the minimum temporal separations of the two a/c pairings HH or HM for that gate. The maximum of these times found in all gates determines the “minimum separation time” MST for that glide path. Similar arguments hold for the use of the adjacent runway, see Section 3.2.

2.5. Wake monitoring by LIDAR

DLR’s 2 µm pulsed Doppler LIDAR was used as the safety net within the WSVBS concept 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, see FIG 2. The LOS velocity in a scanned plane is immediately visible in the so-called “quick-look”. These quick-looks were transmitted via UMTS to the LOC computer and were also accessible via internet. FIG 6 shows a quick-look result from 16. January 2007 at 04:17 UTC in the “centre” vertical scan plane.

At that time most heavy aircraft landed on runway 25R (the northern runway). The colour-coded area shows the line-of-sight (LOS) wind component. Patterns of wind shear and of a wake vortex pair can be distinguished. The quick-look also indicates roughly the position of the two flight corridors for landing aircraft in the scan plane. Thus, it is possible to check if the predicted minimum separation times are correct: the vortices visible in the LIDAR quick-look should not reside within the flight corridors when the forecast system allows the next a/c to enter the control gate. The quick-look, however, only allows for a rough estimate of the vortex location. After signal and image (post-) processing, the spatial resolution of the LOS velocity is 3 m and the wake vortex position (and strength) can be deduced with high accuracy, see Section 4.

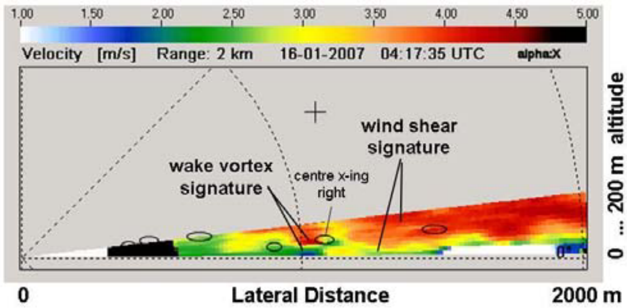

FIG 6. LOS velocity as measured by LIDAR (quick-look after one scan) with signatures of wind shear and a wake vortex pair. The crossings of the laser beam with the glide paths are indicated by small ellipses; "centre x-ing right" identifies the approximate intersection of the beam in scan plane "centre" with runway 25R at 1070 m distance.

3. INTEGRATION INTO ATC PROCEDURES

3.1. 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), FIG 7:

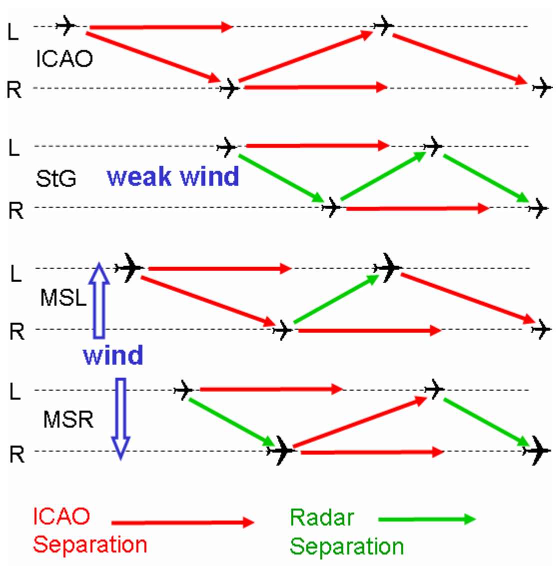

FIG 7. The concepts of operation under IMC for the dependent parallel runway system at Frankfurt Airport.

- "ICAO" – standard procedure under IMC with 4 NM for a HH aircraft pair and 5 NM for a HM pair across both runways;
- "Staggered" (STG) – procedure where both runways can be used independently from each other but obeying the radar (minimum) separation of 2.5 NM;
- "Modified Staggered Left" (MSL) – aircraft on right (windward) runway keep 2.5 NM separated from aircraft of left (lee) runway;
- "Modified Staggered Right" (MSR) – aircraft on left (windward) runway keep 2.5 NM separated from aircraft of right (lee) runway.

Note that in all modes, the aircraft in-trail (approaching the same runway) remain separated according to ICAO standards. The modes STG, MSL, MSR can only be applied on favorable weather conditions (esp. favorable crosswind) and require the use of a wake vortex advisory system as DLR's WSVBS or DFS' wake vortex warning system, WSWS [7]. These modes are not used operationally today.

TAB 1 translates the separation <u>distances</u> for HH, HM and radar separation into separation <u>times</u> which must be followed in each concept of operation and for each runway combination. For 5 and 4 NM separation we applied an approach speed of 74 m/s (144 knots) to all aircraft. For the minimum (radar) separation we took conservative 70 s (instead of 62.5 s).

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

TAB 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).

3.2. The prediction cycle

The installation of WSVBS at Frankfurt Airport was accomplished on 19th of December 2006. It then delivered data on 66 days until 28/02/07. The chain started with the forecast of the local weather twice a day at 0 and 12 UTC. The SODAR/RASS/SONIC ran continuously 24 hours a day and delivered measured weather profiles each 10 min. Based on measured and predicted weather input the vortex habitation corridors and the safety areas were computed for both runways at all 13 gates for 3 runway combinations (LL and RR are the same in this respect), 2 weight class combinations (HH, HM) and 8 aircraft parameter combinations (different sizes for heavy and medium aircraft), resulting in 1248 independent computations each 10 min and with a forecast horizon of 60 min (controllers required at least 45 min). The maximum separation time found in all gates per runway and weight class combination determines the minimum separation time MST. TAB 2 gives an example of an output table as delivered to ATC.

Note that the ICAO separations for HH and HM, namely 100 and 125 s (TAB 2), are considered to be safe, thus, the predictions by WSVBS end at these values. On the other hand, when there is no vortex-related dependency of the parallel runways, the WSVBS predicts MST = 0 s which is set to radar separation (70 s) in the operational procedure.

```
11400   wsvbs_wvu   52
    0 25L25L 100 125
    0 25L25R 100 125
    0 25R25L   0   0
    0 25R25R 100 125
  600 25L25L 100 125
  600 25L25R 100 125
  600 25R25L   0   0
  600 25R25R 100 125
...
```

TAB 2. The minimum separation time output table lists each 10 minutes (column 1) the MST for the weight class combinations HH (col 3) and HM (col 4) and the four runway combinations (col 2).

Based on the MST, landing procedures were eventually recommended and displayed on the PC in the Local Operation Centre as shown in FIG 8 and also accessible remotely via Internet. The figure is updated each ten minutes and adjusted to the progressing time each minute. FIG 8 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 system anticipates a weather change which requires a return to the standard separations (ICAO).

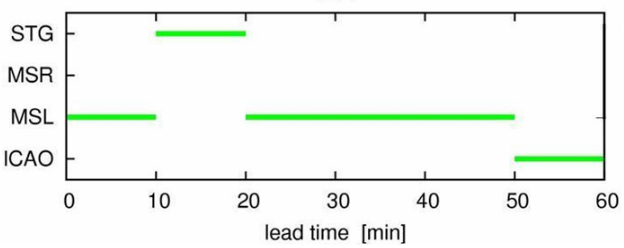

FIG 8. Indicated use of DFS approach procedures within the next hour .

FIG 9 displays the full MST information as it is available in the WSVBS. In addition to the four procedures which were defined by DFS, such a display allows also to survey possible reduced separations for aircraft flying in-trail. The sketched example reads that not only the DFS procedure MSL can be used (no wake-vortex separation required for runway combination 25L25R but full ICAO separation for 25R25L), but that also aircraft which follow each other on the same runway (in-trail) can be radar-separated. The meteorological reason for that case is a strong northerly crosswind that clears both runways quickly from vortices of the leading aircraft.

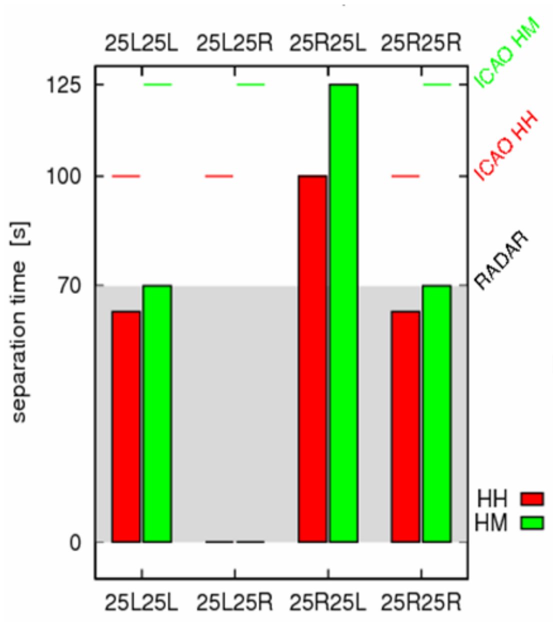

FIG 9. Display of full MST information and derived arrival procedures for Frankfurt Airport on 2007-Jan-25 at 15:10 UTC.

3.3. The Human-machine interfaces

The proposed operational procedures for up to one hour were also displayed on controller screens for the real-time simulations, see next section. The layout has been developed with and accepted by controllers. FIG 10 shows two green bars along the dynamic time scale indicating mode MSL for the period 07:06 until 07:29 and mode STG afterwards. Upon request from controllers also the wind direction and speed at heights FL 70 and 4000 feet and on ground were displayed. The green bars along the final approach paths on the radar display in FIG 11 show another situation where mode STG can be used with a change towards mode MSL.

FIG 10. Controller's planning screen with dynamic time scale and wind information.

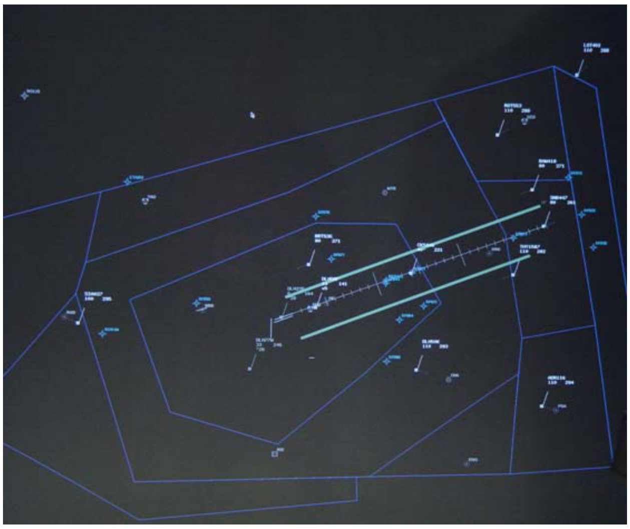

FIG 11. Controller's radar screen.

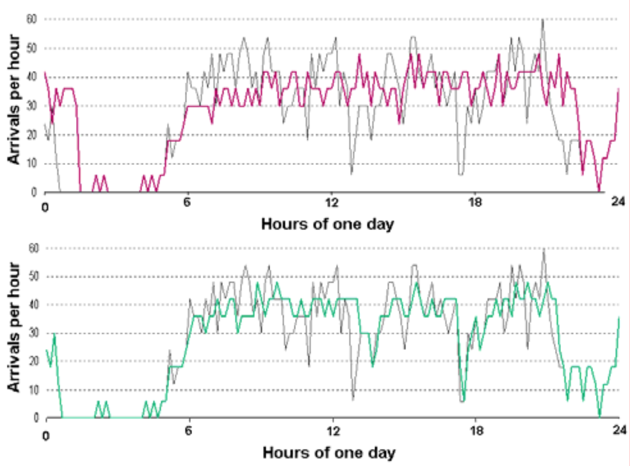

FIG 12. Traffic flow (arrivals per hour) during a day at Frankfurt Airport. Top: demand (grey) vs. ICAO standards (red); bottom: demand vs. WSVBS utilisation (green).

4. PERFORMANCE AND IMPROVED CAPACITY

To check if the WSVBS products and the proposed features on the displays fulfil ATC requirements, are well designed and easy to use, and will eventually improve capacity at Frankfurt Airport, we performed real-time and fast-time simulations using the Air Traffic Management and Operations Simulator (ATMOS II) and the SIMMOD tool of DLR Institute of Flight Guidance at DLR Braunschweig, respectively.

During a period of one week real-time simulations were carried out at the simulator ATMOS II under the assistance of five air traffic controllers from DFS. The investigations aimed at evaluating the behaviour and efficiency of the WSVBS on a real time controller working position and to inquire the controller's judgement of the system.

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

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

The participating controllers generally agreed with the WSVBS system and procedures. In particular, the system does not interfere with their normal working procedures.

We also performed fast-time simulations to obtain capacity figures for the different concepts of operation utilised by WSVBS under real world conditions. To establish a baseline, the simulations were initially performed using ICAO separations. The simulations were then matched with separations derived from WSVBS and re-run (FIG 12). The simulations included flight plans with realistic distributions of wake vortex categories, demand peaks throughout the day, weather data, and the WSVBS proposals for a period of one month.

FIG 12 shows traffic demand and traffic flow for a "heavily loaded" day at Frankfurt with 721 arrivals. Using the WSVBS predictions, MSR separations could be used for 76.4% of the day, with intermittent use of ICAO separations in the morning hours. The peak demand exceeds capacity in both scenarios. However, the WSVBS flow closely follows the demand flow whereas the ICAO flow is unable to cope with the demand and accumulates delayed flights which can only be served in the late evening hours.

Improved capacity at an airport offers a variety of options for future aircraft operations (FIG 13) 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).

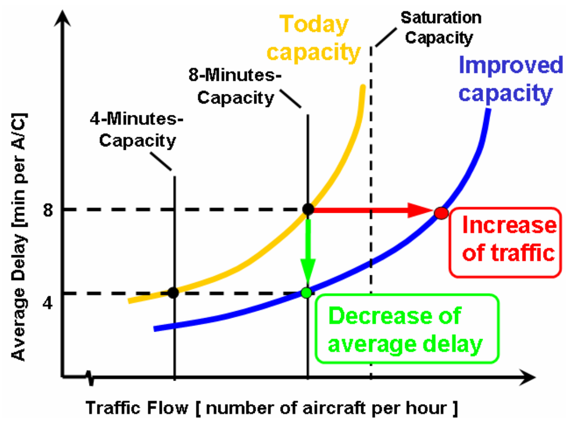

FIG 13. Average delay versus traffic flow, principle.

FIG 14 shows the theoretical capacity gain for the different concepts of operation. A SIMMOD model of the parallel runways at Frankfurt Airport was fed with a constant flow of arrivals assuming a traffic mix of 27, 67 and 6% of heavy, medium and light aircraft, respectively. For each number of arrivals per hour the computed flight plans were randomised over ten iterations. The figure reveals that 2 (5) more aircraft can land per hour when changing from ICAO mode to MSL/R (STG) mode, respectively, and accepting an average delay of 4 minutes. Or, vice versa, the average 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. FIG 14 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.

When taking into account the real traffic mix and operational constraints in that period of one month we received a net capacity gain of slightly larger 3%.

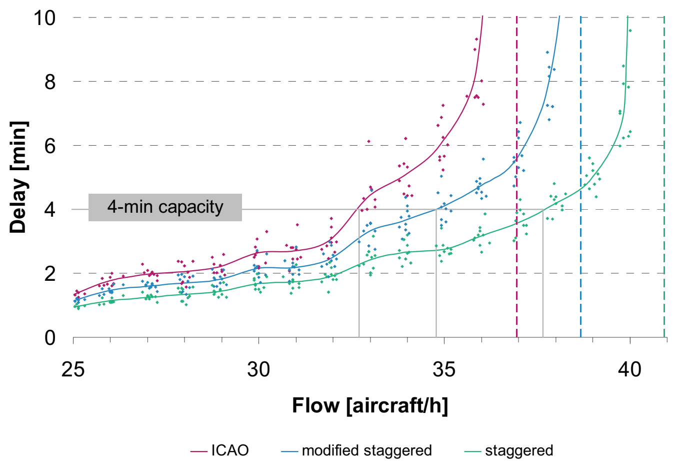

FIG 14. Average delay versus traffic flow (for a mix of H/M/L aircraft of 27/67/6%) for the concepts of operation ICAO (red), MSL/R (blue), and STG (green) from fast-time simulations; the "4-min delay" capacity is indicated by grey vertical lines.

FIG 15 summarises the history of DFS operation modes as proposed by WSVBS during the 66 days of performance at the airport (not considering any traffic mix). It is evident that in the majority of time those modes could have been deployed which allow improving capacity for or punctuality of landing aircraft. The focus on five days indicates that each mode can be deployed throughout a significant fraction of time (minimum 10 minutes).

TAB 3 lists the use of all operation modes as predicted by WSVBS during the 66 days but applying the radar separation of 2.5 NM (70 s) as the minimum to be obeyed. Thus, the table also includes reduced in-trail separation and differentiates between HH and HM aircraft pairs (cf. FIG 9). Hence, 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 a MST of 60 s (but *de facto* separated by 70 s). Another example: in 47.9% of the time a medium aircraft could have landed 2.5 NM behind the preceding heavy aircraft landing on R. The cases where DFS-mode STG could have been used for HH (HM) pairings summed up to 10% (3.6%). All together, the ICAO separation mode was required in only 25% of the time.

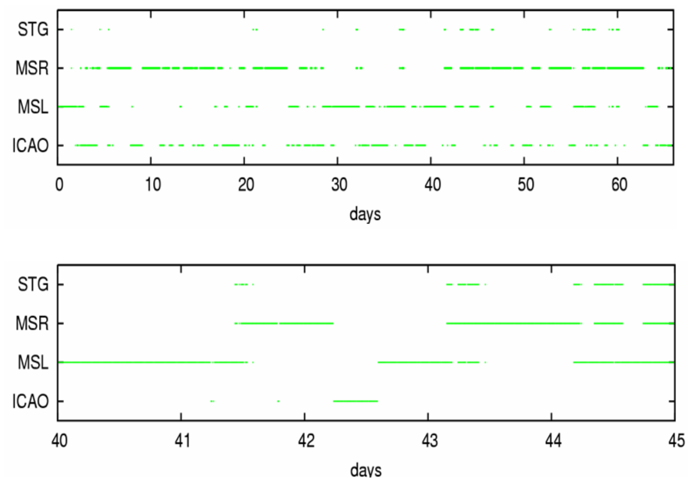

FIG 15. History of usage of the 4 DFS operation modes during the 66 days of the campaign at Frankfurt. Top: full period; bottom: zoom on five days.

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	0	30.7
RL HH	0	54.3
RL HM	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

TAB 3. Average minimum separation time and frequency for HH and HM aircraft pairs landing in-trail (LL, RR) or across (LR, RL) obeying the radar separation as minimum.

TAB 4 displays the same information as TAB 3 but now assuming that all separation times between 0 and 100 s (125 s) for HH (HM) pairs can 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 the values in TAB 3 as these depend predominantly on the question if a vortex reaches the parallel runway or not.

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	1.2	31.0
RL HH	0.5	54.6
RL HM	1.6	48.6
RR HH	75.7	6.6
RR HM	93.5	9.0

TAB 4. As for TAB 3 but all separation times between 0 and 100/125 s are used.

FIG 16 finally shows two examples of traces of the port and starboard vortices of heavy aircraft landing on runway 25R as measured by the safety net LIDAR in the three scan planes shown in FIG 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 hindered the vortices to reach runway 25L (hence, MSR) and the wind became obviously so strong later[1] that also a reduced separation in-trail could have been operated. For the 8th of February, WSVBS recommended to use operations STG followed by MSR. Again, the LIDAR data, now from 32 landing heavy aircraft, confirm the predictions; the wind is very weak and does not transport the vortices to the adjacent runway.

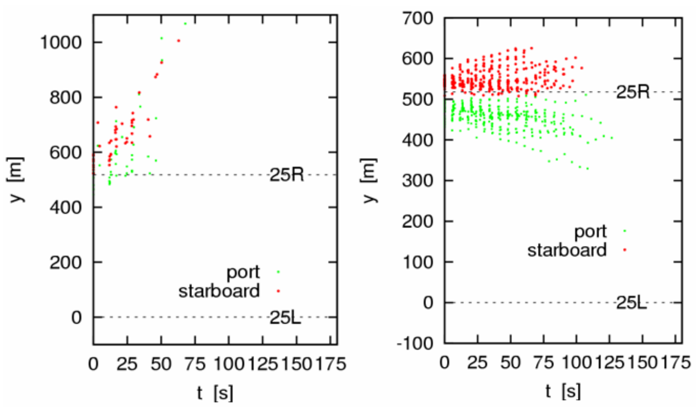

FIG 16. Lateral positions of wake vortices vs. vortex age from 8, 32 heavy aircraft landing on 25 R on 18th Jan. (left) and 8th Feb. (right) 2007, respectively, as traced by the LIDAR in the three scan planes.

The (manned) LIDAR did not measure continuously throughout the campaign. It was operated on 16 days where it traced the wake vortices of about 1100 landing heavy aircraft in the three most critical control gates, see FIG 2. In all these cases it was found that the recommended operation mode was safe – no vortices were detected in the flight corridor after the predicted minimum separation time.

5. CONCLUSIONS

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

The WSVBS has demonstrated its functionality at Frankfurt airport during 66 days in the period from 18/12/06 until 28/02/07. It covers the glide paths of runways 25L and R from the final approach fix to the threshold (11 NM). It combines measured & forecasted meteorological data for wake prediction. P2P and SHAPe components are based on 2-σ confidence levels. From the 66 days of performance test at Frankfurt we found that

- the system ran stable - no forecast breakdowns occurred,
- aircraft separations could have been reduced in 75 % of the time compared to ICAO standards,
- the predictions seem to be safe: at least for about 1100 landings observed during 16 days no warnings occurred from the LIDAR.

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

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

As next steps DLR will expand WSVBS to include also landings on runways 07/L/R and departing traffic in both directions. The LIDAR shall be operated automatically and the traced vortex positions shall be used on-line to check for forecast errors and warn the operators in case of an increased risk. A risk analysis will be pursued and negotiations with the German air safety provider DFS will hopefully lead to the instalment of the system at Frankfurt Airport, first to be run in a shadow mode and eventually to become fully operative.

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[1] The LIDAR stopped operation early that day because of storm *Kyrill* which passed Germany on the 18th of January.

their very reliable and robust meteorological profiler system to us.

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