THE WAKE VORTEX PREDICTION & 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. It 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 and the predicted minimum separation times were safe. The capacity improving concepts of operation could have been used in 75% of the time and continuously applied for at least several tens of minutes. 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 Wake Vortex Prediction and Monitoring System [5]. 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 runway 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 [13]. Here we particularise its performance at Frankfurt Airport and indicate possible gains in capacity if the 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 vortex 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 aircraft 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. All components of the WSVBS are described in detail in [13]. Here we summarise some specific features of the set-up at Frankfurt Airport.

Fig. 2 sketches the instrumentation layout at Frankfurt Airport. It depicts runways 25L and 25 R with the locations of the employed sensors and the local operation centre (LOC) which is situated in the observer house of the German weather service (DWD). Close to the LOC midway between the glide paths a METEK SODAR with a RASS extension provides 10-minute averages of vertical profiles of the three wind components, vertical fluctuation velocity, and virtual temperature with a vertical resolution of 20 m and 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 vertical fluctuation velocity and the vertical wind gradient employing a simplified budget equation [2]. A spectral analysis of the longitudinal velocity measured by the sonic is used to estimate EDR by fitting the -5/3 slope in the inertial subrange of the velocity frequency spectrum. 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. In the LOC a Linux-PC is installed which is connected via ethernet to the SODAR/RASS/USA system and via UMTS to the computers at DLR and to the LIDAR container. This PC serves as a front-end for the weather and wake forecasts and observations.

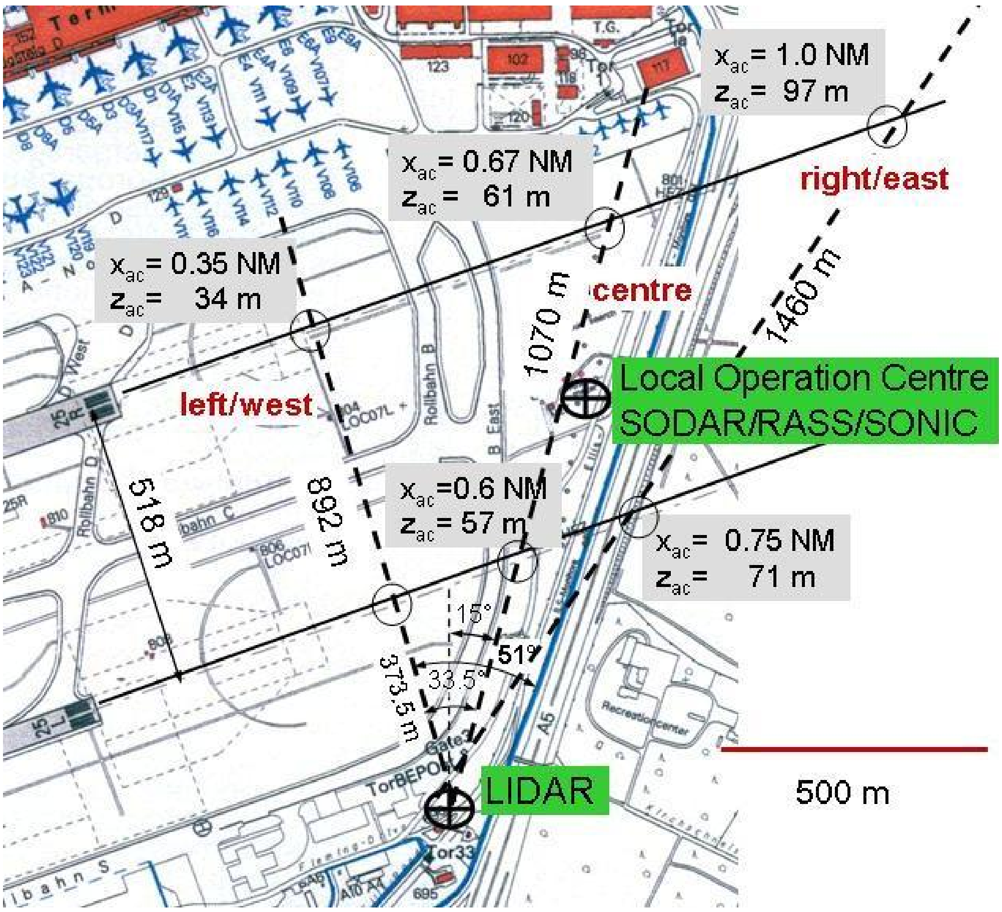

Fig. 2. The instrumentation layout at Frankfurt Airport; x_{ac}, z_{ac} denote the distance to touch-down zone and the height of landing aircraft in the three vertical scan planes of the LIDAR (dashed lines); LOC and the meteorological profiler were situated between both extended runway centrelines.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

The weather forecast model NOWVIV [3, 4, 5] ran twice a day on a massively parallel LINUX cluster at University Stuttgart where it predicted the meteorological conditions for the Frankfurt Airport Terminal Area. The forecast 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).

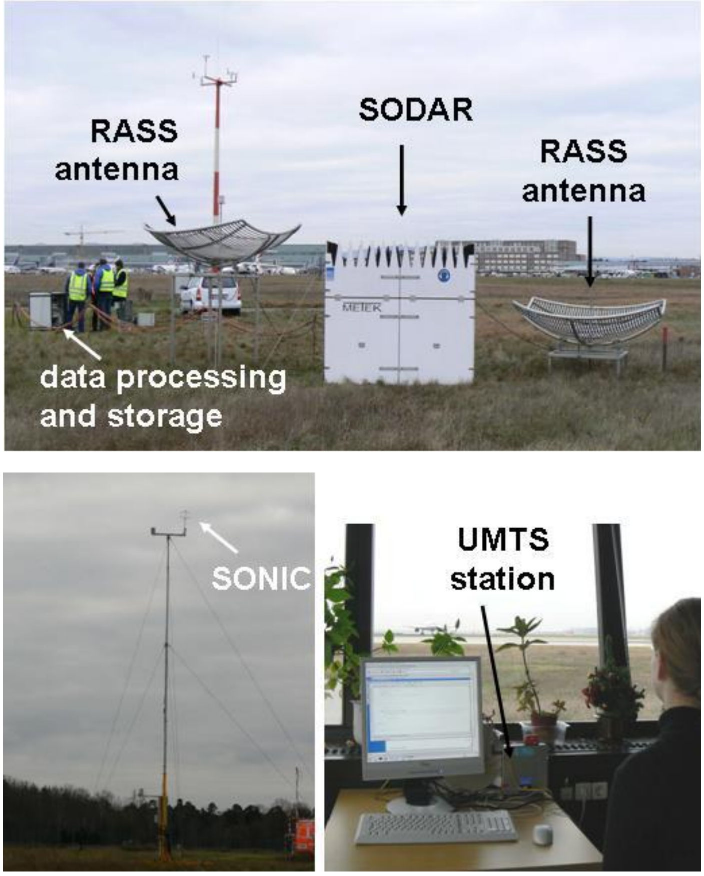

Fig. 3. Meteorological instruments at Frankfurt Airport. Top & lower left: SODAR/RASS and SONIC by Fa. Metek; lower right: the LOC with LINUX-PC & UMTS station in the DWD observer house.

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.

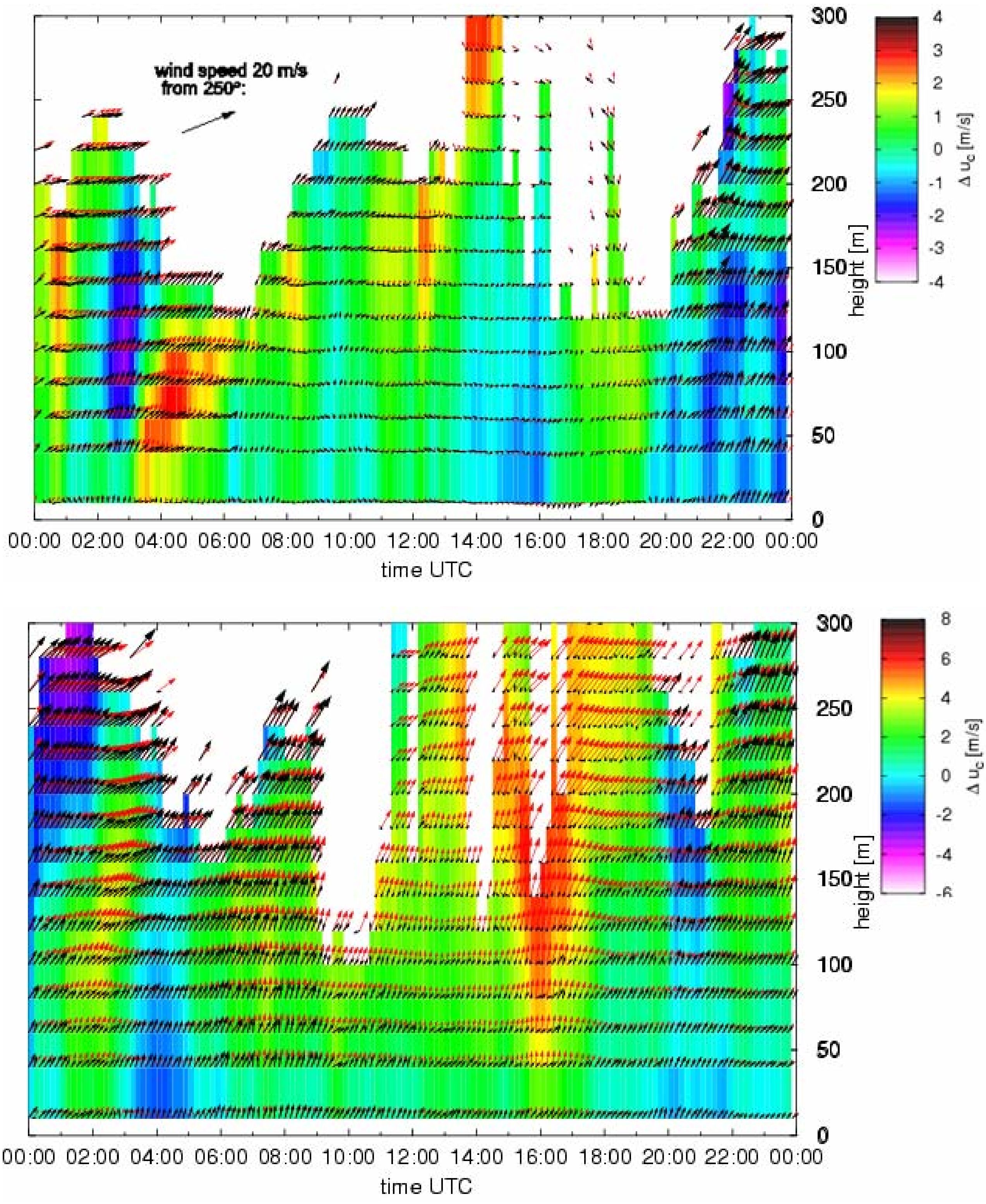

Fig. 4. Diurnal variations of the wind velocity profile measured by SODAR/RASS (black) and predicted by NOWVIV (red) on 15.01.07 (top) and 16.01.07 (bottom). Deviations in cross-wind u_c between observation and prediction are colour coded.

The real-time probabilistic two-phase wake vortex decay and transport model P2P [3, 8, 9, 10, 11, 13] was fed by the measured and forecast meteorological profiles and computed envelopes of the behaviour and location of wake vortices of aircraft from class HEAVY (H) in 13 gates along the glide path to runways 25L/R at the PC in the LOC. The Simplified Hazard Area Prediction (SHAPe) model [7, 13, 14, 15] then computed safety zones around the area contaminated by the vortices.

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 (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. 5 shows a quick-look result from 16. January 2007 at 04:17 UTC in the "centre" vertical scan plane.

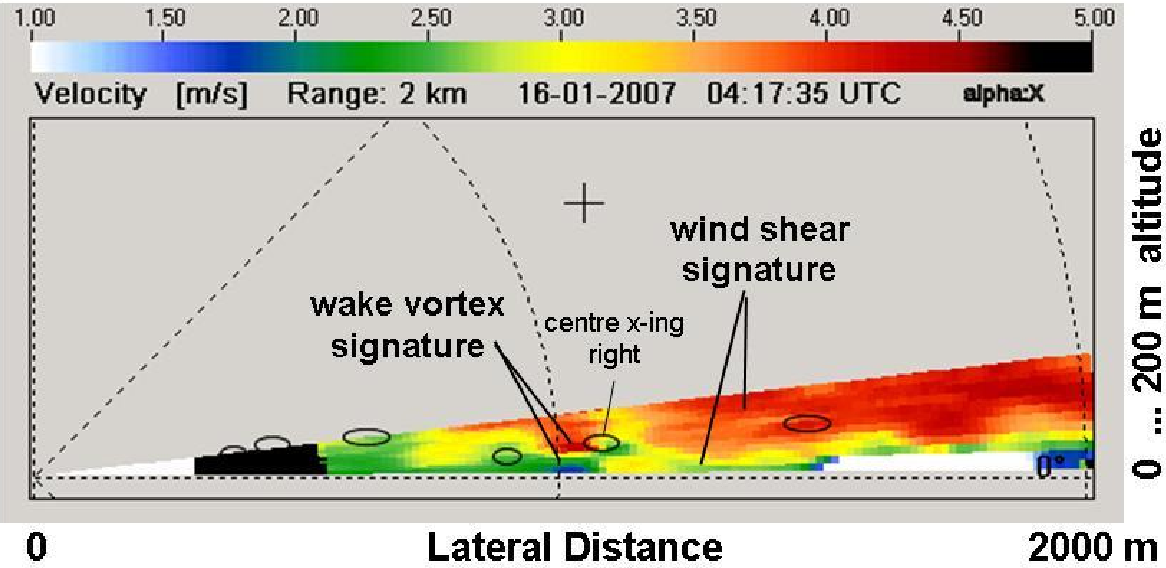

Fig. 5. LOS velocity as measured by LIDAR (quick-look after one scan, positive values indicate velocities away from the instrument) with signatures of wind shear and a wake vortex pair. The crossings of the laser beam with the glide paths are indicated by small ellipses; "centre x-ing right" identifies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

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

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), see Fig. 6 & [6]:

- "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 cross-wind) and require the use of a wake vortex advisory system as DLR’s WSVBS or DFS’ wake vortex warning system, WSWS [6]. These modes are not used operationally today.

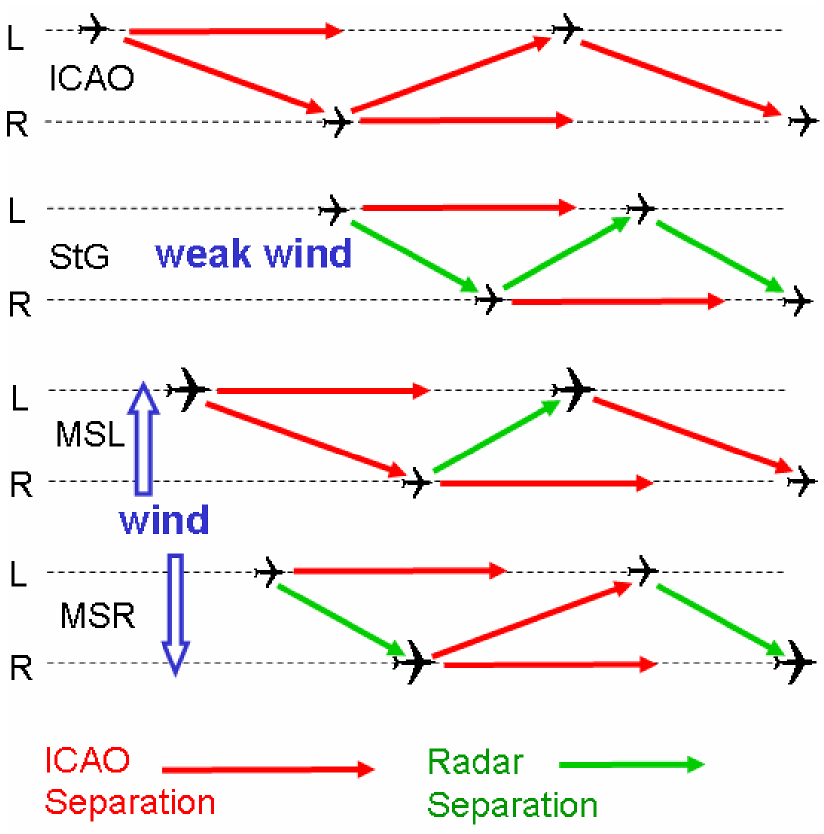

Fig. 6. The concepts of operation under IMC for the dependent parallel runway system at Frankfurt Airport.

Tab. 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 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
LL	100 s	125 s
LR	100 s	125 s
RL	100 s	125 s
RR	100 s	125 s

STG	H-H	H-M
LL	100 s	125 s
LR	70 s	70 s
RL	70 s	70 s
RR	100 s	125 s

MSR	H-H	H-M
LL	100 s	125 s
LR	100 s	125 s
RL	70 s	70 s
RR	100 s	125 s

MSL	H-H	H-M
LL	100 s	125 s
LR	70 s	70 s
RL	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 the 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. With these weather data the areas of possible vortex locations and the surrounding safety areas were computed by P2P and SHAPe. This forecast was made each 10 min for both runways at all 13 gates with a forecast horizon of 60 min (controllers require at least 45 min). The *minimum separation time MST* between two aircraft landing on the same or the adjacent parallel runway is determined by the maximum time, 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 Fig. 7 and Fig. 8 and also accessible remotely via Internet. Fig. 7 is updated each ten minutes and adjusted to the progressing 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 system anticipates a change which requires a return to the standard separations (ICAO).

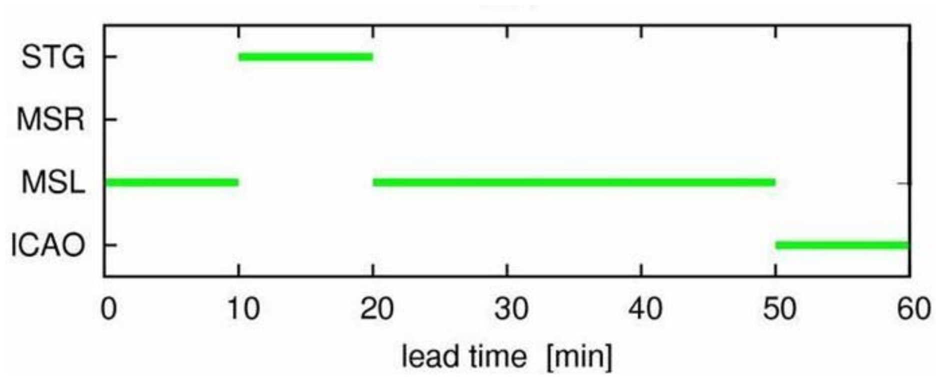

Fig. 7. Indicated use of DFS approach procedures within the next hour.

Fig. 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 allows also to survey possible reduced separations for aircraft flying in-trail and it further distinguishes HH and HM aircraft pairs. The sketched example reads that not only the DFS procedure MSL can be used (no wake-vortex separation required for runway combination 25L25R but full ICAO separation for 25R25L), but that also aircraft which follow each other on the same runway (in-trail) can be radar-separated. The meteorological reason for that case is a strong northerly crosswind that clears both runways quickly from vortices of the leading aircraft.

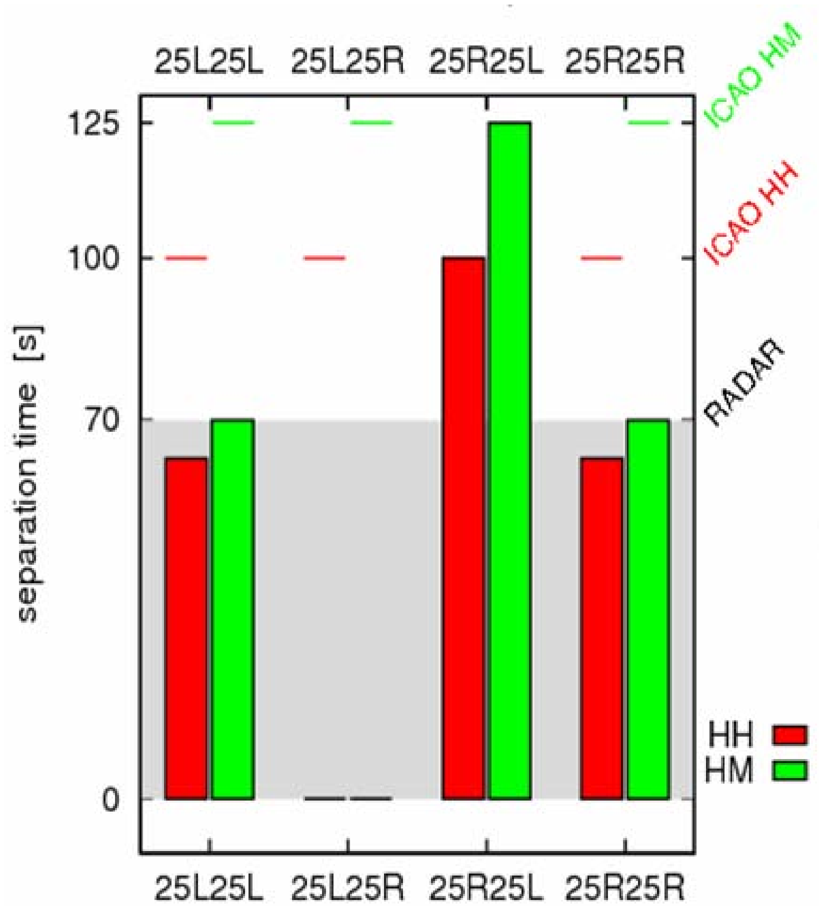

Fig. 8. Display of full MST information and derived arrival procedures for Frankfurt Airport on 2007-Jan-25 at 15:10 UTC.

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. The layout has been developed with and accepted by controllers. Fig. 9 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. 10 show another situation where mode STG can be used with a change towards mode MSL.

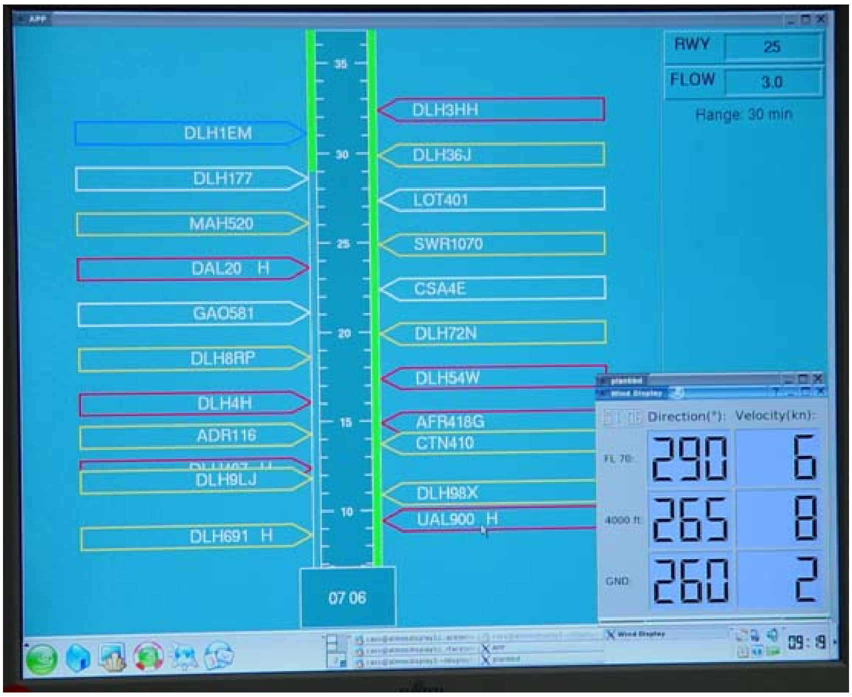

Fig. 9. Controller’s planning screen with dynamic time scale and wind information.

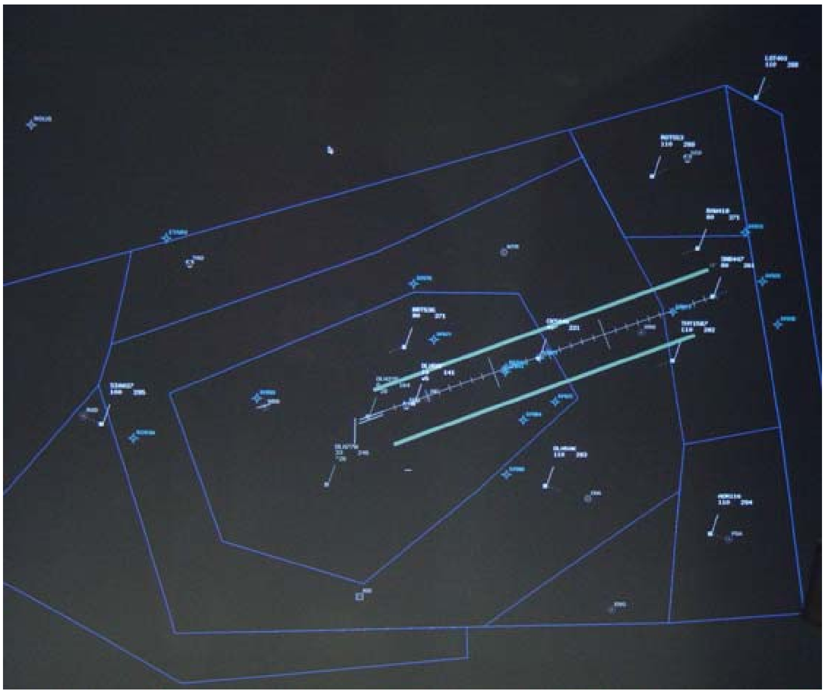

Fig. 10. Controller’s radar screen.

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. 11). 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. 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 served in the late evening hours.

Improved capacity at an airport offers a variety of options for future aircraft operations (Fig. 12) 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 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. 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. 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%.

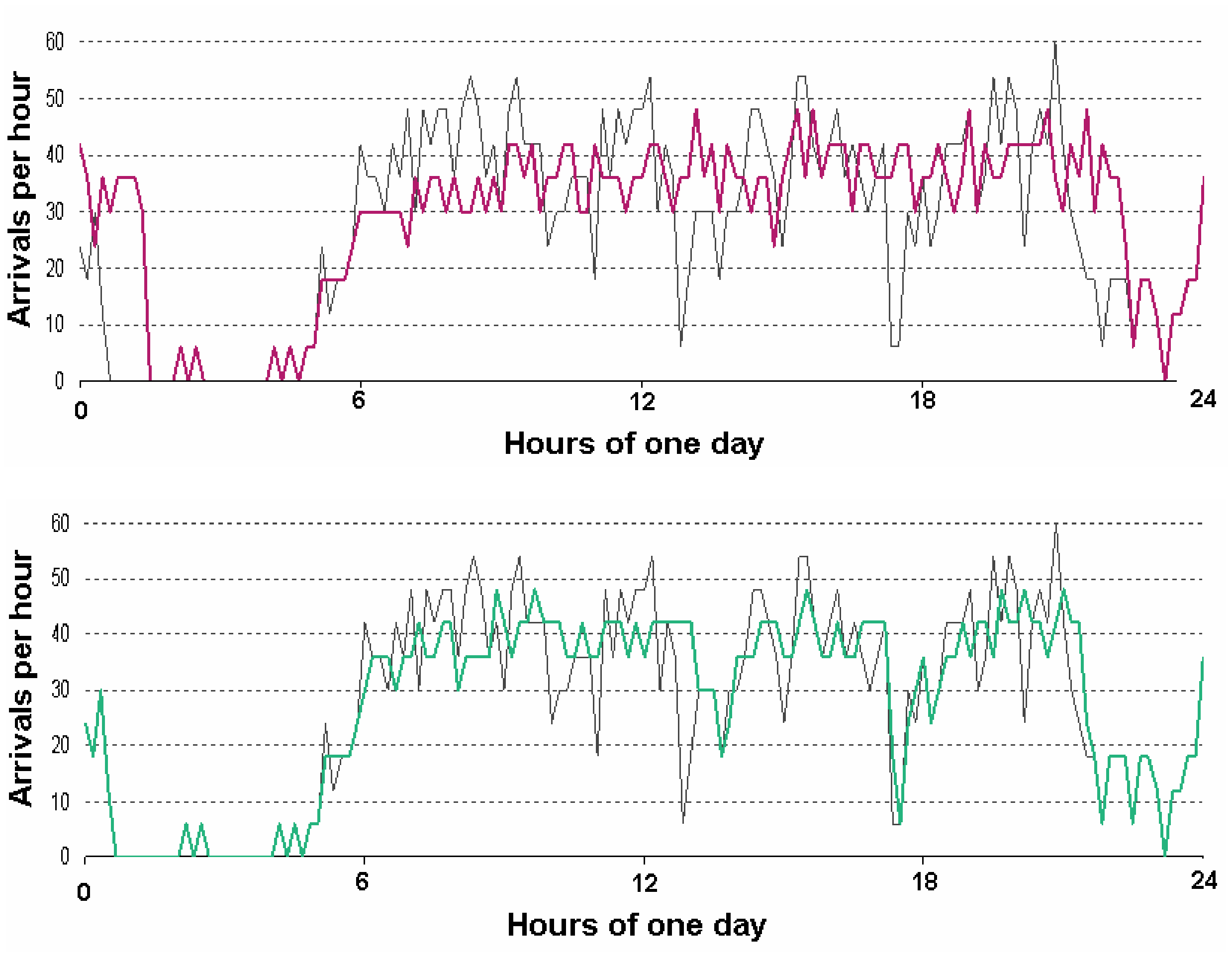

Fig. 11. Traffic flow (arrivals per hour) during a day at Frankfurt Airport. Top: demand (grey) vs. ICAO standards (red); bottom: demand vs. WSVBS utilisation (green).

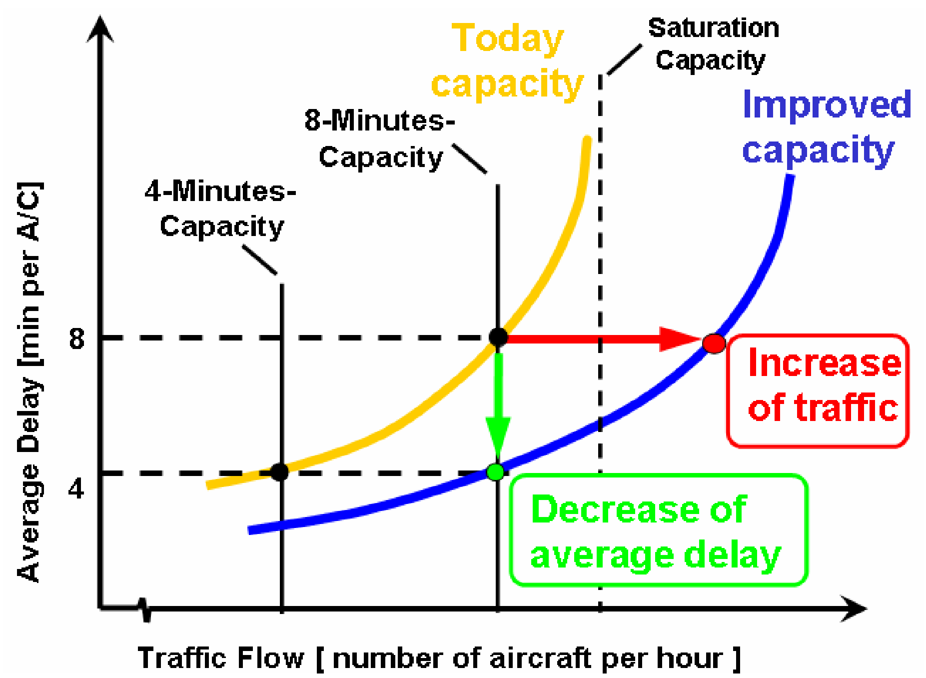

Fig. 12. Principle relation between average delay versus traffic flow (demand).

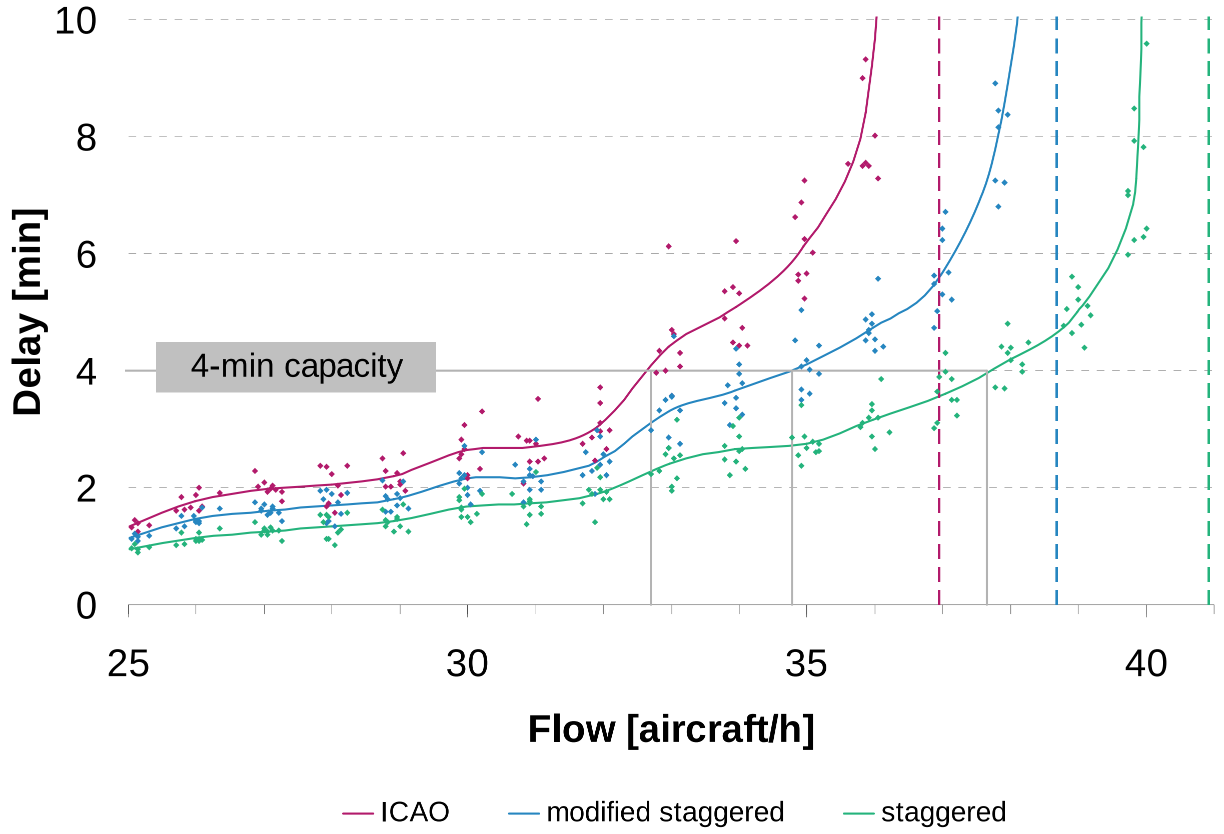

Fig. 13. Average delay versus traffic flow (for a mix of H/M/L aircraft of 27/67/6%) for the concepts of operation ICAO (red), MSL/R (blue), and STG (green) from fast-time simulations; the "4-min delay" capacity is indicated by grey vertical lines.

Fig. 14 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 or punctuality of landing aircraft. The focus on five days indicates that each mode can be deployed throughout a significant fraction of time (see also Fig. 15).

Tab. 2 lists the use of all operation modes as predicted by WSVBS during the 66 days for the fraction of time in which radar separation of 2.5 NM (70 s) was suggested. Thus, the table also includes reduced in-trail separation and differentiates between HH and HM aircraft pairs (cf. Fig. 8). 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 an average 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%). For the DFS operation modes, the ICAO separation mode was required in only 25% of the time.

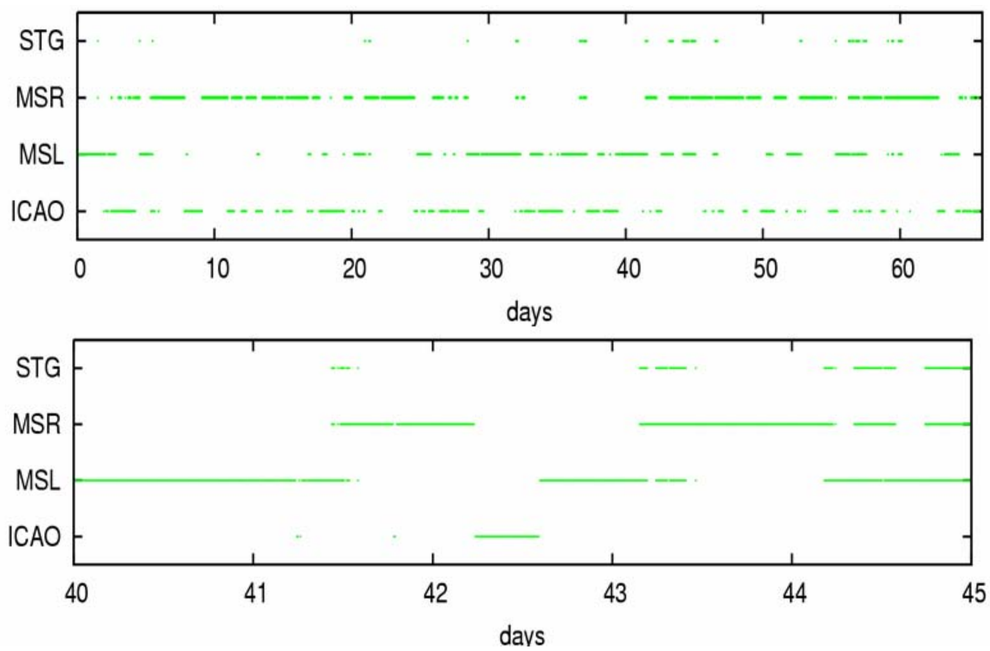

Fig. 14. History of usage of the 4 DFS operation modes during the 66 days of the campaign at Frankfurt. Top: full period; bottom: zoom on five days.

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. 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	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. 3. As for TAB 3 but all separation times between 70 and 100/125 s are used.

Tab. 3 displays the same information as Tab. 2 but now assuming 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 the values in Tab. 2 as these depend predominantly on the question if a vortex reaches the parallel runway or not.

The question how long the DFS ConOps MSL, MSR, STG or no one of them (ICAO) could continuously be used and how often this happened during the campaign is answered in Fig. 15 for pairs of Heavy/Medium aircraft. In the 66 days the procedures MSL/MSR/STG could have been used 36/7/14 times for 10 minutes only. However, a continuous use of these ConOps for 1 hour would have been possible 16/13/10 times, respectively. Even a usage as long as 8 hours would have been feasible still 2/2/1 times. Somewhat higher numbers hold for the aircraft pairing HH and somewhat reduced numbers for single runway approaches (not shown). Due to the strong wind conditions in January it would even have been possible to use MSR for HH pairings once throughout almost 4 days (93 hours).

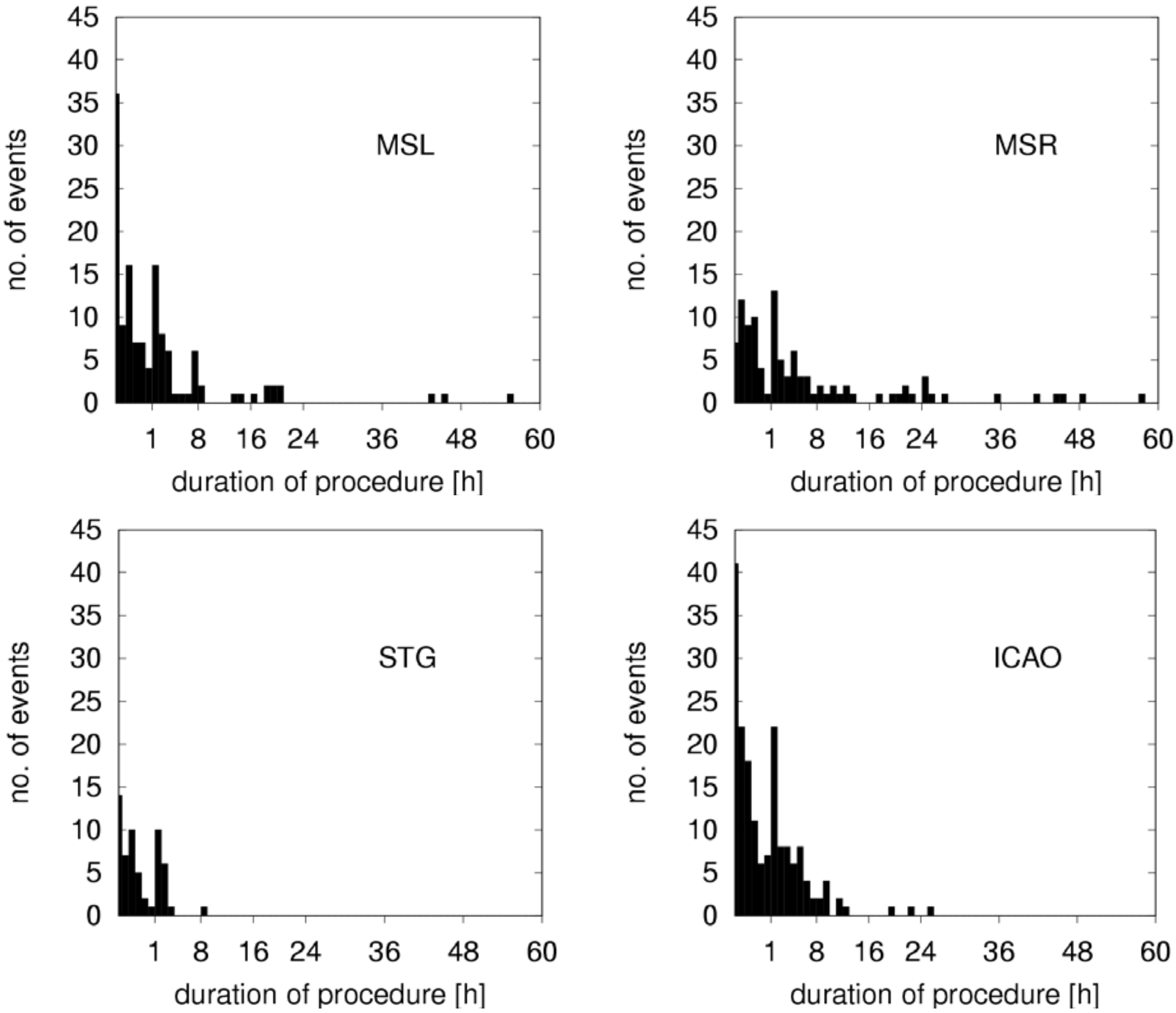

Fig. 15. Number of events versus duration of DFS procedures in hours for HM aircraft pairs; a 10 min interval is used in the 1st hour, the interval is 1 hour afterwards.

For the interested reader it is further analysed which gates impede reduced aircraft separations. This analysis reveals 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, which is another evidence for the bottleneck close to the ground. Interestingly though, also gate 1 (the far-out gate at 1077 m height) blocks reduced separations in almost 31% of the cases which 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 with 26 to 48%. 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 to the 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 (see [13]). 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.

Fig. 16 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.

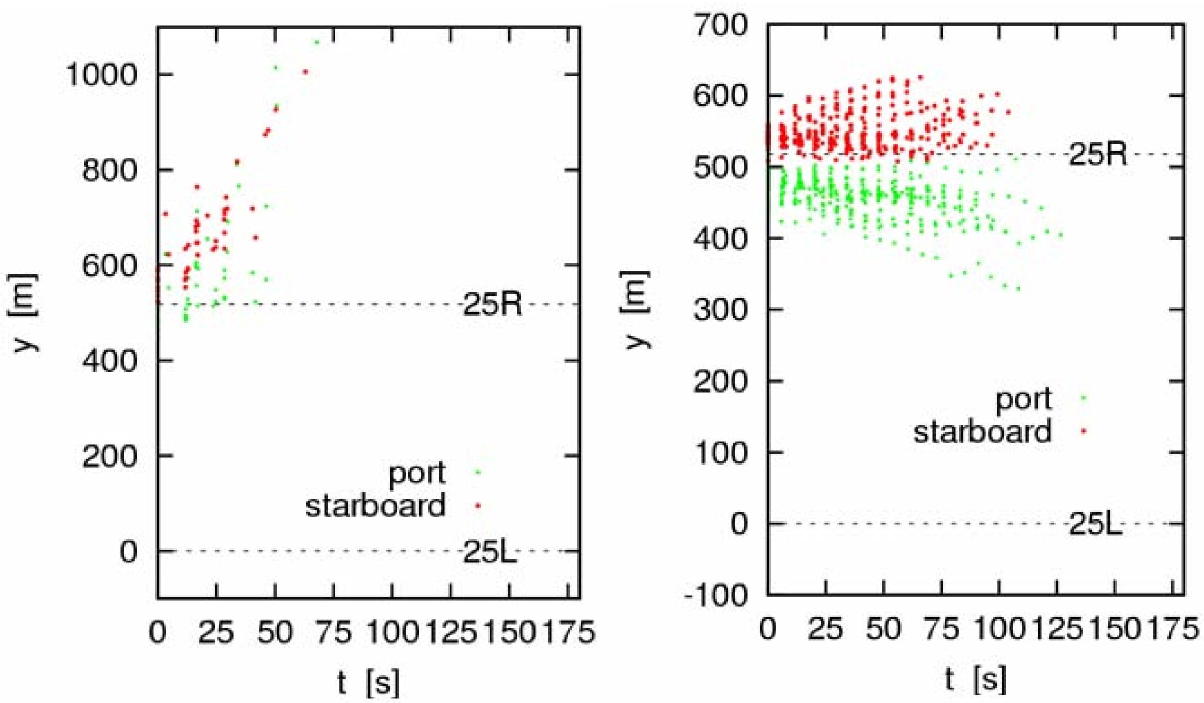

Fig. 16. Lateral positions of wake vortices vs. vortex age from 8, 32 heavy aircraft landing on 25 R on 18th Jan. (left) and 8th Feb. (right) 2007, respectively, as traced by the LIDAR in the three scan planes.

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 (Fig. 2). In all these cases it was found that

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

the recommended operation mode was well predicted – 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 of DLR. 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. 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,
- reduced separation procedures could have been continuously applied for at least several tens of minutes and up to several hours occasionally,
- the predictions were correct as 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.

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

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REFERENCES

[1] de Bruin A., Speijker L., Moet H., Krag B., Luckner R., Mason S. 2003: S-Wake – Assessment of wake vortex safety. NLR-TP-2003-234, 77 pp.

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

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

[4] 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.

[5] 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.

[6] 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.

[7] 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.

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

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

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

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

[12] Holzäpfel F., Frech M., Gerz T., Tafferner A., Hahn K.U., Schwarz C., Joos H.-D., Korn B., Lenz H., Luckner R., Höhne G. 2006: Aircraft Wake Vortex Scenarios Simulation Package – WakeScene. Proc. 25th International Congress of the Aeronautical Sciences (ICAS), Hamburg, pp 1-12.

[13] Holzäpfel F., Gerz T., Frech M., Tafferner A., Köpp F., Smalikho I., Rahm S., Hahn K.-U. & Schwarz C. 2008: The wake vortex prediction and mointoring system WSVBS. Part I: Design. See this issue.

[14] 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.

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