NLR-TP-2003-243

# S-Wake
# Assessment of Wake Vortex Safety
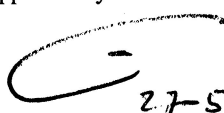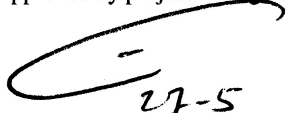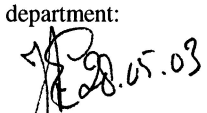## Publishable Summary Report

A.C. de Bruin (with input from partners)

| Approved by author: | Approved by project manager: | Approved by project managing department: |
|---|---|---|
| 27-5 | 27-5 | 28.05.03 |

**Contents**

 6 Tables

43 Figures

(76 pages in total)

## 1 Introduction

With increasing air-traffic congestion problems around major airports and the approaching introduction of larger transport aircraft, the problem of wake vortex induced risks for aircraft following other aircraft has gained new interest. The S-Wake project (January 2000 until March 2003) addressed these problems by considering the different aspects contributing to the wake vortex safety issue and by developing tools for assessing and monitoring the wake vortex safety levels. The highly inter-disciplinary project involved the participation of 14 partners. The consortium was co-ordinated by NLR and participation involved: an aircraft manufacturer (Airbus); aeronautical research institutes (NLR, DLR, ONERA and CERFACS); an airport service/safety provider (DFS); an air-traffic management research group (NATS); meteorological institutes (Met Office and Météo-France); an airline (British Airways); a flight data recording processing service provider (Spirent Systems) and flight mechanical, flight simulation and flight testing experts from three universities (IST-Lisbon, TU-Berlin and IFF/TU-Braunschweig). A more extensive list of the role of the different partners in the S-Wake project and a list with points of contact are given in table 5 and table 6 at the end of this report.

The general objective of the S-Wake project was to develop and apply tools for assessing appropriate (safe) wake vortex separation distances. The specific objectives of S-Wake were: vortex safety for aircraft on the approach glide path.

- To improve the physical understanding of wake vortex evolution and decay in the atmosphere.
- To establish realistic flight simulation environments for investigating wake vortex encounter safety aspects and pilot's response.
- To develop encounter severity (safety hazard) criteria, which relates the dynamic response of a wake vortex encountering aircraft to the encounter severity as perceived by the pilot.
- To establish a probabilistic safety assessment environment.
- To analyse the safety aspects for current practice.
- To define possible new concepts which allow a safe mitigation of current separation rules under certain conditions.

The work in the S-Wake project was performed in five interrelated Work Packages (WP1 until WP5):

In **WP1** (managed by CERFACS and with contributions from Airbus, DLR, MO, MF and NLR) wake vortex transport/decay and the influence of weather conditions were investigated by a team of wake vortex modellers, with input from meteorological experts. Numerical simulation results of wake vortex behaviour in the atmosphere, under a variety of ambient atmospheric conditions (turbulence, stability, wind shear) were used to gain improved understanding of the

transport and decay mechanisms. Simplified wake vortex transport and decay models were developed and were used in Work Packages 2-4. Weather dependent "Wake Vortex Behaviour Classes (WVBCs) were defined and their predictability and possible application in a dynamic (weather dependent) separation matrix was explored. Detailed analysis of a large pre-existing database (Memphis database), showed that the WV decay alone is not sufficient to allow a reduction of separations. Wake vortex transport seems mainly responsible for the existing levels of safety. In particular a crosswind in excess of 2 m/s provided a WV-free flight corridor near ground. This concept might be further explored for an operational ATM system with reduced wake vortex separations.

In **WP2** (managed by DLR and with contributions from Airbus, IFF/TU-Braunschweig, NLR, ONERA and TUB) Wake Vortex Encounter (WVE) models for quantifying the disturbing aerodynamic forces and moments were considered. A Strip Model was developed by ONERA and a Lifting Surface method was developed by TU-Berlin. These models were initially validated against available wake encounter wind tunnel data from the previous WAVENC project. Wake vortex encounter flight tests with instrumented Dornier DO-128 aircraft (IFF/TU-Braunschweig) and the Cessna-Citation II (NLR) aircraft behind the ATTAS aircraft of DLR were made to measure the vortex flow field and validate the Aerodynamic Interaction Models (AIMs). It was possible to obtain the main properties of the wake vortex pair (lateral vortex spacing, circulation strength and core radius) from the flow sensor data of the aircraft, using parameter identification techniques. The observed flight trajectories and aircraft movements and accelerations agreed satisfactorily with those predicted by the developed AIMs. These models could therefore be used in the flight test simulations of WP3 and in the probabilistic safety assessment study made in WP4.

In **WP3** (managed by Airbus with contributions from CERFACS, IST-Lisbon, DLR, NLR, ONERA and TUB) flight simulations were made for vortex encounters of different aircraft sizes, wake strengths, wake intercept angles and wake intercept heights. This work is an extension of the pioneering work performed in the WAVENC project. Based on the results of WP1 and WP2 a portable WVE software module was installed in four different flight simulators (for different wake encountering aircraft). Test pilots and airline pilots participated in wake encounter flight sessions. Pilot's perceptions of aircraft response and the level of safety during the encounter were inquired with pilot questionnaires. In total 1623 wake vortex encounters were flown. The results were analysed and yielded interesting results for the safety hazard criteria, revealing a large influence of flight altitude on pilots perception of safety. In addition simplified and specialised simulation models were developed. A high-fidelity off-line simulation model, which was used to search for worst-case encounter conditions was developed and successfully demonstrated with results in agreement with the flight simulator tests. A

simplified aircraft/pilot wake encounter model was developed for probabilistic safety assessments in WP4. Finally, simple analytical models were developed by IST to estimate wake encounter characteristics.

In **WP4** (managed by NLR and with contributions from DFS, DLR, NATS and ONERA) a quantitative safety assessment of wake vortex induced risk related to single runway approaches under ICAO flight regulations has been carried out. A risk management framework defining risk requirements - and enabling to judge the acceptability of wake vortex induced risk - was established, using historical wake incident data from Heathrow airport. These risk requirements have been reviewed externally by EUROCONTROL and the FAA within the frame of their Action Plan 3 on "Air Traffic Modelling for Separation Standards". The WAVIR methodology of NLR provides a method to derive safe and appropriate separation distances. The method was upgraded with the improved wake evolution and wake encounter models of WP1, WP2, and WP3. An extensive safety assessment, with different aircraft landing behind a Medium Jet and a Large Jumbo Jet (like Boeing 747-400) and a Medium Jet (like Airbus A320) under different operational, weather and wind conditions was carried out. It was found that the largest runway capacity improvements might be achieved through exploiting favourable wind conditions such as crosswind and strong headwinds. In the area close to the runway threshold wake vortex risk mitigation measures are most effective. Warning for unfavourable evolution of the vortices (in terms of position in relation to the follower aircraft) is there also most efficient. It was also found that ATM procedural changes further away from the glide slope are not effective in reducing the risk related to single runway approaches. Therefore, weather based prediction, monitoring and warning systems should focus on weather and wind conditions near the runway threshold. New concepts and ATM procedures have been evaluated with respect to their potential for capacity improvements, and it was concluded that implementing local airport procedures might lead to significant capacity increases.

In *WP5* (managed by NATS and with contributions from British Airways, MO, NLR and Spirent Systems) actual wake vortex incident data were collected and initially analysed. Before this S-Wake study, wake vortex encounter statistics was only available from voluntary pilot reports collected by NATS. Additional qualitative data on pilot reported wake vortex encounters can be found in the Aviation Safety Reporting System (ASRS) database (Ref. 55). It is believed that the number of reported wake encounters is less than the actual number of encounters. Therefore, within S-Wake, an extensive amount of routinely collected FDR data of BA aircraft on approach and landing into Heathrow airport was collected and analysed. NLR developed a wake vortex detection and classification method (NLR-VORTEX) based on the processing of the FDR data. Extensive radar tracking information, runway log information, local meteorological (METAR) data and meteorological data along the ILS track (from the processed

FDR data), as well as detailed information on detected wake vortex encounters (from the processed FDR data) were collected in the London Heathrow Database (HDB). It covers the period September 2001 until August 2002. This proved to be a very challenging effort. The quality of the FDR data needed continuous attention. Yet, an initial statistical analysis of the data has been made, and demonstrated the potential benefits of using an automatic WVE detection tool for getting improved statistics for WVE in an operational system. It confirmed the beneficial effect of crosswind on WVE rates. Further analysis of these data is needed in order to get a full appraisal of the obtained results. Additional data from the NATS voluntary WVE reporting base (covering a much longer period) was also used for a supporting statistical analysis.

The prime potential application areas of the S-Wake results are:

**Define safely reduced (dynamic) separation rules that improve airport capacity.**
For the NASA Aircraft Vortex Spacing System (AVOSS) significant (average) gains in airport capacity (between 1 and 13 %) have been claimed. Potential gains depend on the traffic mix, the prevailing weather conditions at a particular airport and the available runway topology (Ref. 26). For airports operating near their maximum throughput limits this may lead to very substantial decreases in average delay time and large potential economic savings. Wake vortex movement and decay prediction will be an essential element for developing an operational system, with dynamic (weather dependent) separation rules. Predictable weather dependent Wake Vortex Behaviour Classes (WVBC) were considered in S-Wake. It was concluded that crosswinds and strong headwinds might be suitable candidates to be used in a dynamic (weather-dependent) aircraft separation method. The results from S-Wake are used in developing a Wake Vortex Prediction and Monitoring System (WVPMS) in the framework of ATC-Wake.

**Possible harmonisation and re-definition of the current separation rules.**
The current wake vortex separation rules define separation **distances** depending on the MTOW of the paired aircraft. At present, there are no world-wide uniform rules for wake vortex separation minima. There are regional differences and even variations per airport. EUROCONTROL recently started discussion within the EUROCONTROL/FAA Action Plan initiative to see whether the present separation rules can be harmonised and can perhaps be modified into separation *times*. S-Wake outcomes and tools can be used for assessing the wake vortex safety implications of new ATM proposals and the tools from WP5 can be used for monitoring the effects on the actual wake vortex encounter rates, once such changes in the ATM system are introduced.

**Safety assessment of wakes behind a scheduled Very Large Transport Aircraft (VLTA).**
In a FAA policy statement it is proposed that a safety assessment should be part of the aircraft certification procedure for a VLTA. The tools developed in work packages 1-4 of S-Wake can be used to compare the levels of safety of future Very Large Transport Aircraft (VLTA) with current very heavy aircraft, provided the wake characteristics of the VLTA are known (e.g. from C-Wake). The tools developed in WP5 can in principle be used to monitor wake vortex encounter rates when a new VLTA is introduced in the air-transport system. For all safety assessments and probabilistic investigations criteria are needed that relate aircraft/wake interaction and the operational significance of the wake encounter. The criteria developed in WP3 represent a sound basis for these tasks.

## 2 The wake vortex problem and European Commission research projects

### 2.1 Introduction

With the introduction of new large transport aircraft and increasing air-traffic congestion problems around major airports, the problem of wake vortex induced risks for aircraft following other aircraft has gained new interest, both in Europe and in the US. In the US extensive research programs existed for developing a wake vortex spacing system (AVOSS, see Refs. 25-26) and wake vortex advisory systems. In Europe, air traffic service providers and airport operators put large efforts in introducing new approach procedures that allow a safe mitigation of separation distances between aircraft on closely spaced parallel runways. In particular the efforts of DFS and Frankfurt Airport on High Approach Landing System/Dual Threshold Operation (HALS/DTOP, see Ref. 27) should be mentioned. EUROCONTROL and FAA have also started collaboration on the subject of wake vortices in the framework of an EUROCONTROL/FAA Action Plan (see Ref. 28). Recently, EUROCONTROL decided to address the problem of safe wake vortex separation between aircraft under headwind and tailwind conditions. It has to be noted that today's navigation accuracy in principle allows radar separations to be 2.5 NM or less, but that the minimum wake vortex separations often require much larger separations (see figure 1). There is therefore a large potential gain in airport capacity if the current separation rules can be relaxed under certain circumstances.

Within the S-Wake project, a consortium of 14 partners co-ordinated by NLR, made an assessment of the wake vortex safety issues. The S-Wake project extends the work done in the previous WAVENC project (Ref. 29), which ended in March 2000. Tools were developed and applied to assess appropriate (safe) wake vortex separation distances. As described in section 4 of this report, the project consists of five technical Work Packages (WP's).
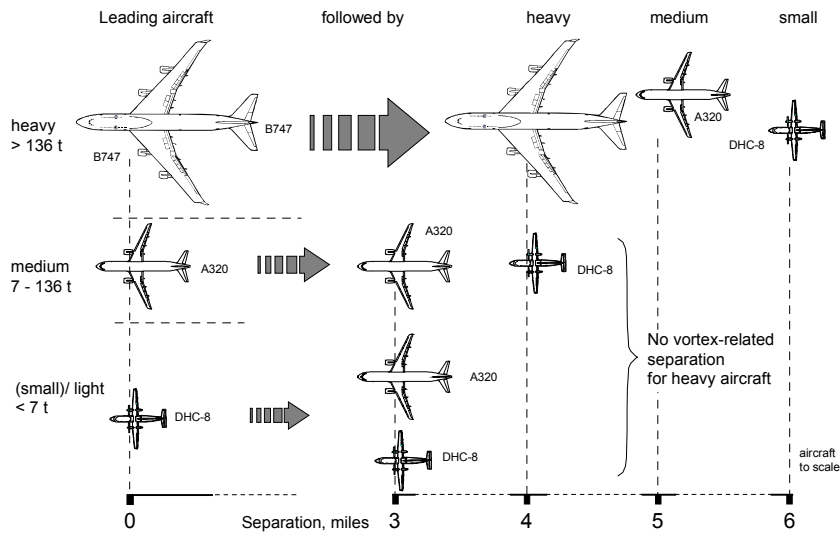
*Fig. 1  ICAO separations*

## 2.2 Other Wake Vortex related European research projects

Since the wake vortex issue considers a broad spectrum of technologies and disciplines the European Commission is funding the Thematic Network WakeNet-2-Europe (which is co-ordinated by NLR, duration 2003 until 2006) with the aim to promote exchange of information between researchers, airline operators, pilots and air-traffic controllers. It is intended to promote active exchange of information on the topic with US partners. The Wakenet-2-Europe project is a continuation of WakeNet (co-ordinated by Airbus, 1999-2002). S-Wake partners have given a large number of contributions to the WakeNet workshops (see e.g. 56-68).

Collection and analysis of FDR data from pilot reported wake vortex encounters has been done in ETWIRL (co-ordinated by RED-Scientific, period 1998-1999, Refs. 53-54). Wake vortex characterisation and control is being considered in the C-Wake project (co-ordinated by Airbus, period 1/2000-6/2003). This project is a follow on of the previous EUROWAKE project. Flight testing of wake alleviation concepts is considered in task 1.1 of the AWIATOR project (co-ordinated by Airbus, 7/2002-6/2006). On-board wake detection and warning is considered in the I-Wake project (co-ordinated by THALES, period 5/2002-4/2005). This project is a follow on of the MFLAME project. Wake vortex situational awareness has been one of the subjects considered in the ISAWARE project. Integration of dynamic (weather dependent) separation distances in the Air Traffic Management system is the aim for the ATC-Wake project (co-ordinated by NLR, period 7/2002-6/2005). It should be noted that these projects are becoming more and more focussed on possible applications that may lead to improved levels of safety and increased airport capacity.

## 3    Objectives of the S-Wake project

The S-Wake project continued and extended the work done in the previous WAVENC project (Ref. 29), which ended in March 2000. It looked more specifically to the safety aspects, by developing and applying tools for assessing appropriate (safe) wake vortex separation distances. The specific **objectives** of S-Wake were:

To define suitable wake vortex behaviour classes depending on weather categories for wake vortex safety for aircraft on the approach glide path.

- To improve the physical understanding of wake vortex evolution and decay in the atmosphere.
- To establish realistic flight simulation environments for investigating wake vortex encounter safety aspects and pilot's response.
- To develop encounter severity (safety hazard) criteria, which relates the dynamic response of a wake vortex encountering aircraft to the encounter severity as perceived by the pilot.
- To establish a probabilistic safety assessment environment.
- To analyse the safety aspects for current practice.
- To define possible new concepts which allow a safe mitigation of current separation rules under certain conditions.

## 4    Scientific and technical progress

The work in the S-Wake project resulted in 63 Technical Notes and a summary of the technical deliverables is given in Table 1. The results and technical progress have been summarised in the final reports of the Work Packages (Refs. 1-5). A discussion of the main results is given below.

Table 1  List of other deliverables (other than Technical Notes)

| nr. | Description | Developed by |
| --- | --- | --- |
| 1 | database with results from numerical simulations | DLR, CERFACS |
| 2 | analytical wake vortex model for flight simulator | Airbus, CERFACS |
| 3 | numerical wake vortex model for flight simulators | Airbus, CERFACS |
| 4 | probabilistic Wake Vortex transport and decay model | NLR |
| 5 | aerodynamic Interaction Model based on Strip Method | ONERA |
| 6 | aerodynamic Interaction Model based on Lifting Surface | TUB |
| 7 | database with flight test data | DLR, IFF/TU-Braunschweig, NLR |
| 8 | integrated WVE software module for flight simulators | Airbus, CERFACS, ONERA, TUB |
| 9 | database with flight simulation data | Airbus, TUB, NLR |
| 10 | high-fidelity offline model for wake encounter simulation | Airbus |
| 11 | Reduced Aircraft Pilot Model (RAPM) | Airbus, DLR, ONERA |
| 12 | probabilistic Wake Vortex Encounter model | NLR, ONERA |
| 13 | vortex detection and classification algorithm for FDR data | BA, NATS, NLR |
| 14 | Heathrow DataBase | NATS |

## 4.1 WP1: Wake vortex behaviour in the atmosphere, modelling and validation

Work Package 1 (WP1) had the objective of extending knowledge of wake vortex evolution in the atmosphere under various weather conditions and to demonstrate and improve the predictive capabilities of both simple and advanced numerical methods for vortex evolution and decay. The results coming from WP1 were used in WP2 (wake encounter models), WP3 (wake encounter simulations) and WP4 (probabilistic safety assessment). The work in WP1 was an extension of the previous WAVENC project and also used results from other projects and measurement campaigns (e.g. the Memphis database, Ref. 30). The work consists of three subtasks. The first subtask considered the numerical simulation of wake vortex behaviour under a variety of atmospheric conditions. In the second subtask an existing simple wake vortex transport and decay model was significantly adapted and validated. This model is part of the WVE software used in WP's 2-4. Within the 3rd subtask, WVBCs were established and validated using the Memphis database. Climatologies of WVBC and their predictability were investigated in order to assess the potential benefit of the new concept at various airports. A summary of the work performed in WP1 is given below. A more extended description can be found in the final summary report of WP1 (Ref. 1).

### 4.1.1    CFD studies of wake vortex behaviour in the atmosphere (Task 1.1)

Dedicated numerical simulation studies were performed by DLR and CERFACS. These included the effects of ambient turbulence, thermal stratification, crosswind shear and the effect of vortex core/vortex spacing ratio on wake vortex decay. Also, the well known Heathrow rebound case (as measured by LIDAR; Ref. 38) was simulated. The results of these numerical simulations led to increased understanding of the mechanisms of wake vortex decay in the atmosphere. A rather complete picture of the decay mechanisms has emerged from these (and other) simulations and is reported by DLR and CERFACS in Ref. 8. The simulations also helped CERFACS to develop a new wake vortex decay model (Ref. 6) and supported DLR in developing a probabilistic prediction method (P2P method, see Refs. 7 and 39-41).

### Effect of ambient turbulence on vortex evolution

A field of homogeneous isotropic turbulence (HIT) has been used by CERFACS to represent the ambient turbulence flow field. HIT fields were initially generated in the spectral space using the formulation of Von Kármán and Pao (Ref. 42). Several spectra were calculated and these evolve into HIT fields using the LES model. HIT fields were generated for turbulence intensities ($I_u$) equal to 1, 7, 10.5 and 24%. The longitudinal integral turbulence length scale ($\Lambda_f$) of the most energetic eddies was taken sufficiently large with respect to the lateral vortex spacing. As an example the turbulence field and the kinetic energy spectrum of a HIT field is shown in Figure 2. For the higher Fourier modes the kinetic energy spectrum follows the proper $k^{-5/3}$ inertial sub-range behaviour and this validates the LES model for this type of simulations.
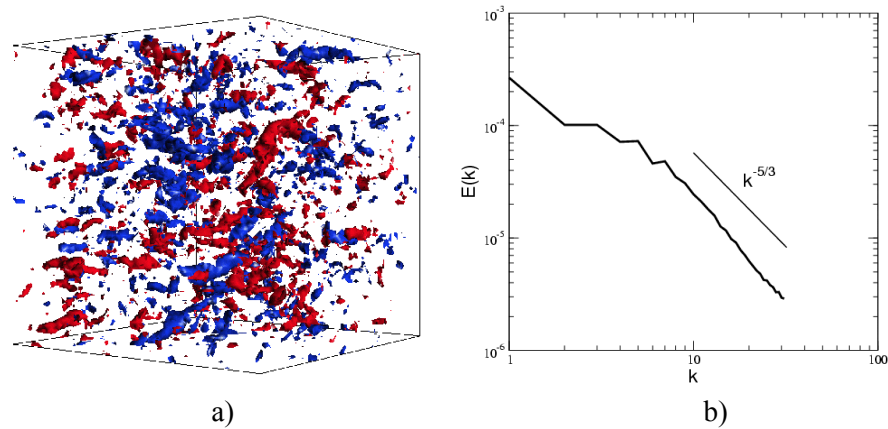
*Fig. 2 a)  Iso-surfaces of z-vorticity component (blue: negative; red: positive);*
*b)  kinetic energy spectrum for the homogeneous isotropic turbulence field (LES: CERFACS)*

Single vortex and Lamb-Oseen vortex pairs of fixed circulation strength ($\Gamma$) and core radius ($r_c$), but with various spacing ($b_0$), were superimposed on the HIT fields. All computations were carried out on a $64^3$-nodes regular grid with a domain size given by $L_x=L_y=L_z\cong30\ r_c$ at a nearly realistic flight Reynolds number $Re_\Gamma = \Gamma/\nu \cong 10^7$ ($\Gamma \approx 70\ \mathrm{m}^2/\mathrm{s}$) and with periodic boundary conditions in all three directions.

The parametric studies show that the decay depends on the turbulence intensity ($I_u$), the longitudinal integral length scale of turbulence ($\Lambda_f$), and on the vortex core radius/vortex span ratio $r_c/b_0$. Figure 3 shows the decay of circulation for three different vortex spacings, affected by different levels of turbulence intensity. The single vortex decay and the vortex pair with modest vortex spacing ($b_0=8r_c$) show gradual and quasi linear decay. The decay rate is about proportional to $I_u$. The decay for a vortex pair with a very small vortex spacing ($b_0=4r_c$) is significantly different (see figure 3c). Small vortex spacing (or increased vortex cores) lead to a rapid growth of long-wavelength instabilities causing large-scale vortex deformations, leading to an accelerated decay. Note that here the non-dimensional time scale is defined by dividing the time t with ($V_{\theta max}r_c$), where $V_{\theta max}$ is the peak tangential velocity. This allows a comparison of the decay of the single vortex with that of the vortex pair.
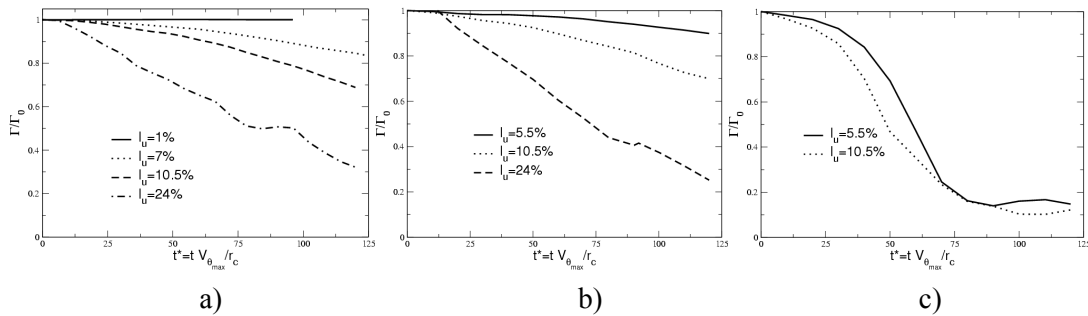
Fig. 3 *Time evolution of the circulation calculated at $r=4\ r_c$ for a range of turbulence intensities;*
*a) single vortex: b) vortex pair with modest vortex spacing $b_0=8r_c$;*
*c) vortex pair with very small vortex spacing $b_0=4r_c$ (LES simulations by CERFACS)*

The spatial structure of a vortex pair with a modest vortex spacing ($b_0=8r_c$) evolving in weak/ moderate turbulence is shown in figure 4. The vortex pair is subject to some deformation but decays primarily due to the exchange of vorticity through the process of vorticity stretching, which is creating azimuthal structures of vorticity wrapped around the vortices (see Fig. 4c). Further details can be found in reference 1 and in two publications that resulted from this work (Refs. 6 and 8).
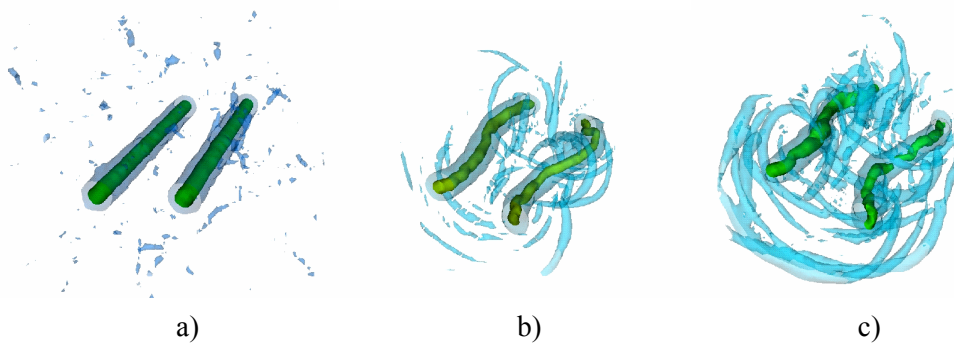


Fig. 4   *Spatial structure of a vortex pair evolving in weak/moderate turbulence ( a) $t*=0$, b) $t*=60$, c) $t*=120$; LES simulations by CERFACS); $b_0= 8r_c$.*

**Effect of thermal stratification on vortex evolution**
The effect of thermal stratification was investigated by CERFACS using the same LES technique as for the turbulence study. A gravitational source term was added in order to simulate a stratified atmosphere. Simulations were made for a wake vortex pair descending in a thermally stratified environment. The results were compared against Sarpkaya's experimental data (Ref. 46). A detailed discussion of the results can be found in the final report of WP1 (Ref. 1) and in a publication that resulted from this work (Ref. 8).

Different constant temperature gradients were assumed and these were defined by the Brunt-Väisälä frequency $N =(g/\theta\ \partial\theta/\partial z)^{1/2}$, with $\theta$ the mean potential temperature and g the

gravitational acceleration. Different normalised values of the Brunt- Väisälä frequency were considered: $N^*$=0.0, 0.375, 0.5 and 1.0 ($N^*$=$N$ $b_0/V_d$, with $V_d$=$\Gamma/(2 \pi b_0)$). The computational domain is fixed by $(L_x, L_y, L_z)$=(6 $b_0$,20 $b_0$,8.2 $b_0$). A Lamb-Oseen vortex pair was placed inside this box and periodic boundary conditions were used in horizontal (x) and axial (z) direction. Non-reflecting boundary conditions were used in the vertical (y) direction.

The vortex trajectories $Y=y/b_0$ of both vortices of the vortex pair are shown in figure 5 as a function of the non-dimensional time $t^*=t/t_{ref}$ (with $t_{ref}=b_0/V_d$). The vortex trajectories compare well with towing tank experiments of Sarpkaya (Ref. 46). Thermal stratification decelerates the vortices due to buoyancy effects. This is particularly well visible for the case with strong stratification ($N^*$=1.0) where the buoyancy effects are sufficiently strong to stop the vortex descent and cause even a vortex rebound.
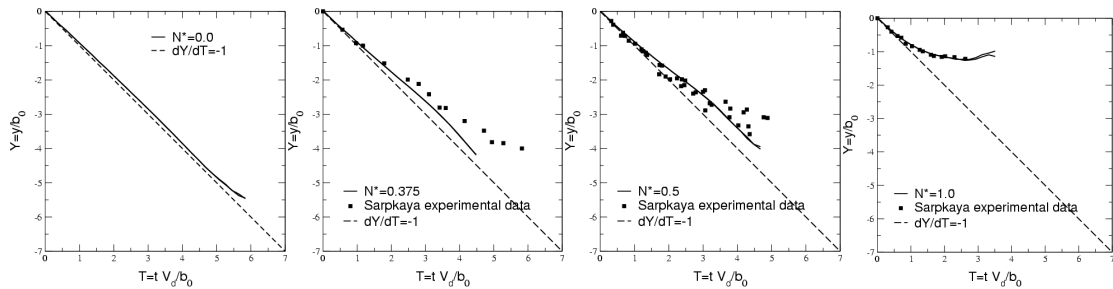


Fig. 5    Vertical position $Y=y/b_0$ of the vortices. LES computations by CERFACS compared with experimental results of Sarpkaya (Ref. 46). Stratification levels: $N^*$=0.0, 0.375, 0.5 and 1.0.

Due to the stratification, the vortex spacing *decreases* with time $t^*=t/t_{ref}$ (see Fig. 6a). The circulation shows an initial gradual decay (this decay rate depends on the background turbulence level). The initial phase is followed by an accelerated decay phase (see Fig. 6b). This is caused by the development of co-operative instability mechanisms. The onset of instability seems to be earlier if $N^*$ becomes larger. The circulation profile $\Gamma(r/r_c)$ develops a negative circulation region (see figure 6c), which indicates the presence of countersign vorticity. This 'baroclinic' vorticity is generated directly around the vortex oval, where the density gradient is the largest.

The simulations also showed the development of two co-operative instability mechanisms. For neutral/weak stratification the decay is governed by the Crow instability (Ref. 45). In strong stratification short wavelength/elliptic instabilities do develop as well.

a)                                        b)                                        c)
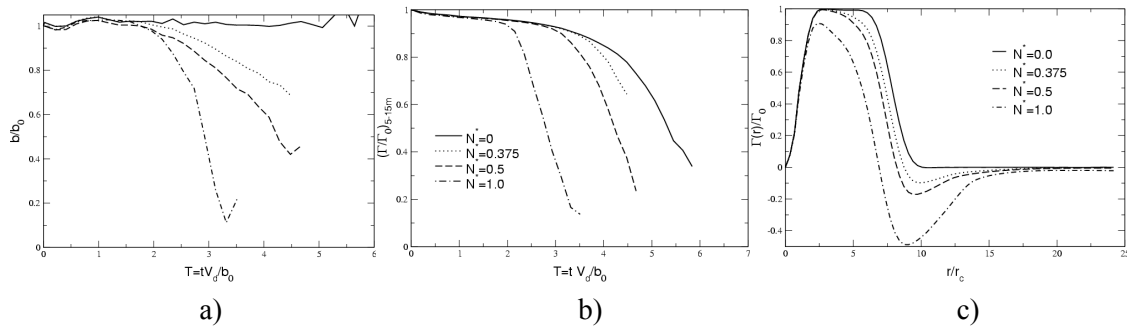
Fig. 6    The evolution of a) the vortex spacing, b) the normalised circulation and c) the circulation profiles as a function of the distance from the vortex centre $r/r_c$ at $t^*=2.35$ (LES simulations by CERFACS)

**Effect of crosswind shear on vortex evolution – parametric study**

3D DNS simulations of the shear effect on wake vortex transport and decay were made by DLR. A wake vortex subjected to a laminar and turbulent jet was simulated. This is of practical interest because of the risk of vortex rebound causing a long-living isolated vortex. The features that were observed in the simulations are vortex tilting, vortex rebound and unbalanced vortex decay rates for the upwind and downwind vortex. Figure 7 gives a perspective view of iso-surfaces of $\lambda_2$ (black), $\omega_x$ and $\omega_z$ (grey) for a vortex pair interacting with a ground jet in turbulent surroundings.
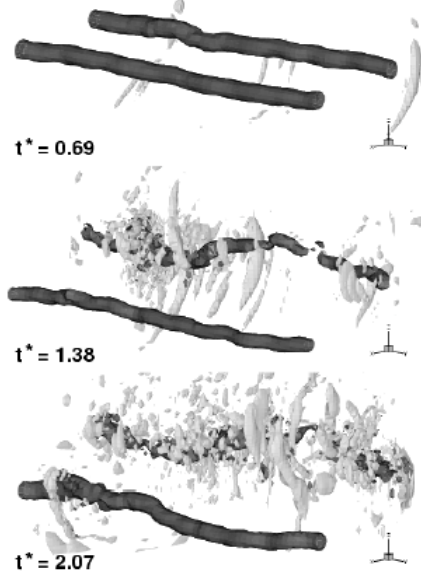


Fig. 7    Perspective view of $\lambda_2$ (black), $\omega_x$ and $\omega_z$ (grey) showing local breakup of upwind vortex in a turbulent cross-flow jet (direct numerical simulations by DLR)

The upwind vortex is strongly perturbed. At later times the downwind vortex reveals the same kind of behaviour. The stretched turbulent eddies enhance the turbulent diffusion of the primary vortices. The interaction between vortex pairs and shear layers was also studied in a 2D parametric study. Complex vortex transport behaviour was observed, even for a seemingly simple idealised case. No direct relationship between shear layer strength and depth and the WV

decay and trajectories could be derived. However, a conservative upper limit of rebound height was obtained: $\Delta x = w_0 \Delta t$. The lateral transport of the WV out of ground effect is well described by the crosswind profile.

**Effect of crosswind shear on vortex evolution – Heathrow case**

In 1996 and 1998, Vaughan (Ref. 38) reported exceptional vortex rebound behaviour during the London-Heathrow measurement campaign in 1994/1995 (Fig. 8). This case was successfully reproduced in LES simulations by DLR.
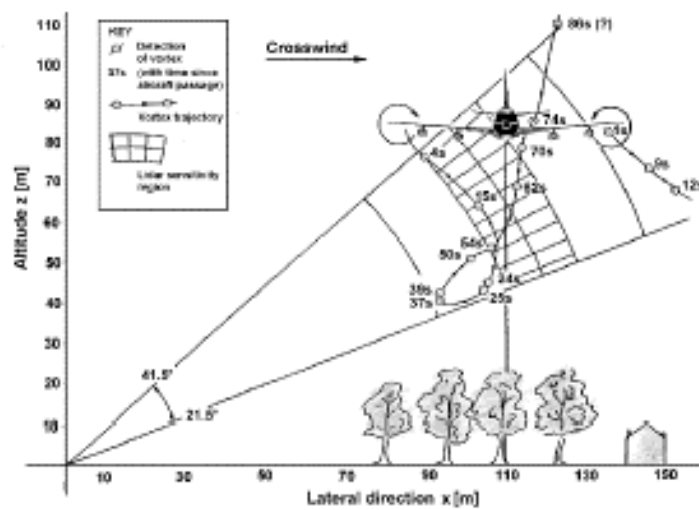


Fig. 8    *Vortex trajectory of a Boeing 747-200 in terminal approach to London-Heathrow (Ref. 38)*

A realistic reproduction was obtained by including the effect of vegetation, lateral wind and atmospheric turbulence, as shown in figure 9.



a)                                                                     b)
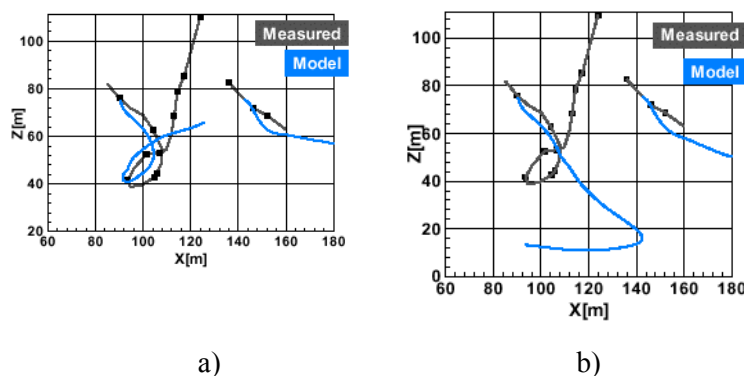
Fig. 9    *Trajectories of measurements (black) and simulations (blue);*
*a) vegetation modelled*
*b) vegetation modelling neglected (LES simulations by DLR)*

**Effect of $r_c/b_0$ ratio on wake vortex decay**

CERFACS used a LES model to investigate the effect of vortex core radius on vortex decay. Lamb-Oseen vortex pairs of given spacing and strength but different core radii were superimposed on HIT fields. The vortex systems that were considered have a relatively large spacing. Modelled ambient turbulence levels range from moderate to strong. It was found that the vortex core radius has no significant effect on the decay behaviour. So low-vortex designs aiming at a larger core radius seem to have no effect on the vortex decay behaviour, unless the core-radii become very large.

### 4.1.2   Improvement and application of the VORTEX model (Task 1.2)

The original VORTEX model of CERFACS (Ref. 44), that itself is based on the model of Greene (Ref. 43), was considerably extended by CERFACS. A whole range of circulation decay models is made available: the models of Greene, Sarpkaya (Ref. 47), Donaldson & Bilanin, Robins & Delisi, and Han et al.. The wake vortex induced velocity fields can be selected from a series of analytical profiles: Lamb-Oseen, Burnham-Hallock (Ref. 48), Proctor and Winckelmans (Ref. 49). A comparison of the velocity profiles is shown in figure 10. Note that conditions at the velocity core radius were used for the normalisation. For equal vortex circulation strength (which implies equal velocities at larger radii) and equal core radius, the peak velocity is lowest for the Burnham-Hallock model and largest for the Lamb-Oseen model.
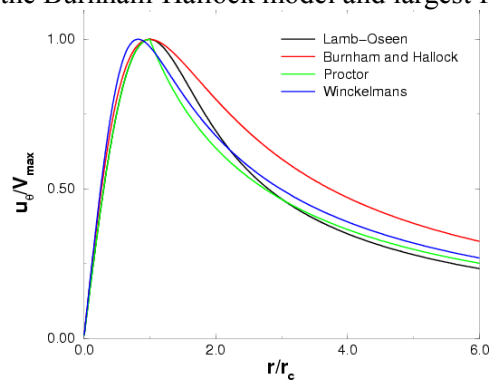


*Fig. 10    Analytical vortex velocity profiles*

A new model (called the *analytical model*) was developed satisfying the simulator requirements defined by Airbus. This was implemented in the WVE software tool for its usage in the flight simulations (WP3). In addition also a special interface was developed that enables to supply any wake vortex flow field (e.g. from numerical simulations) to the flight simulators. Figure 11 shows the wake vortex encounter scenario that is used in the flight simulators. The wake intercept conditions are controlled by user input parameters:
$x_{EF,gr}$, $y_{EF,gr}$, $\Delta H_{wv}$, $\Delta\Psi_{wv}$, $\Delta\gamma_{wv}$.
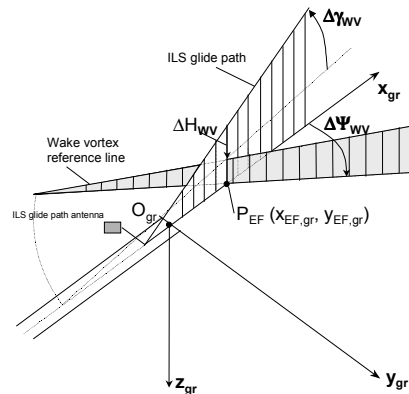
*Fig. 11   Wake vortex encounter scenario*

In parallel with this work the Green, the Sarpkaya and the Donaldson & Bilanin decay models were also implemented in a probabilistic environment, to be used in (WP4). Extensive Monte-Carlo simulations were made and these were input to the probabilistic safety assessment of WP4. Simulations were made (using the Sarpkaya model) at different positions along the ILS glide path, for different wake generating aircraft, for different cross- and tailwind conditions and for a variety of weather conditions. Weather conditions for individual cases were defined with the eddy-dissipation rate (EDR: is input for the Sarpkaya model) and the Brunt-Väisälä frequency. These values were randomly selected from the parameter space.

Prior to these simulations the three decay models were applied to the Memphis database (Ref. 30). DLR developed a special interface for the analysis of the data-base. This work consisted of: an extensive analysis of the wake vortex behaviour in the database, a validation of the WVBC concept, a validation of the wake transport and decay models for each of the WVBCs, and the development of an improved physical model. Results were used in Task 1.3 to define a refined WVBC classification.

Numerical simulation (see section 4.1.1) showed that wake decay consist of two phases. Initially decay behaves quasi-linear, followed by a rapid decay phase at later times. This motivated CERFACS and DLR to develop new two-phase circulation decay models (see Refs. 6-7), but these were not yet used in the S-Wake project. When analysing the wake vortex behaviour in the atmosphere in LIDAR databases such as Memphis, the large spread in wake vortex behaviour due to variability of weather conditions is to be noted. DLR developed therefore a Probabilistic 2-Phase decay model (P2P, see Ref. 7 and Refs. 39-41) that is able to reproduce the observed spatial and temporal variability of WV transport and decay. This P2P model, which was developed outside the S-Wake project, might be considered for future applications as a wake vortex prediction method as part of a dynamic wake vortex separation scheme.

### 4.1.3 Wake Vortex Behaviour Classes

The idea behind the introduction of the Wake Vortex Behaviour Class (WVBC) concept is that it is a challenge to predict the wake vortex decay and behaviour of individual vortices along the complete glide path in an operational system. This is largely due to the variability of the weather conditions along the glide path. Yet, from careful analysis of available databases, distinct wake transport and decay behaviour is observed under different weather conditions (see e.g. Ref. 39). This led to the idea to define WVBCs depending on meteorological parameters that are routinely available and predicted for airport meteorological conditions (viz. wind conditions, bulk-Richardson number and Brunt-Väisälä frequency). Background information on the WVBC concept and on its possible exploitation in an operational system is given in references 9-14.

At the start of the project an initial WVBC definition was given by DLR in collaboration with Met Office and Météo-France. Further statistical analysis with the Memphis data, showed that differences in wake vortex behaviour could better be classified with a refined WVBC definition. It also showed that depending on atmospheric conditions a significant portion of wake vortices are still alive under the current ICAO separation standards (see Fig. 12). Even for the rapid decay WVBC for ICAO separation of 5 Nm (Medium behind heavy) still more than 10 % of the vortices will be alive. This indicates that the high levels of safety observed under current ICAO separation standards must to a large extent be due to the transport of wake vortices out of the flight corridor.
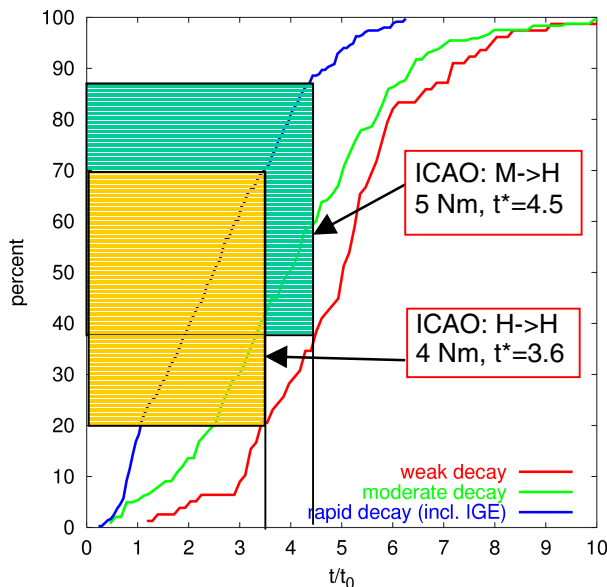


Fig. 12    *Cumulative distribution of WV detection time for a given WVBC.*
           *At a given time (corresponding to ICAO separations Heavy behind*
           *Heavy and Medium behind Heavy) the percentage of "decayed" WVs*
           *for a given WVBC is shown for the Memphis data (DLR)*

The cases in the Memphis database where the vortices remain out of ground effect (OGE) have been further analysed by DLR with respect to the effect of crosswind. Figure 13 shows the

lateral position of these wake vortices as function of time as a 2D frequency distribution (in ‰)
for all wind conditions (554 cases) and for a subset where cross winds are larger than 2 m/s (251
cases). This clearly illustrates that the vortices are blown out of the flight corridors by the
crosswind and separations can be reduced under these conditions.
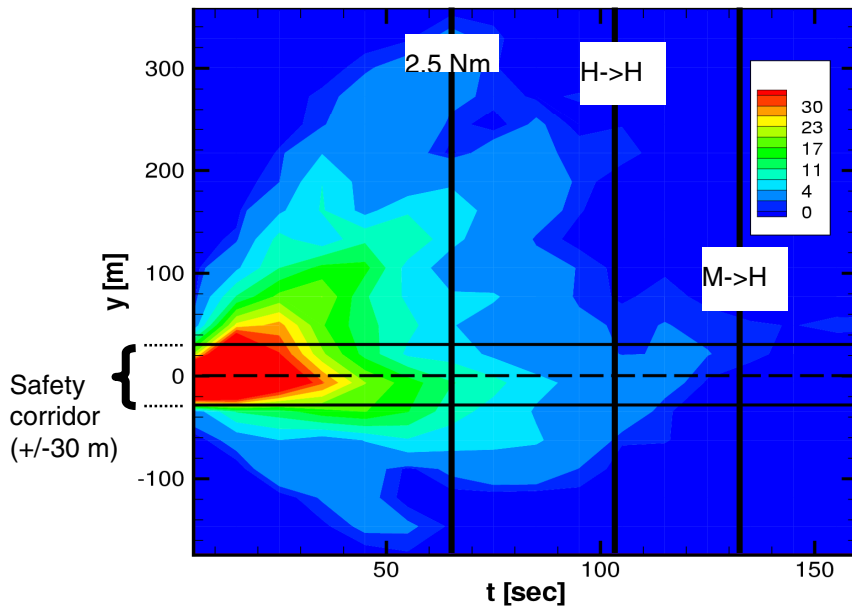


*a) all winds: 554 cases*
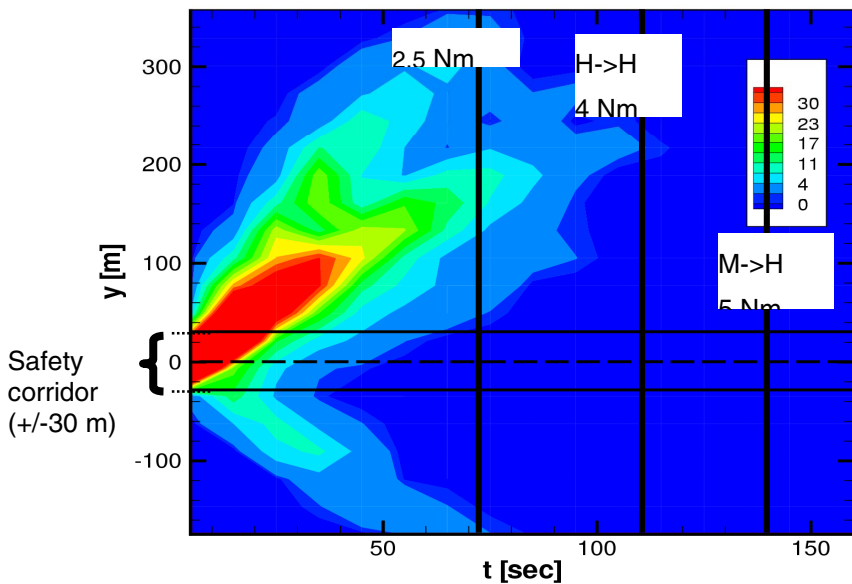


*b) cross wind > 2 m/s: 252 cases*

Fig. 13    Lateral transport of vortices out of the flight corridor due to crosswind, 2-D frequency
distributions (in ‰). Analysis of the Memphis data for vortices out of ground effect
(DLR)

The wake encounter data analysis in WP5 later confirmed that the wake encounter rate substantially decreased in crosswinds (see Ref. 5). Similar results had already be reported from the less extensive ETWIRL database analysis, as performed in WAVENC (see Refs. 29 and 53). This shows a potential for safe reduction of aircraft separation under crosswind conditions and furthermore indicates the necessity of high quality wind observations and forecast. A key issue for the applicability of the WVBC in an operational system is that they can be predicted with sufficient accuracy. This was investigated by Met Office and by Météo-France. Météo-France applied a Numerical Weather Prediction (NWP) method and compared these with actual weather observations for Paris-Orly. Met Office initially used weather forecasts of the original *Turbulence, Stable stratification* and W*ind Shear* WVBC from the "WAFTAGE" (Winds Analysed and Forecast for Tactical Aircraft Guidance over Europe) tool. This work was then repeated in a more extensive study using both WAFTAGE and a Site Specific Forecast Model (SSFM) to predict the Turbulence and Crosswind class. The sensitivity to WVBC definition thresholds was also investigated. It was concluded that the predictive capability for the turbulence class is insufficient, but that the quality of crosswind class predictions is encouraging.

Climatologies of WVBC were determined by Met Office and Météo-France for a large number of major European airports in order to assess the potential of the new concept if it is implemented in an operational system designed to re-stagger aircraft. Elements of this work have been presented in references 12-14. Estimates have been made of the proportion of time for which the entire glide slope is in the *Rapid decay* or *Transport* WVBC state. Estimates range from 24 % for Frankfurt up to 49 % for Schiphol Airport. The persistence time for such favourable conditions has also been investigated. It is concluded that a 'green' glide slope based on *Turbulence*, *Ground Effect* and *Crosswind* classes offers the greatest promise for the further development of an operational wake vortex reduced spacing system.

## 4.2 WP2: Aerodynamic models for wake vortex encounter

The objectives of WP2 were:
- The development and validation of aerodynamic interaction models (AIM's) for calculating the additional forces and moments acting on an aircraft when entering a wake vortex. The models have to be used in the real-time computational environment of flight simulators (WP3) and in the "Probabilistic Safety Assessment" (WP4).
- The execution of wake vortex encounter (WVE) flight tests, involving a wake generating aircraft (ATTAS) and two different well instrumented wake chasing aircraft (Do128 and Cessna Citation II). The aim of these flight tests was to validate the AIM's against flight conditions.

An extensive description of WP2 results is given in Ref. 2. The work also led to two publications (Refs. 15-16).

### 4.2.1 Model requirements for implementation in flight simulators

To enable a piloted simulation of a real vortex encounter in an existing flight simulator a wake vortex encounter model has to be coupled to the basic aircraft simulation. Airbus and TUB were responsible for the definition of model requirements, model interfacing and definition of the input/output data. The Aerodynamic Interaction Models were implemented as incremental force and moment models.

### 4.2.2 Aerodynamic Interaction Models

Two simplified aerodynamic calculation methods suitable for real-time calculations of the wake vortex induced aerodynamic forces and moments were improved and tailored for application to realistic aircraft configurations.

**Strip method (SM)**

ONERA had developed an AIM based on a Strip Method (SM). It had already been used during the WAVENC project. For S-Wake the software was significantly adapted to comply with the new interface definitions. In the SM the aircraft is represented as a wing and a horizontal and vertical tail surface (the fuselage is not taken into account). Each surface is divided into chord-wise strips, which are treated as two-dimensional airfoils. Figure 14 gives an impression of an aircraft represented by the strip model. For each strip element the vortex-induced angle of attack is computed. An ad-hoc limitation of maximum angle of attack was implemented in order to prevent unphysical local lift predictions. The fuselage contribution to forces and moments was not taken into account, since for vortex encounters under small wake interception angles (which was the main situation investigated in S-Wake) the fuselage effect is assumed to be rather small.

*Fig. 14     Strip Method: Horizontal and vertical surfaces of the aircraft
are divided into a number of lift generating strips*

**Lifting Surface Method (LSM)**

A Lifting Surface Method (LSM) was developed, based on a Lifting Surface Theory (LST)
multi-point, real-time model developed by TUB. The lifting surfaces are panelled by vortex
elements, as depicted in figure 15. Each vortex element consists of two horseshoe vortices,
arranged in a row one behind the other. The LSM yields lift distributions across both the wing
span and the wing chord. Induced drag contributions and down- and side-wash effects due to the
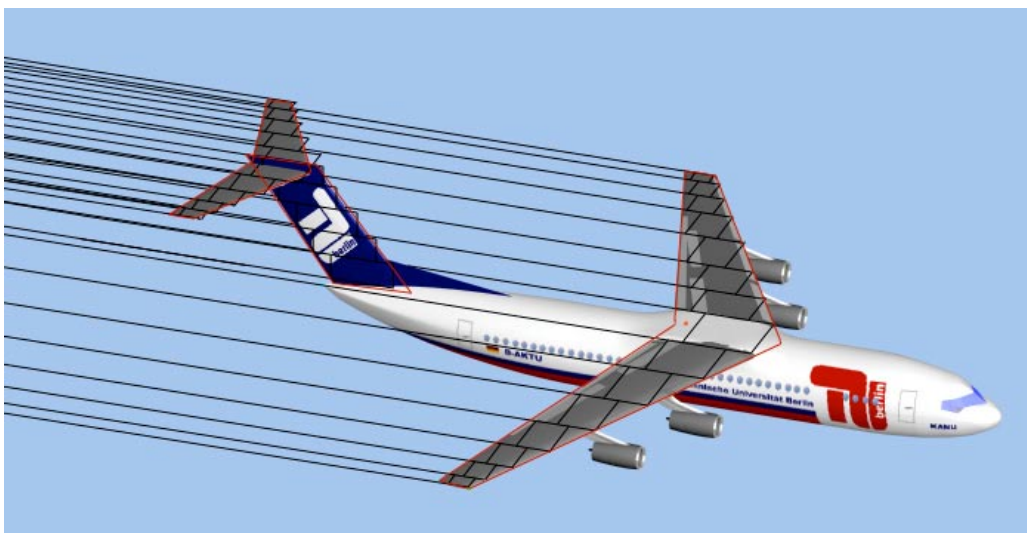main wing are automatically included.



*Fig. 15     Example of substitution of all aircraft lifting surfaces by wing elements*

As described for the SM, again restrictions of the local angle of attack were implemented. Changes to the wing plan-form (e.g. due to flap deflections) as well as modified aerodynamic properties of the lifting surfaces due to control surface deflections are taken into account. The method can be used in a real-time computing environment, provided that the matrices with influence factors (based on the geometric and aerodynamic properties of the surfaces) are pre-computed. Flap deflections change the wing's influence matrix, which is taken into account by an additional interpolation matrix. The extensive input files required for the simulator software, including matrices, have been pre-computed by TUB for all the aircraft considered in the flight simulations and have been distributed to the partners.

### 4.2.3   Initial validation of the SM and LSM method

Both AIMs were tested against available wake encounter wind tunnel test results from the WAVENC project (Ref. 29). In these tests a small model with extended flap and a straight wing had been traversed through the wake of a larger model. The wake velocity field and the forces and moments on the traversed model had been measured. Both models were successfully validated.

In a next step, both methods were applied to an Airbus A330-300 configuration under a variety of wake encounter conditions. The ten most influencing aircraft and wake parameters have been varied and the effects on the results of both AIMs have been studied. It was concluded that both methods are capable to describe the influence of the wake on the aircraft's aerodynamics. Yet some differences do exist between both methods. Generally the LSM results for side force and yawing moment are considerably smaller than those from the SM. In most cases, the SM predicts larger maximum, but smaller average induced rolling moment values than the LSM. Pitching moments calculated by SM are usually smaller than LSM results, reflecting the missing chord-wise lift-distribution in the SM. Such mutual comparison of results is useful but is not sufficient for a full validation of the methods, which should include a detailed validation of the model inputs (both methods need essential different input).

### 4.2.4   Flight Tests

Dedicated flight tests were made to validate the AIM's with real flight test data. Flight safety issues were investigated and a detailed flight test plan was prepared. DLR's experimental aircraft VFW614-ATTAS was used as the vortex generating aircraft. A smoke trail was deemed necessary to enable controlled entries into the wake. Unforeseen difficulties with the certification of the smoke generator caused a delay of nearly one year. These difficulties could ultimately be solved and figure 16b shows the smoke generator mounted on top of the ATTAS wing.

In separate flight tests two laboratory aircraft, the Do128 of TUBS and the Citation II of NLR, were flown through the wake vortices of ATTAS (see Fig. 16a). The Do128 was equipped with four precision flow direction probes mounted at different positions on the aircraft (see Fig. 16c) and the Citation aircraft had vane anemometers at its nose-boom (see Fig. 16d). Both aircraft carried precision accelerometers and rate gyros to measure the reaction of the aircraft. Differential GPS-position equipment was used to measure the relative positions between ATTAS and the follower aircraft.



Fig. 16a  The VFW614 ATTAS of DLR



Fig. 16b  The smoke generator on the ATTAS wing



Fig. 16c  Do128 of TUBS with 4 flow sensors



Fig. 16d  Citation II of NLR with vane nose boom

Flight tests with the Do128 were conducted in September 2001. Approximately 50 vortex encounters were flown at several distances ranging from 3.5km to 500m behind ATTAS. There were no difficulties for the pilots to see the smoke trace and fly the encounters. With horizontal encounters from left and right as well as encounters from above and below. The latter encounters caused the most violent reactions. One flight was devoted to observations and measurements of the flow field when disturbances generated by oscillating DLC-flaps of ATTAS were introduced. This type of flow field is characteristic of an aged vortex. Observations of the smoke trace indicated some influence of the moving flaps on the development of the wake vortex (see Fig. 17).

*Fig. 17    ATTAS seen from behind. Effect of oscillating flaps on smoke trace*

Additional flight tests with the Citation II aircraft were made in March 2002. In this test campaign the low temperatures at altitude caused the smoke oil to constipate the oil lines and the smoke generator frequently shut off automatically. Despite poor visibility of the smoke trail about 27 encounters were flown successfully. The smoke generator worked properly and reliable at temperatures above – 10 °C. Under good conditions the smoke trace reached out up to 3 NM behind ATTAS and could be observed without problems. At temperatures below – 10 °C the smoke oil became too thick, the smoke trail became thin and could be barely seen against the cloud layer. In most cases the response to the wake vortex was less violent than expected. The pilots had no difficulties to recover from the upsets.

### 4.2.5    Determination of vortex model parameters

The wake vortex flow field behind ATTAS was determined from the flow sensor data (see Fig. 18) by fitting the parameters of an analytical wake vortex model to the measured data.
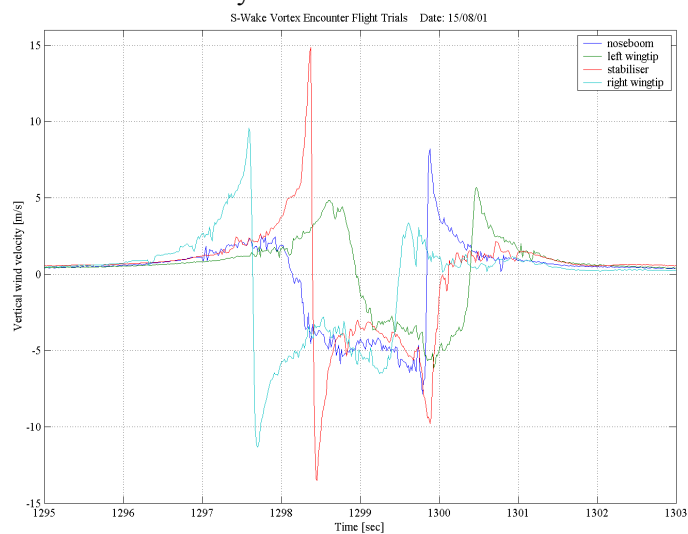


*Fig. 18    Vertical velocities measured with the four flow sensors of Do 128 of TUBS, during approximately horizontal intercept through the wake of ATTAS*

Two wake vortex profiles were considered: the Lamb-Oseen model and the Burnham-Hallock model. Parameter IDentification (PID) Techniques were used to achieve an optimal match between the modelled and the measured velocity field. The Burnham-Hallock vortex profile gave the best fit to the data. Initial data evaluations with the PID technique were made with available data from earlier DLR Falcon tests behind ATTAS (these were no specific wake encounter tests). Figure 19 summarises the results obtained from an evaluation of all encounters between 0.5 NM and 3 NM behind ATTAS. The matching parameters (circulation strength, core radius and lateral vortex separation distance) are plotted against the non-dimensional vortex life-time $t/t_0$. The resulting maximum tangential velocity (although not a matching parameter) is also shown. The vortex circulation strength decreases with increasing time (distance) while the core radius is slowly increasing. The vortex profile models used have a different shape of the velocity profile and their matching to the measured flow field leads to small differences, especially for the core radii. The flight path reconstruction method gives reliable results for the vortex parameters and is therefore a suitable method for measuring vortex characteristics at altitudes hitherto not reached by LIDAR.

### 4.2.6   Strip model validation against the flight tests

The basic aerodynamic models of the encountering aircraft (Do128 and Citation) were extended with the Strip Model. The identified wake vortex flow field is input to the models. The simulated response of the aircraft is compared with the measured response. PID techniques were only applied to match the initial conditions of the individual time sections used for evaluation.

### Do128 Results

A typical result of using the Strip Model is shown in figure 20. Two consecutive encounters are presented: one from right to left (left side of the plot) and one from left to right (right side of the plot. The wake intercept angles are between 12 and 20 degrees. From top to bottom lateral acceleration ($a_y$), vertical acceleration ($a_z$), roll rate (p), pitch rate (q), yaw rate (r), bank angle (Phi), pitch angle (Theta) and yaw angle (Psi) are shown against time. With the standard SM settings, the agreement between measurement and simulation is good. Risk assessments performed during piloted simulations in WP3 are being based on the interpretation of vertical acceleration, roll rate, pitch rate and bank angle. Despite some discrepancies in the fit (which could be attributed to the lack of a fuselage model and non-modelled propeller slipstream effects) the SM seems well suited for application in the flight simulators.
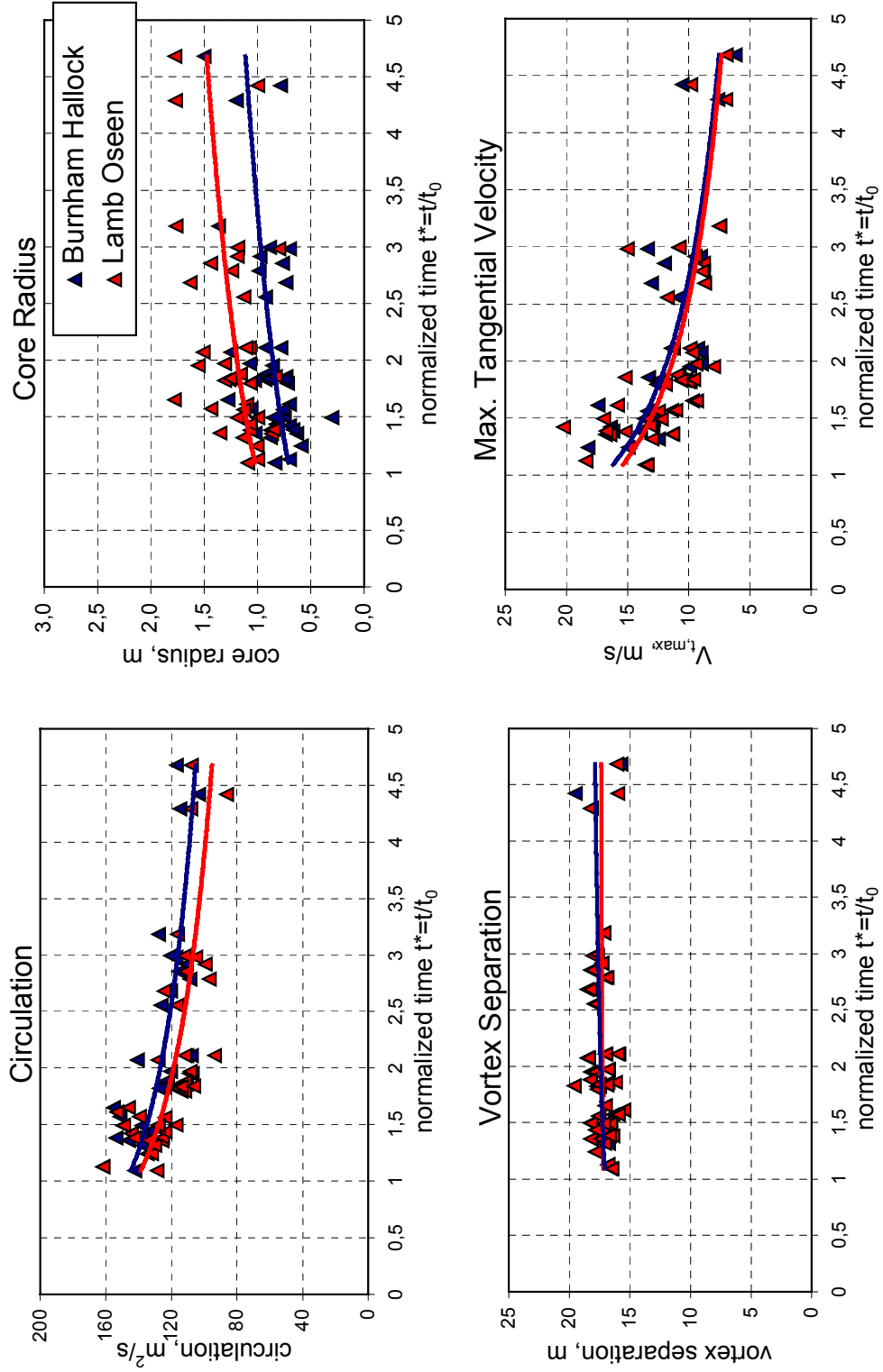
Fig. 19    Comparison of determined wake model parameters (Lamb-Oseen,Burnham-Hallock) , ATTAS/Do128 wake encounter flight tests

**Cessna Citation Results**

This time the flow was only measured with flow vane sensors mounted on the nose boom. Yet, it was still possible to categorise the wake flow field properties. Figure 21 compares two Citation encounters calculated with the SM against the corresponding flight test data. The wake intercept angles varied between 6° and 12° for these tests. The lateral response (lateral acceleration $a_y$ and yaw rate r) of the model is stronger than the measured response of the aircraft. The fit of the longitudinal parameters (vertical acceleration ($a_z$), pitch rate (q) and pitch angle (Theta)) is of better quality. Roll rate (p) and bank angle (Phi) show a sufficient good agreement with the measurements. The discrepancies are probably due to inaccuracies in the estimated vortex induced wind field, because the Citation had only one flow sensor at its nose-boom.

### 4.2.7   Discussion of SM and LSM validation results

The same procedures were repeated for the Lifting Surface Model (LSM). Some characteristic differences are observed. Figure 22 shows selected plots of both Do128 and Citation evaluation with SM and LSM. Typically simulation results fit the measured data slightly better when using the LSM.

In case of the Do128 the calculated roll rate (p), pitch rate (q) and vertical acceleration ($a_z$) turn out better using the SM model which is most likely due to pre-calibration of input data based on PID results. Differences between simulation results using either aerodynamic interaction model are small (20 %) compared to overall simulation quality which also depends on the measurement quality, the flight path reconstruction accuracy, the vortex model and base simulation model. Fitting qualities are slightly worse in case of the Citation data, which can be attributed to the less well defined vortex flow field.
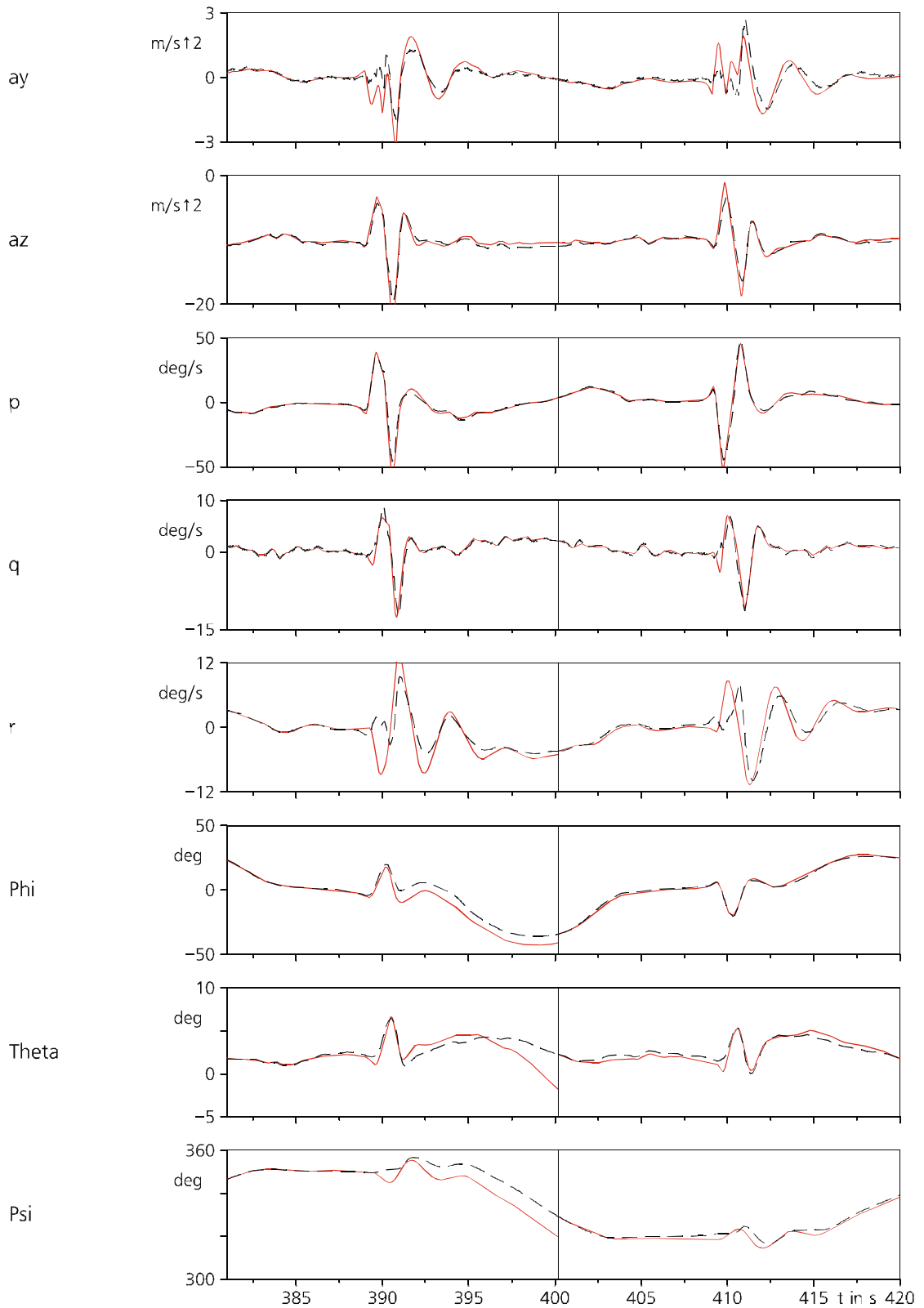
Fig. 20    *SM model validation for two encounters with Do128: 1st from right to left, 2nd from left to right. (distance 0.63 NM; (- - -) measured; (-----) SM model output*
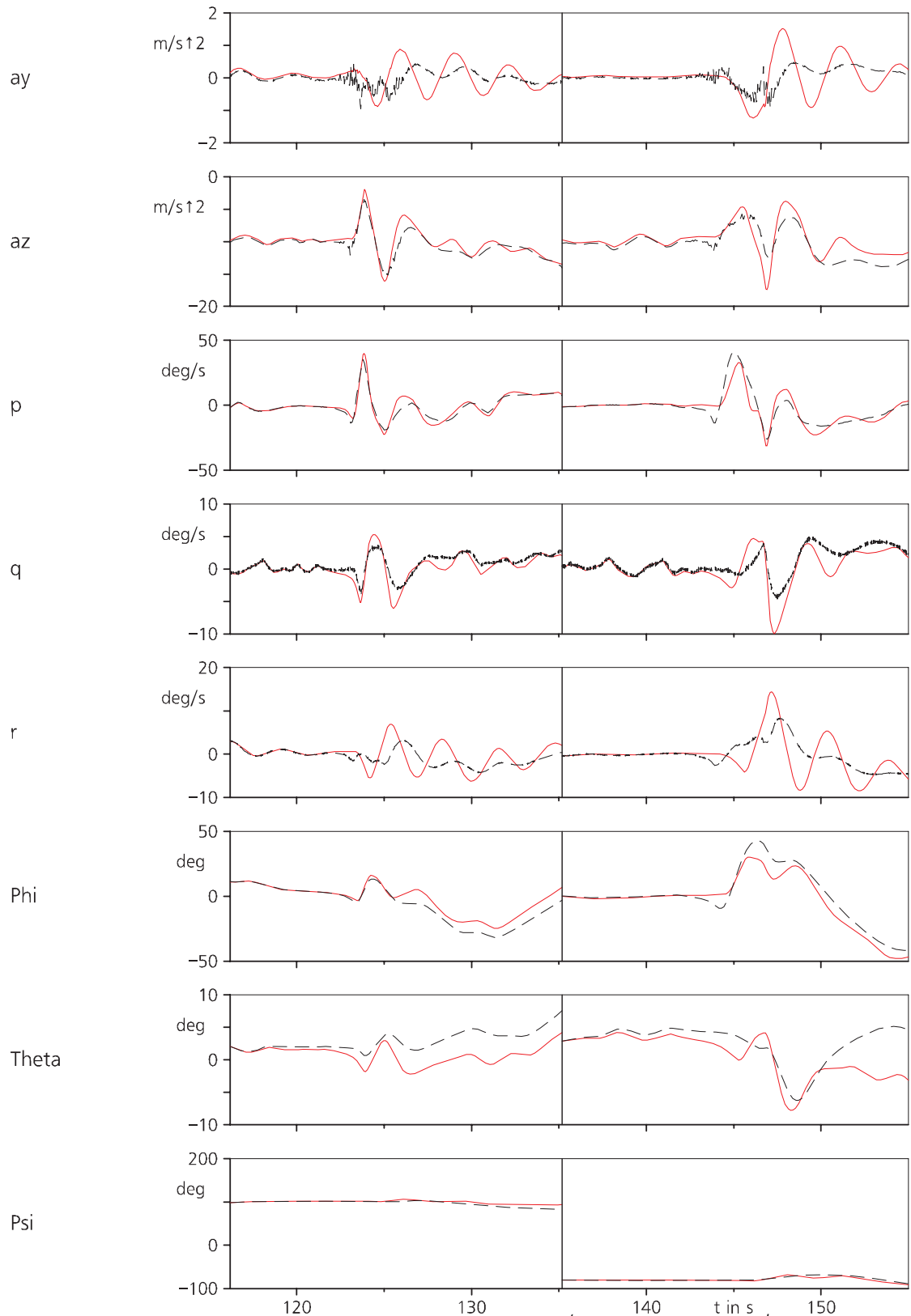
Fig. 21    *SM model validation from Citation encounters: 1st from right to left, 2nd from left to right (distance 0.52 NM; (- - -) measured; (------) model output)*
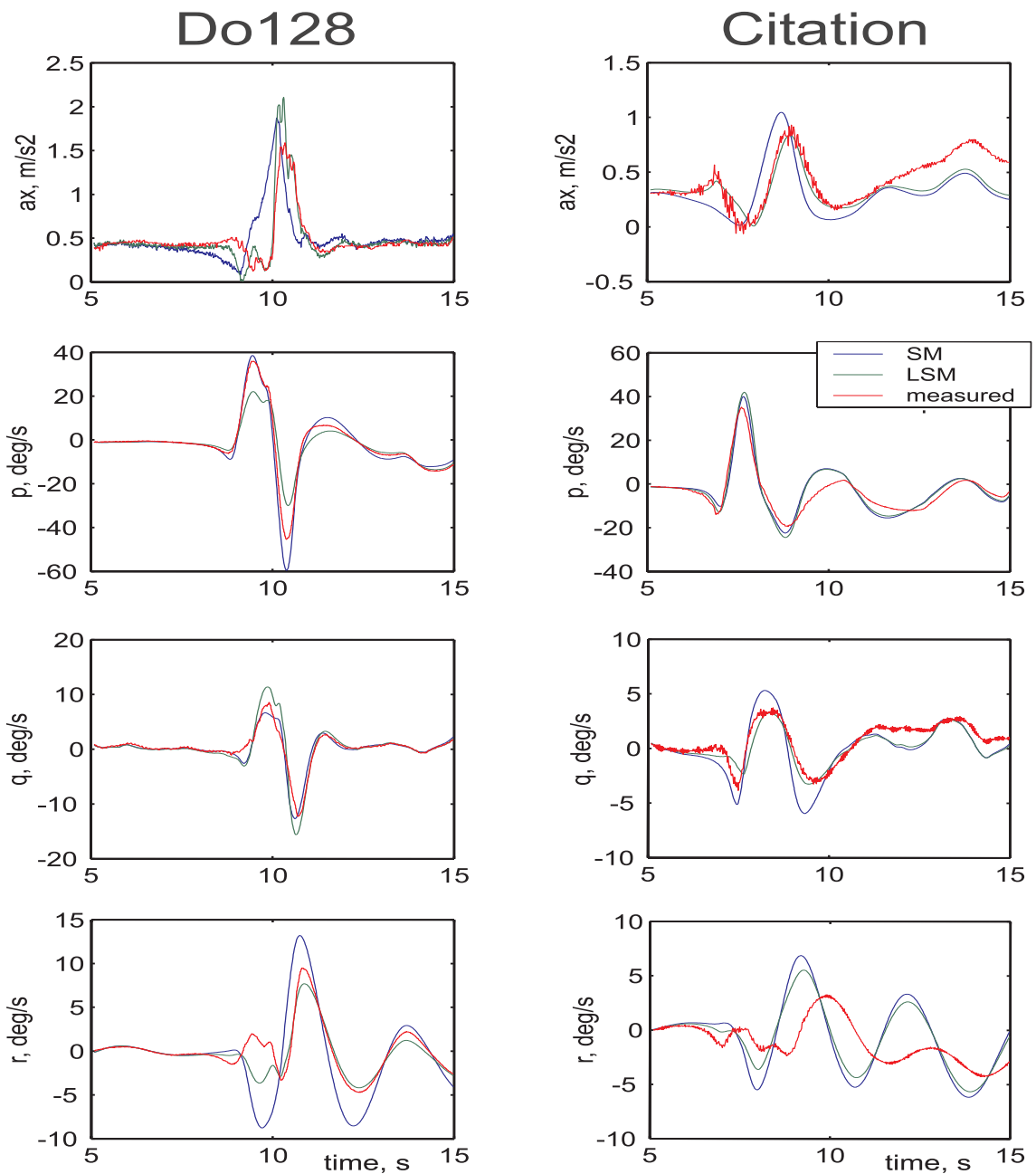
*Fig. 22    Typical example for the comparison of SM and LSM models.*
*Measurements (-------), Strip Model SM (------), Lifting Surface Model LSM (------)*

## 4.3 WP3: Flight simulations

For safety assessments the following questions have to be answered: when is a WVE safe, when is it a nuisance only and when is it hazardous? In case of such a complex and highly dynamic event the answer can only be found in flight or in piloted flight simulations. Since flight tests are very expensive (and limited for safety reasons), flight simulations are the best option for

systematic WVE studies and hazard criteria development. In the US, several WVE flight simulation investigations were performed (see e.g. the simulations performed by NASA, Ref. 50). In Europe, initial WVE flight simulation capabilities had been developed in the WAVENC project (see Ref. 31) but this could then not be sufficiently validated and only a few tests were performed.

The objectives of Work Package 3 (WP3) were:
- To provide flight simulation capabilities for WVE simulations for five aircraft types of different geometry, size and weight.
- To define metrics, which are well suited to describe the safety hazard, and to develop hazard criteria, which relate the dynamic response of the encountering aircraft and the severity of the encounter that is determined by the pilot ratings.
- To develop a reduced parametric flight mechanic model (including a pilot model) for probabilistic WVE simulations in WP4.
- To develop a numerically efficient, high-fidelity, offline simulation model for WVE investigations, in which worst-case conditions can be determined.
- To determine critical encounter conditions (worst-case conditions) for WVEs during landing approach.

The next subsections summarise the work performed and the results obtained in the four sub-tasks of WP3. A more extensive overview on the WP3 results is given in reference 3.

### 4.3.1    Preparation and validation of flight simulators

The S-Wake approach for WVE simulations was to supplement the simulators' basic flight mechanics model with an add-on WVE software package. The WVE software package consists of the Wake Vortex Model (WVM) from WP1 and the Aerodynamic Interaction Models (the SM and the LSM models, which can be used alternatively) from WP2. In order to prevent problems encountered in the previous WAVENC project, the WVM uses spatially fixed vortices. The WVE software module computes the delta aerodynamic forces and moments as a function of wake vortex-induced velocities. Figure 23 illustrates how it is linked to the flight simulator. In this way the basic aircraft simulation model needs no adaptations. The Wake Vortex Model supplies the input vortex flow field and the AIM calculates the vortex-induced forces and moments in each time step and adds them to the forces and moments computed with the basic aircraft simulation. A dedicated model calculates the impact of the vortex-induced velocities on the air data sensors whose values are displayed in the cockpit and are inputs to manual and automatic flight control systems. The WVE model was designed as an encapsulated software package. It could easily be adapted to each of the five aircraft models by changing input data files and to each of the four simulators by adapting a site-specific common block interface.
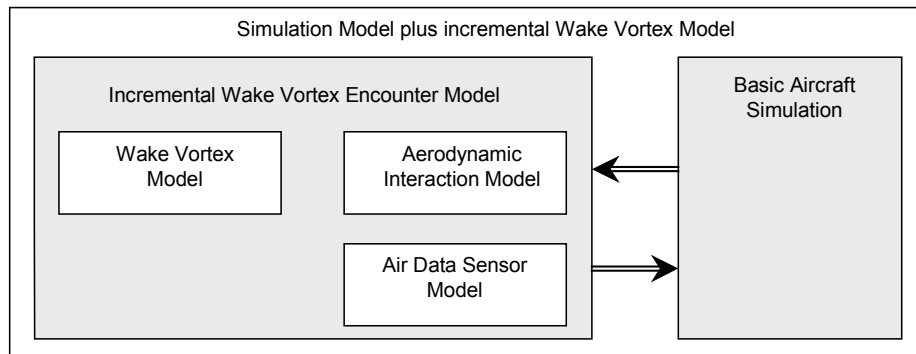
*Fig. 23  Basic aircraft simulation and the incremental wake vortex encounter model*

The six equations of motion are computed by the basic aircraft simulation model. The vortex-induced forces and moments are simply added. All S-Wake simulations were performed in this manner[1]. Additionally, various tools were developed to monitor the simulator tests and for visualisation and off-line analysis of test results. Playback visualisation was developed as well.

Flight simulation capabilities for WVE investigations were developed for five aircraft types of different geometry, size and weight (see figure 24). Four flight simulators were prepared: the Certified Training Simulator (CTS) of Simtec, the Research Flight Simulator (RFS) of NLR, the development flight simulator (THOR) of Airbus and the Certified Airline Training Simulator (CATS) of TU-Berlin (see Tab. 2). The flight simulator cockpits are shown in figure 25.

Table 2   Aircraft types and flight simulators used in S-Wake

| Aircraft | Flight Simulator | | MTOW [lb] | Characteristics | ICAO Weight Category |
|---|---|---|---|---|---|
| | type | motion platform | | | |
| Dornier Do 228 | CTS (JAR-B; Simtec) | Y | 13000 | Turboprop | Small |
| Cessna Citation | RFS (NLR) | Y | 13300 | Turbofan | |
| VFW614-ATD | THOR (Airbus) | N | 46000 | Jet engines on top of wing, fly-by-wire with side stick | Medium |
| Fokker 100 | RFS (NLR) | Y | 95000 | Jet engines at fuselage, mechanical control with control column | |
| Airbus 330-300 | CATS (FAA-D; TU-Berlin) | Y | 385000 | Jet engines at wing, fly-by-wire with side stick | Heavy |

---

[1] It was later found (see section 3.3.4) that this type of coupling has certain limitations.

Fig. 24    Aircraft types simulated in S-Wake flight simulators: Airbus A330 (heavy),
           VFW614-ATD, Fokker 100 (medium), Cessna Citation, Dornier 228 (small)



a) Airbus THOR flight simulator          b) NLR Research Flight Simulator (RFS)

c) A330 Training simulator at TU Berlin   d) Do228 training simulator of Simtec

Fig. 25    The cockpits of the flight simulators used in S-wake

### 4.3.2   Piloted simulations

An overview of the piloted simulation results is given in the final WP3 report (Ref. 3). A brief summary is given here. The WVEs were simulated with test pilots and airline pilots. A test plan was de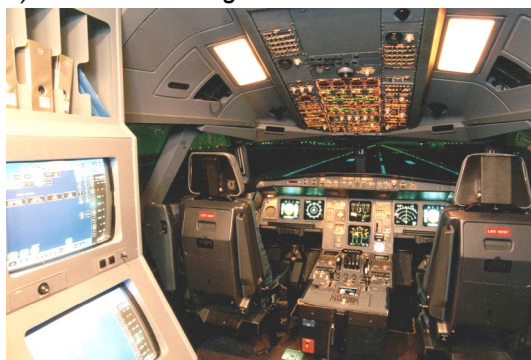fined to co-ordinate the tests of the different sites. The simulator sessions only considered ILS landing approaches, where the aircraft is nearly aligned with the vortex axis and the WVE mainly causes a roll response. Pilots were asked to follow the ILS track closely. The wake vortices were introduced, as described in section 4.1.2 and shown in figure 11. The geometric positioning and orientation of the vortices was varied according to the test plan. The strength of the vortices was selected empirically as to obtain a sufficient number of Go Around (GA) situations (about 50 %). The simulations therefore focussed to relatively strong WVEs. For the largest investigated aircraft (A330) extremely strong input vortices were required (see Tab. 3 for the employed range of input variables). The Winckelmans analytical vortex velocity model was used (Ref. 49). Either vortices of given strength, or about 20% decayed vortices were used (employing the decay model of Sarpkaya and a relatively low atmospheric turbulence level). The aircraft were flying near their minimum weight, as light aircraft are more vulnerable. WVE simulations were made both under VMC and IMC conditions and with platform motion on or off. Two different AIMs were used: strip method (SM) and lifting surface method (LSM).

Table 3   Vortex encounter parameter ranges for the different simulated aircraft

| Aircraft | Encounter height [ft] | Vortex characteristics | | | Remark |
|---|---|---|---|---|---|
| | | Core size $r_c$ [m] | span $b_v$ [m] | strength $\Gamma$ [m²/s] | |
| Do 228 | 88 - 605 | 3.02 1.27 | 47.5 20.0 | 180 - 800 | function of height above ground, Sarpkaya 4Nm |
| Citation | 50 - 500 | 4 | 62.83 | 50 – 300 | function of height above ground |
| VFW614 | 100 - 1000 | 4 | 62.83 | 330 | Constant, no decay |
| Fokker100 | 50 - 500 | 4 | 62.83 | 175 - 450 | function of height above ground |
| A330 | 89 - 607 | 3.02 | 47.5 | 450 - 1500 | function of height above ground, Sarpkaya 4Nm |

A few days before the tests, the pilots received briefing information, which was discussed with them prior to the simulator session. During a simulator session a pilot flew typically 40 ILS approaches. In total 48 sessions were made, involving 1623 simulated encounters (see Tab. 4).

Each case began with the aircraft stabilised on glide slope and on localiser, usually 1000 ft or more above ground. The pilot was requested to follow the ILS glide path as accurate as possible and following normal flight procedures. If, during the course of the approach, a GA became necessary, it had to be performed immediately. It was the pilot's decision to initiate the GA

Table 4   Overview on simulator sessions

| Aircraft | No. of pilots | Simulator sessions | No. of encounters |
|---|---|---|---|
| A330 | 12 | 14 | 497 |
| VFW614-ATD | 14 | 14 | 502 |
| F100 | 4 | 4 | 163 |
| Citation II | 4 | 4 | 153 |
| Do 228 | 6 | 12 | 308 |
| Total | 40 | 48 | 1623 |

when he believed that a safe landing was compromised. After each test run the pilot had to fill in two questionnaires:

1. The O*verall Hazard Rating* (OHR) questionnaire with a rating scale between 1 and 6, where high ratings mean higher hazard (used by Airbus, TUB and NLR).

2.a The *contribution to hazard* questionnaire, with a rating scale between 1 and 10 for various flight parameters (bank angle, roll rate, etc.) (used by NLR and TUB).

2.b The *importance to hazard* questionnaire, with a rating scale between 0 and 3 for various flight parameters (bank angle, roll rate, etc.) (used by Airbus).

The duration of the wake influence on the encountering aircraft and the sequence of events depend quite critically on the encounter geometry, especially on the wake intercept angles. Depending on these, four encounter types with different aircraft reactions were observed:

- roll motions are dominant in almost all nearly parallel encounters;
- vertical motions occur when encountering the wake from above or below with a small offset from the vertical wake symmetry plane;
- yawing motions are obtained if the aircraft passes one of the vortices closely below or above the vortex core;
- combination of motions in all three axes: roll, vertical, and yaw; either simultaneously or sequentially.

The encounter types could be explained by relating the aircraft trajectories , which were recorded during the simulations, to the contour plots for vertical accelerations, roll and yaw accelerations as computed with the WVE software package. Figure 26 shows as an example contour lines for aircraft accelerations for the VFW614 aircraft in the wake of a VLTA (for a wake intercept angle that is equal to zero). Contour lines are depicted for $10°/s^2$ of roll acceleration, for $2°/s^2$ of yaw acceleration, and for 0.15g of vertical acceleration (boundary for passenger comfort). Inside the contours the accelerations are larger and outside they are smaller.

It is interesting to note that the roll contour lines are not symmetrical, due to the influence of the vertical tail plane.

Figure 27a shows aircraft traces of nine simulator flights, which were flown by different pilots. The time span from start to end of the trajectory (top to bottom) is about 60s. The aircraft approached the vortex slowly and they were exposed to the vortex influence for a relatively long time. The induced yawing moment (see Fig. 26) caused a lateral drift to the right. Initially, pilots hardly recognised that a WVE was ahead: localiser deviations were still small. It is visible that three pilots (starting points on the left side and in the centre) had compensated localiser deviation, which resulted in two cases in a trajectory far to the left of the vortex core. With slow wake intercepts, the resulting encounter trajectories are very sensitive to variations in the location of the starting point and the initial aircraft state. In only two cases the vortex core has been penetrated.

Figure 27b shows eight aircraft traces where the aircraft entered with a relatively large intercept angle from the left. The time from the left to the right end of the trajectory is now only about 6s. In this case all trajectories remain close together and the vortex centre was passed within less than 4m vertical distance.



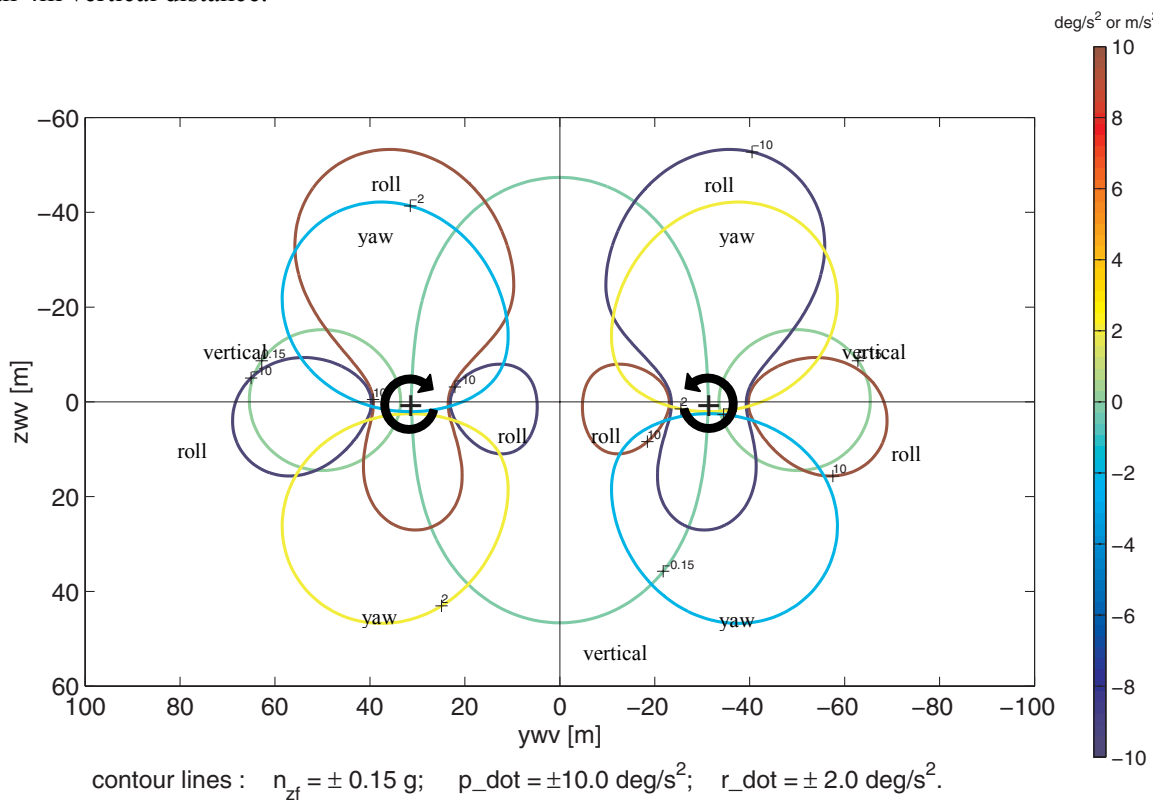contour lines :  $n_{zf} = \pm 0.15$ g;   p_dot $= \pm 10.0$ deg/s$^2$;   r_dot $= \pm 2.0$ deg/s$^2$.

Fig. 26   Areas with dominating roll, yaw, and vertical accelerations (VFW614-ATD behind VLTA, $\Gamma_0 = 679$ m$^2$/s, separation 5 Nm, Winckelmans, Sarpkaya, app. 80 % decay)

a)  slow intercept from above
    (vertical intercept is 2 deg.)

b)  quick intercept from aside
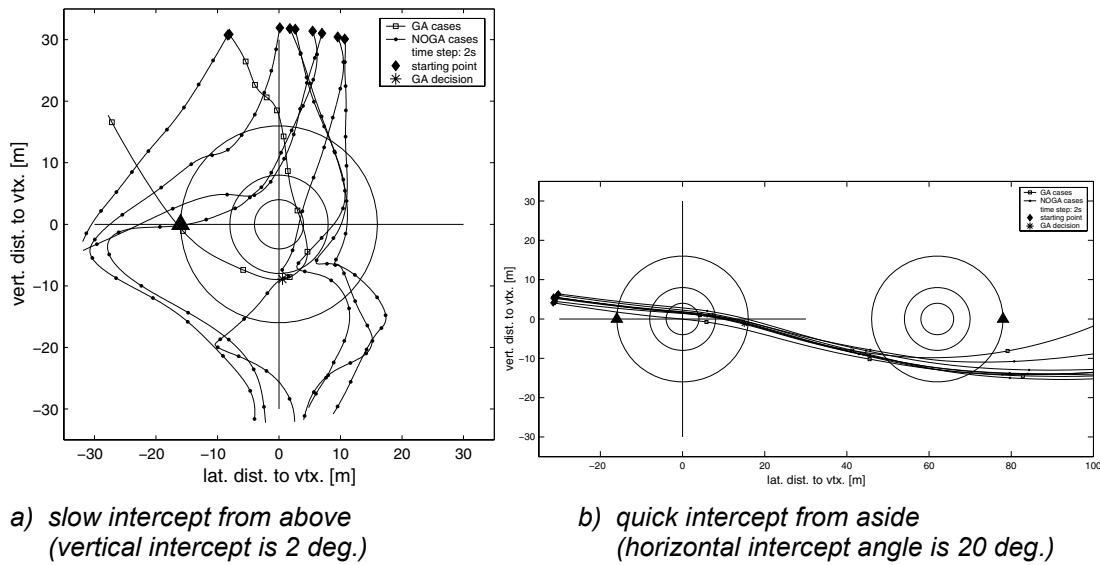    (horizontal intercept angle is 20 deg.)

Fig. 27 Differences in aircraft trajectories during slow and rapid wake intercepts

**Hazard metrics** are the relevant aircraft parameters for the pilot's assessment of the safety hazard during a WVE. They are a prerequisite for the development of hazard criteria that assess and quantify the encounter severity. When pilots assess the encounter severity, their ratings are based on aircraft response and the required control inputs. After an encounter, pilots might conclude that the disturbance was caused by a WVE, but they do not know anything about the vortex strength and how the vortex was penetrated. Consequently, hazard metrics have to be found, that are based on the aircraft reactions (bank angle, roll rate, etc.) or the pilot's corrective actions (side stick input, rudder pedal input, etc.). Candidate hazard metrics might be anything from a single parameter to combined expressions of two or multiple quantities. A hazard metric may be a function of the altitude, the control technique, or the visibility (IMC / VMC). For instance, a bank angle excursion might be dangerous close to ground whereas it might only a nuisance at higher altitudes. Each partner determined hazard metrics independently by analysing his simulator results, using slightly different methods. Nevertheless similar parameters were identified as suited for the hazard metrics:

- AIRBUS (VFW614): bank angle, roll rate, glide slope deviation, and roll control ratio; all as a function of height above ground,
- TUB: for A330, sink rate, bank angle, pitch angle, ILS deviation and roll rate; and for Do228, bank angle, roll rate and pitch angle, all as a function of height above ground.
- NLR (F100 and Citation): bank angle, roll rate, glide slope deviation, and heading change; all as a function of height above ground.

Each partner derived different metric expressions based on those parameters.

**Hazard criteria** quantify the encounter severity and relate the hazard that is perceived by the pilot to objective measurable data. Hazard criteria consist of boundaries between acceptable and unacceptable WVE conditions. These boundaries correlate objective hazard metrics with subjective hazard ratings. Each partner determined and validated the hazard criteria independently, by analysing his simulator results and using slightly different methods.

One of the criteria derived by Airbus, relates pilot ratings to roll control ratio and glide slope deviation. It is called the RG criterion and is shown in figure 28 for VFW614-ATD. The grey-shaded region in the middle of the diagram represents the region for which NO Go Around (NOGAs) will occur. The open circles correspond to NOGA cases and the closed circles to Go around (GA) cases. The developed criterion predicts more than 90% of the GA cases. The simulations showed the important influence of flight altitude on pilots perception of safety.
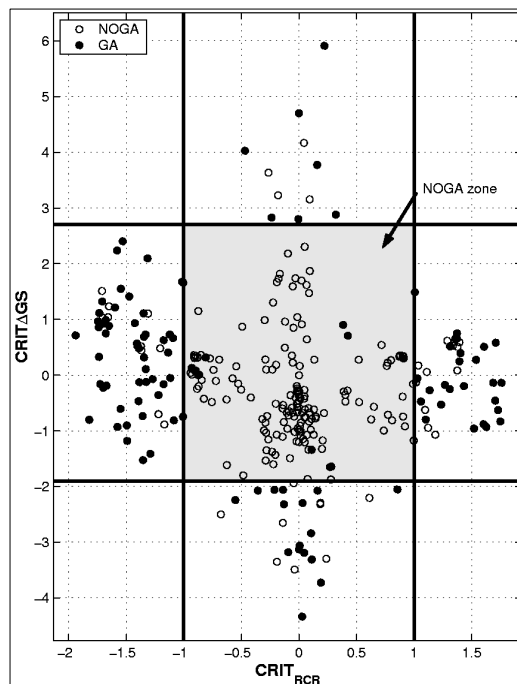


Fig. 28    RG criterion with respect to the GA decision for
VFW614-ATD in VMC conditions

### 4.3.3    Simplified encounter models

Simplified WVE models were developed for different applications. These are briefly described here.

**High-fidelity, offline simulation model**

A high-fidelity, offline simulation model was developed that was applied to worst-case encounter condition search in Task 3.4. This model includes the flight simulator aircraft

simulation model, the WVE model and a pilot model. The pilot model combines a high dynamics pilot model for aircraft recovery in a WVE, a low dynamics pilot model for ILS tracking and a go around model. The GA model does not perform a GA, but stops the simulation when a normal continuation of the approach after a WVE is not feasible. Decision on GA depends on height depends on the following criteria: height, bank angle, the sink rate, the glide slope deviation and for the localizer deviation. DLR and ONERA developed the WVE pilot model and Airbus developed the ILS tracking and the GA pilot model.

**Reduced aircraft / pilot model (RAPM)**
This model was developed for the large number of Monte-Carlo type wake encounter simulations that had to be made in WP4. The RAPM consists of the WVE model (WVM and SM only), a simplified five degrees of freedom (DOF) model developed by ONERA and the WVE pilot model for bank angle control (same as the one used in the high-fidelity model).

**Probabilistic WVE model**
Two probabilistic WVE models were developed. The first one is based on the RAPM described above. The second one is a simpler model based on a 1 DOF model for roll (Tatnall; Ref. 52) and is called the Extended Roll Control Ratio (ERCR) model ('extended' here refers to the even more simple Roll Control Ratio (RCR) model that was used in the initial probabilistic simulations). Their integration into a probabilistic environment requires additional assumptions. The most important of these are that the encounter duration has to be limited and that it is implicitly assumed that the encounters are roll-dominated. One difficulty that could not be completely solved (especially for the RAPM), is how to combine the model with the principle of stochastic variation of model input parameters. An encounter severity classification scheme has been developed to classify the encounter as weak, moderate, severe or extreme. It is based on maximum bank angle and the encounter altitude. Both the RAPM and ERCR model have been used in the probabilistic simulations at several x positions along the glide path. At each of these positions both the wake generating and following aircraft positions were stochastically positioned around the 3 degrees glide path. Figure 29 shows computed max bank angle versus height for the ERCR model, for a medium class aircraft behind a heavy one. The dots represent the individual encounters. The curves (green = weak, yellow = medium, red = severe) indicate the boundaries of the different wake encounter severity classes.
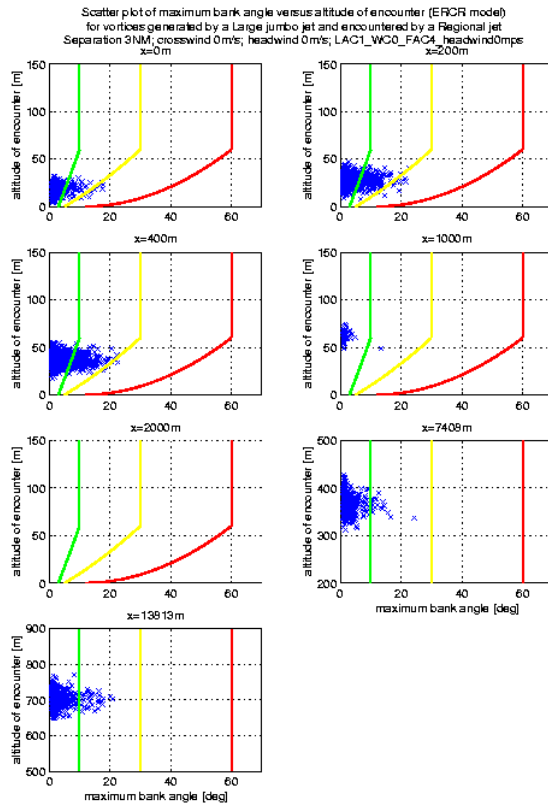
*Fig. 29    Max bank angle versus altitude of Monte Carlo simulations
using the ERCR model at different longitudinal positions
from the runway threshold*

**Analytical WVE studies**

Analytical wake vortex encounter studies were performed by IST. Wake vortex encounter
response was investigated for 5 different aircraft (of different weight category). The advantage
of using an analytical approach is that it shows the main features in a more direct way than in
(piloted) simulations. The approach closely follows the work of Tatnall (Ref. 52). In a next
study by IST the WVE results were combined with theoretical predictions of wake decay and
this resulted in an analytical expression for the safe separation distance. The formula was
applied to all combinations of the 5 aircraft (25 cases, reported in Ref. 17). In a final study IST
considered also the effect of roll damping and active roll-control input.

**4.3.4    Critical encounter conditions and improvement of flight simulator model**

In Task 3.4 two subtasks were performed.

**Worst case scenario search**

First the worst-case search method was developed, based on the high-fidelity, offline simulation model and the optimisation tool MOPS that is developed by DLR, Institute of Robotics and Mechatronics. Then, critical encounter conditions (worst-case scenarios) were determined for the VFW-614 aircraft. Plausible results are obtained. Knowledge of worst-case conditions permits to perform future WVE simulator tests more efficiently. The test program can be confined to critical scenarios so that simulation time and costs are saved. The generalisation of these results for other follower aircraft and other flight phases has to be verified and should be subject to further studies.

**Improvement of the WVE software integration into the flight simulators**

It was discovered at a late stage in the project that the coupling of the add-on WVE model strategy (by delta forces and moments) has certain limitations, because it ignores the effect of the wake vortex induced flow-field on the basic aerodynamic properties of the aircraft. A solution to this problem has been found. From the delta forces and moments equivalent transverse and rotational wind components are calculated which are added in the velocity equations of the basic simulation and which result then in nearly identical vortex induced forces and moments. It was implemented at the Airbus flight simulator and in the high-fidelity, offline model. Though the effects of the deficiency are visible, it is assumed that their impact on the developed hazard criteria is negligible.

**4.4 WP4: Probabilistic safety assessment**

A probabilistic WAke Vortex Induced Risk assessment model (WAVIR method of NLR) has been developed to assess safe separation distances. It is based on a stochastic framework that incorporates sub models for wake vortex evolution, a flight mechanics model for wake encounter and pilot response and a flight path evolution model. The severity of encounters is related to possible risk event classes (i.e. incidents/accidents, see Refs. 18-19). Based on historical WV incident data, Target Levels of Safety (TLS) have been defined for each of the possible risk event classes. As shown in figure 30, this then allows the assessment of safe separation distances that satisfy the TLS for each of the risk event classes.
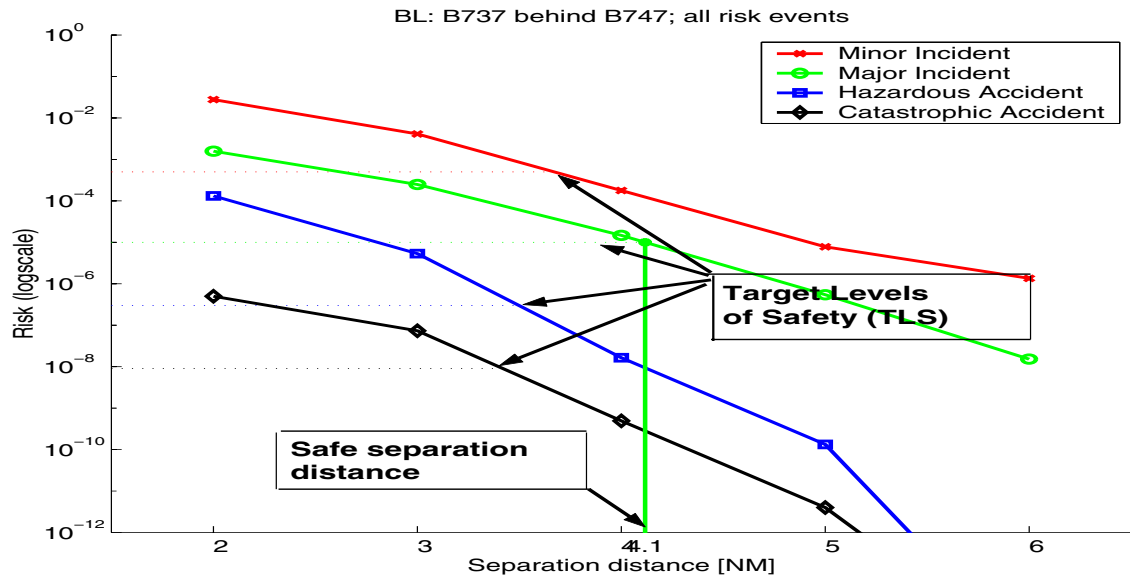
*Fig. 30    Risk management procedure to derive safe and appropriate separation minima*

The methodology was applied to study the safety related to single runway approaches. An extensive risk assessment – with different aircraft landing behind a Heavy aircraft and a Medium aircraft – was carried out. The impact of weather and wind conditions (e.g. turbulence, stratification, crosswinds and headwinds and tailwinds) and procedural aspects (e.g. glide slope intercept altitudes, navigation performance, glide path angles, steep descent approaches) on incident/accident risk was evaluated.

Along with the probabilistic safety assessments, new wake alleviation concepts (including HALS/DTOP, AVOSS, WVWS) were evaluated with respect to potential airport capacity improvements.

The work was managed by NLR and involves contributions from NATS, DFS, ONERA and DLR.

### 4.4.1   Objectives
The overall objective was to extend a probabilistic safety assessment model for wake vortex induced risk (WAVIR) and to apply this model to evaluate the risk of single runway approach operations under current practice flight regulations. The work also included the development of a risk management framework, which is based on a Target Level of Safety approach.
The specific objectives of WP4, probabilistic safety assessment were:

- To assess wake vortex safety in relation to the separation distance between aircraft landing on a single runway, and under different weather and operational conditions.

- To develop a risk management framework, which consists of appropriate risk metrics and associated risk requirements for wake vortex induced risk.

- To extend an existing probabilistic model for wake vortex induced risk (WAVIR), with updated deterministic models for wake vortex evolution and decay (from WP1), for wake encounter flight mechanics (including a model for pilot response).

- To improve an existing flight path evolution model, which describes the nominal flight paths of aircraft and probability distributions for the deviations from these nominal paths.

- To carry out a sensitivity analysis, so as to provide insight into how sensitive the accident risk assessment results are to the different parameters.

- To identify the key safety bottlenecks (safety criticalities) that have the largest contribution to the overall wake vortex induced risk.

- To allow for a sufficient level of validation, through evaluation of the safety assessment results, comparison with the outcomes of the S-Wake WP5 Heathrow DataBase (HDB) collection and analysis of "current practice" single runway approaches.

- To define and evaluate promising new concepts for reduced separation under certain operational or weather and wind conditions.

- To feedback operational recommendations to ATM designers of single runway approach procedures, so as to support the design of new and advanced risk reducing ATM procedures.

### 4.4.2   The probabilistic safety assessment model

Prior to the actual safety assessment a qualitative safety assessment was made and some aspects of wake formation and decay and the consequences for following aircraft were investigated. An initial quantitative safety assessment was then made with the existing WAVIR method, which consisted of probabilistic sub-models for wake vortex evolution, wake encounter and flight path evolution. In this initial simulation the risk severity classes were based on the wake vortex induced rolling moment (a simple roll-control ratio criterion was used) and wake encounter height. During the project these initial models were upgraded or replaced. A new probabilistic wake evolution model was developed (see section 4.1). A new flight path evolution model was developed and validated against actual flight track data from Schiphol Airport. The simple wake encounter model was replaced by a 1-DOF (Degree Of Freedom) roll model (the Extended Roll Control Ratio (ERCR) model of Tatnall (Ref. 52), that computes the maximum bank angle. A more advanced model based on a 5-DOF model of ONERA, supplemented with a pilot reaction model of DLR (the Reduced Aircraft Pilot Model (RAPM), see section 4.3) was also implemented. A new safety assessment was then made with the updated method. In this case risk severity classes were based on maximum bank angle versus height. Figure 31 shows the relations and dependencies between the different models.
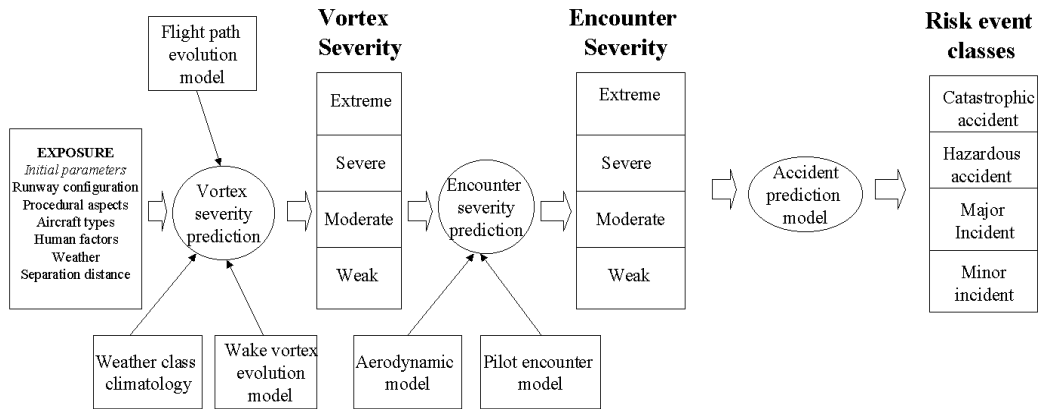
*Fig. 31    Overview of modelling relations and dependencies*

The models were integrated in the WAVIR workflow. The WAVIR workflow is itself integrated in NLR's information system for safety and risk analysis (ISTaR) and is operated through its SPINEware based user-interface (see Fig. 32).

### 4.4.3    Initial quantitative safety assessment

The existing WAVIR method (Refs. 18-19) of NLR was used for an initial quantitative safety assessment for paired approaches to single runways. For a B737 behind a B747-400 extensive sensitivity studies were made to analyse the effect of weather conditions, navigation accuracy, and modified flight path slope and ILS intercept height. Based on the prescribed target levels of safety, safe separation distances were computed. Figure 33 shows instantaneous risk results of the base-line simulation (with average turbulence and atmospheric stratification conditions and no crosswind) for each of the four defined risk events (catastrophic accident, hazardous accident, major incident and minor incident) at five different separation distances. Conditions near the runway threshold appear to define the main safety bottle-neck.

Figure 34 summarises the safe separation distances from the sensitivity study. The current ICAO separation of 5 NM for a B737 behind a B747-400 is assessed as sufficiently safe, except possibly under low turbulence conditions. For the scenarios investigated, weather conditions have the largest effect on the minimum required separation distance. Reduced separations might be considered for strong atmospheric turbulence, for crosswind conditions and with strong headwinds.
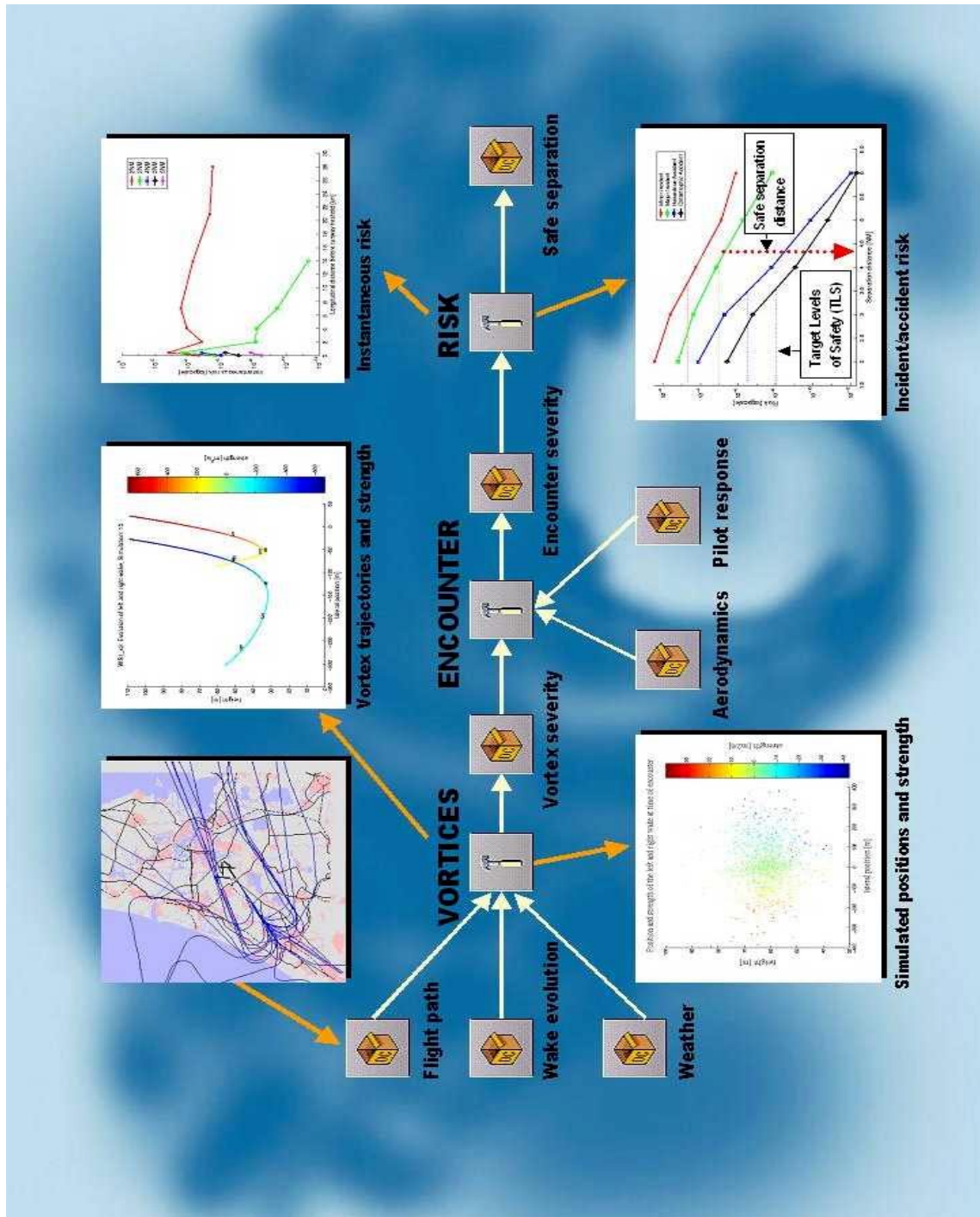
*Fig. 32    WAke Vortex Induced Risk (WAVIR) assessment Tool*

a)  minor incident risk

b)  major incident risk



c)  hazardous accident risk

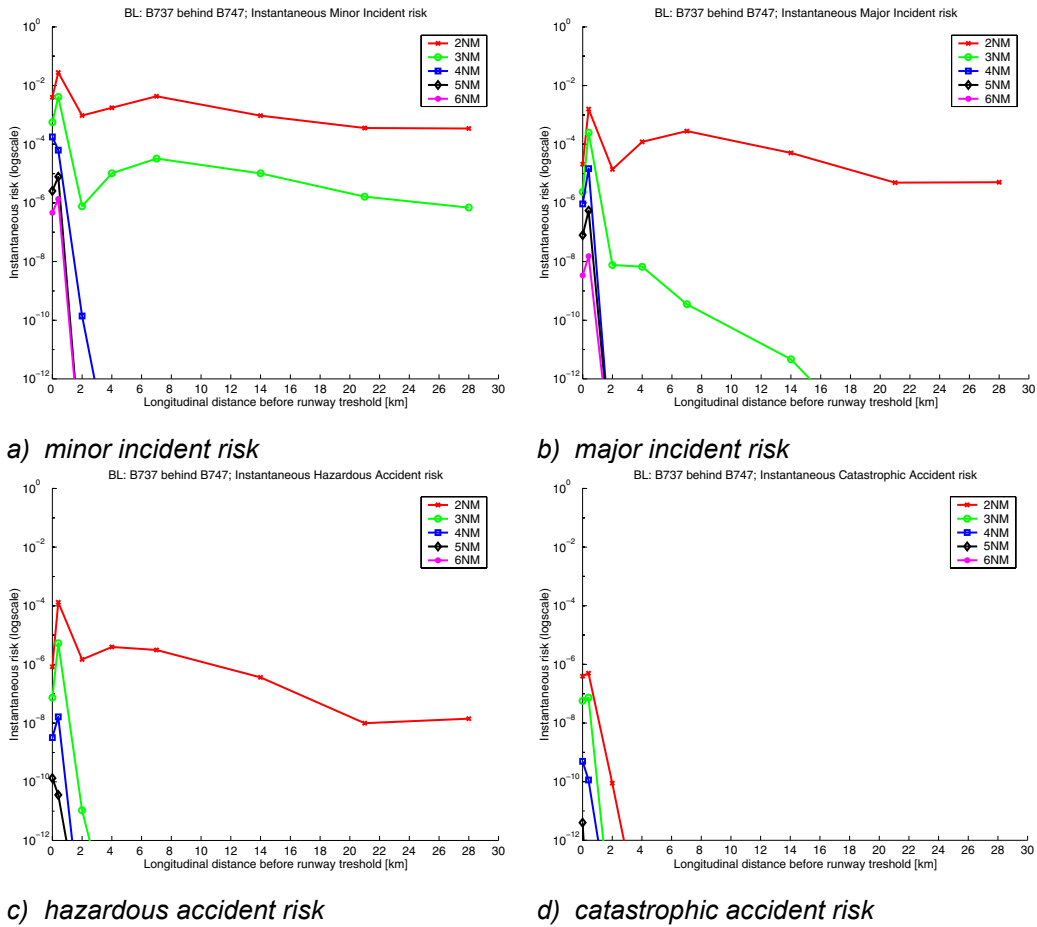d)  catastrophic accident risk

Fig. 33  Instantaneous risks along the glide slope for different separation distances (baseline scenario for B737-400 behind B747-400, initial safety assessment with WAVIR)
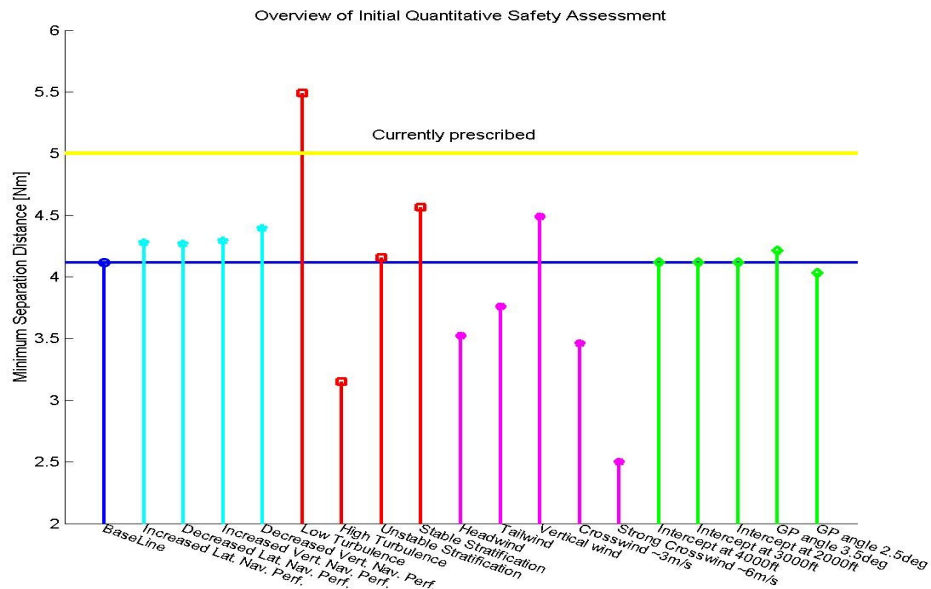


Fig. 34  Derived Separation Minima under different operational and weather conditions (sensitivity study with initial WAVIR safety assessment method)

### 4.4.4 Quantitative safety assessment with the extended method

The probabilistic WVE models were upgraded with the outcomes of WP1, WP2 and WP3. An additional set of simulations was performed and evaluated. Two wake generating aircraft: a "Large Jumbo Jet" (like Boeing B747) and a Medium Jet aircraft (like Airbus A320) were considered. Four different follower aircraft were considered: the mentioned Large Jumbo Jet and Medium Jet, plus a Regional Jet (34,000 kg and wingspan of 34 m) and a Light Turbo Prop (4000 kg and a wingspan of 14 m). In the simulations the atmospheric turbulence and stability parameters for the Sarpkaya wake vortex decay model (viz. the Eddy Dissipation Rate and Brunt Väissälä frequency) were fitted to the Heathrow situation. The Wake Vortex Behaviour Class and airport climatology study in WP1 showed that crosswind conditions occur frequently at most major European airports and that these conditions can be forecasted rather well (Ref. 1). The initial safety assessment showed that reduced separations are possible in crosswind conditions. In the extended safety assessment study, attention was therefore focussed on the effect of discrete headwind and crosswind conditions (see Fig. 35). Figure 36 shows, as an example, the computed safe separation distances for the four aircraft types behind the Large Jumbo Jet and the different wind conditions. The situation with a small crosswind of 1 m/s appears most unfavourable. Small crosswind conditions make the upwind vortex in ground effect stay approximately at its lateral position. Crosswind and strong headwind conditions require less separation distance. Some of the wind scenario's imply separations above 6.5 Nm.
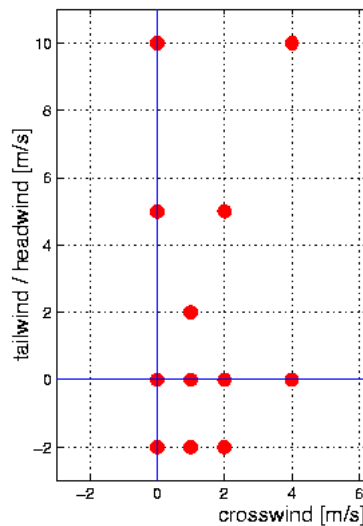


*Fig. 35  Investigated headwind and crosswind scenarios*

Figure 37 shows that for sufficient crosswind or strong headwind conditions the minimum safe separation distances might be reduced to minimum radar separation (for all aircraft pairs investigated).

*a) Large Jumbo Jet behind Large Jumbo Jet b) Medium Jet behind Large Jumbo Jet*

*c) Regional Jet behind Large Jumbo Jet    d) Light Turbo Prop behind Large Jumbo*
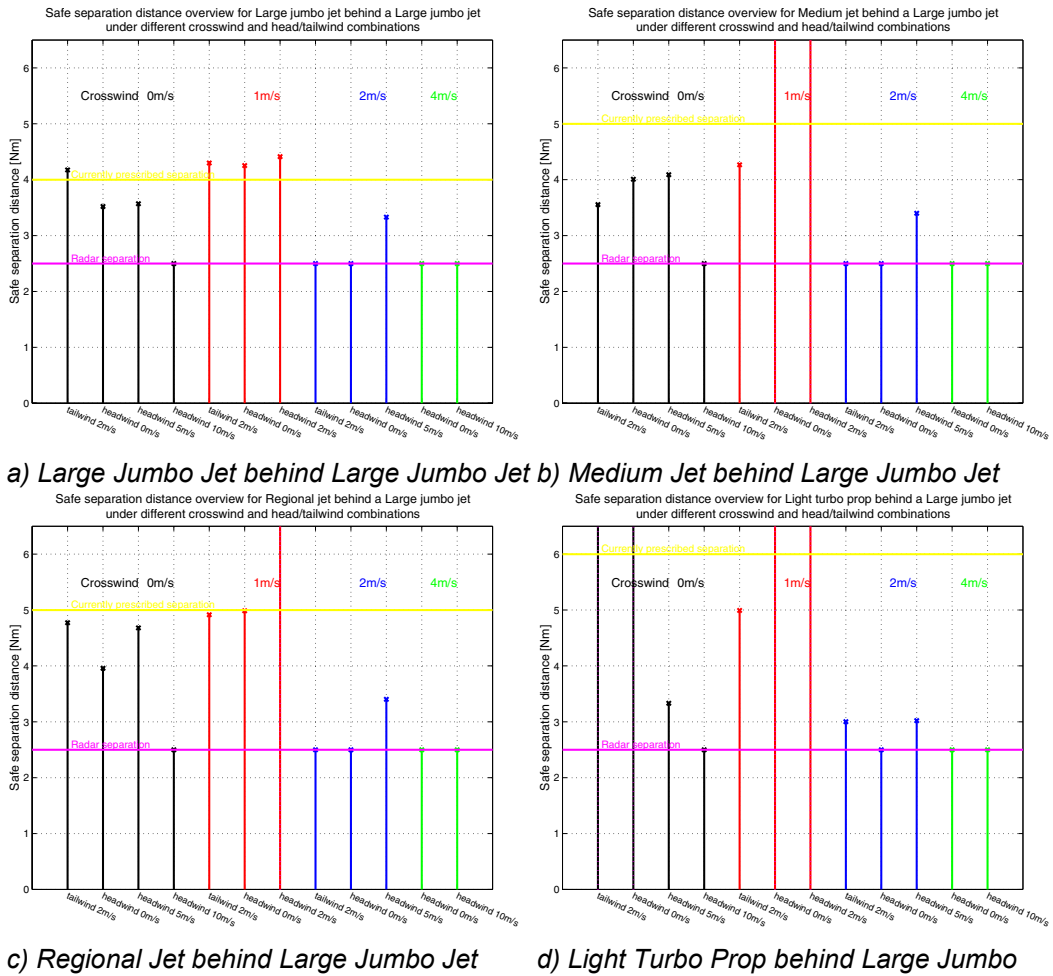
*Fig. 36  Safe separation distances depending on wind conditions (safety assessment with the extended WAVIR method)*

a) crosswind of 2 m/s, headwind 0 m/s    b) headwind of 10 m/s, crosswind 0 m/s
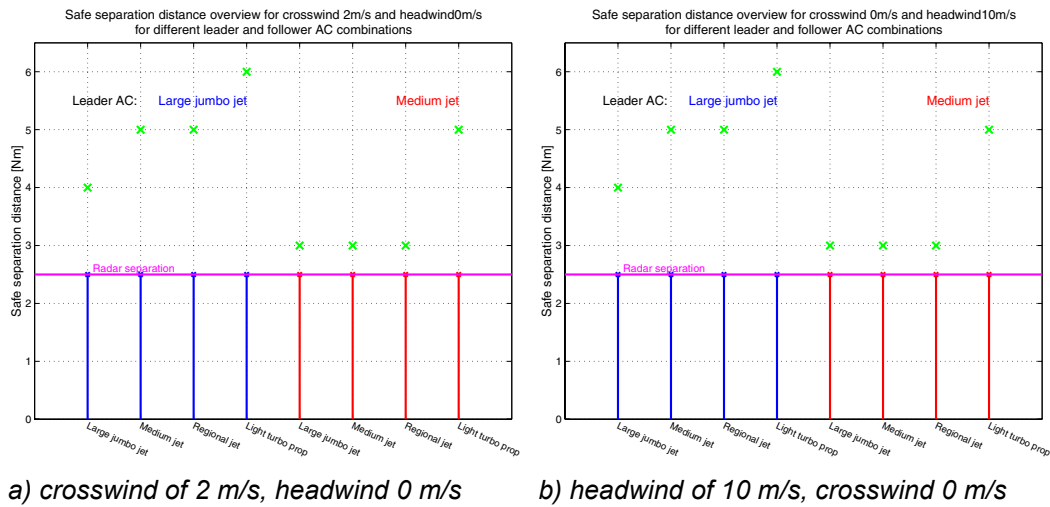
Fig. 37  *Safe separation distances for four different follower aircraft behind Large Jumbo jet and Medium Jet. Favourable wind conditions (extended safety assessment with WAVIR; green crosses denote minimum separation distances according to ICAO)*

### 4.4.5    New concepts and procedures for capacity improvements

A review of new concepts and procedures for reduced wake vortex separation minima was performed by ONERA, DLR and NLR. This study involved a brief analysis of the potential benefits of the Wake Vortex Behaviour Class (WVBC) concept, the Wake Vortex Warning System (WVWS) concept, the Aircraft VOrtex Spacing System (AVOSS), the HALS/DTOP concept, the time-based separation strategy recently proposed by EUROCONTROL and on-board WV detection strategy of I-Wake. Also, a brief investigation of wake vortex alleviation measures, including passive and active measures was made. A runway capacity model was developed by ONERA and was applied to the closely parallel runway situation of Frankfurt airport. Influence of traffic mix was investigated for the standard ICAO case, the HALS/DTOP concept, HALS/DTOP with reduced (2.5 NM) radar separation and for the WVWS. Calculations showed significant (up to 20 %) potential gains in airport capacity, but further work is needed to validate this work.

### 4.5 WP5: Safety assessment from FDR data collection

This section summarises the work that has been performed and the technical achievements obtained within S-Wake WP 5 "Safety Assessment from Flight Data Recording collection". An empirical safety assessment was performed through the statistical analysis of actual wake vortex incident data. This safety assessment was intended to be a validation of the tools developed in WP's 1-4.

The WP Manager, NATS, has been collecting voluntary pilot reports since 1972 (Refs. 32-33). However, it is not known how close the reported rate of encounters is to the actual rate of encounters. In addition, only limited information is available on the severity of the reported encounters. As a result, these data are not reliable enough for a comprehensive assessment of the current wake vortex safety levels around major airports.

Woodfield (Ref. 34) showed that data from Flight Data Recordings (FDRs) might be used for the automatic detection of WVEs and this could be a more reliable source of statistical data on the occurrence of WVEs. The EC 4th Framework project ETWIRL (European Turbulent Wake Incident Reporting Log, see Refs. 53-54) also showed that the collection and inspection of FDR data from pilot-reported encounters could be very useful for the analysis of WVE severity's. In WP5, therefore, the collection of large amounts of FDR data and the automatic inspection of these data to identify the occurrence of WVEs has been undertaken.

### 4.5.1    Validation and refinement of an algorithm to identify WVEs in FDR data

The first part of the WP 5 programme (Task 5.1) was therefore aimed at developing, implementing and validating an algorithm for the automatic processing of Flight Data Recordings (FDR). This algorithm was developed by NLR and is known as NLR-VORTEX (Refs. 35-36 and Refs. 59-60). The algorithm routinely produces a limited set of parameters along the flight path (including local Met data). In the same processing loop the algorithm also produces a more extensive set of parameters from which it automatically detects whether a Wake Vortex Encounter (WVE) has occurred. If a WVE is detected, a more extensive set of output parameters is maintained for further analysis. An initial validation of the WVE detection algorithm has been performed by NATS, which shows that it can successfully identify WVEs from flight data. Figure 38 shows a flight segment for a pilot reported encounter, which was identified as a definite WVE by visual inspection, and which was also detected as a WVE by NLR-VORTEX from the FDR data processing. In a second validation step, the algorithm has been applied to the Cessna Citation data sets obtained during the WVE flight tests performed in WP2.
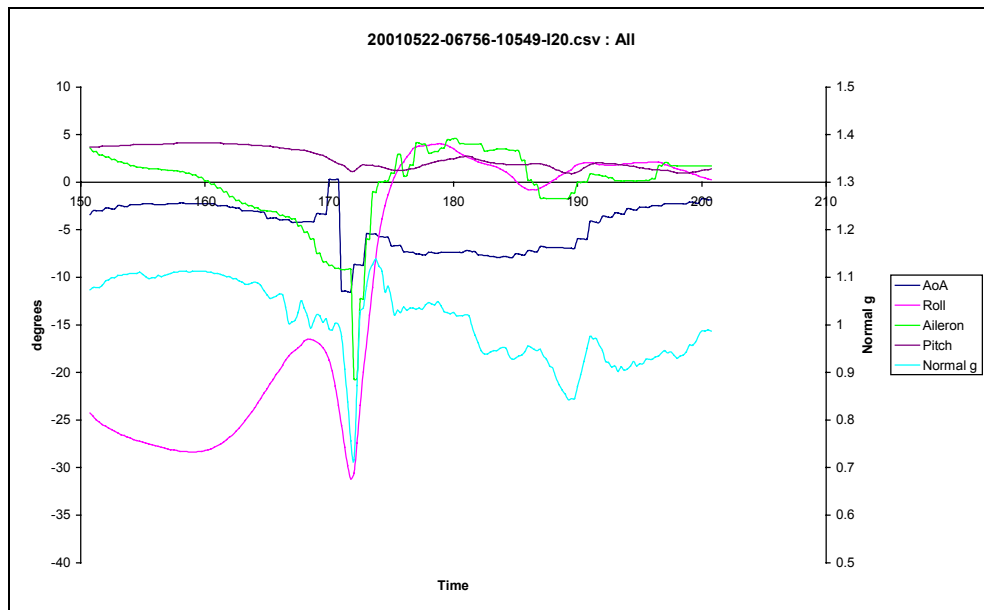
*Fig. 38  A pilot reported WVE that was also detected by NLR-VORTEX*

### 4.5.2  Creation of a WVE database and statistical analysis of the results

Subsequently, in Task 5.2.1 of the project a massive data collection was performed for incoming flights at London Heathrow. It covered a one-year period from September 2001 to August 2002 and involved (see Fig. 39):

- The development of an automatic tool for producing aircraft separations from radar approach data. This tool was used to produce extensive radar tracking information for over 170,000 arrivals into Heathrow.
- The collection of segments of FDR data from flights of BA aircraft into London Heathrow. The flight data collection was performed using the PRISM system developed and implemented by Spirent Systems. In total 30,000 FDR flight segments were successfully gathered.
- The collection of ground-based meteorological data (METARs), at ½ hour intervals;
- The collection of runway logs in order to correlate the different data to the landing aircraft.
- The application of the NLR-VORTEX algorithm to the collected FDR data segments in order to:
  - Create a limited set of parameters (including Met data along the flight path) for each successfully processed FDR output segment.
  - Detect the occurrence of WVE's (about 210) in the processed FDR output segments and, in that case, store a more extended set of parameters for further analysis.
- The storage of all these data in the Heathrow Database (HDB). This enables the correlation between FDR Met data and ground based (METAR) met data, the determination of actual

radar separations between trailing aircraft and the identification of the wake generating aircraft and the local atmospheric conditions when a WVE is detected.

Figure 39 gives an overview of the HDB data collection activities.
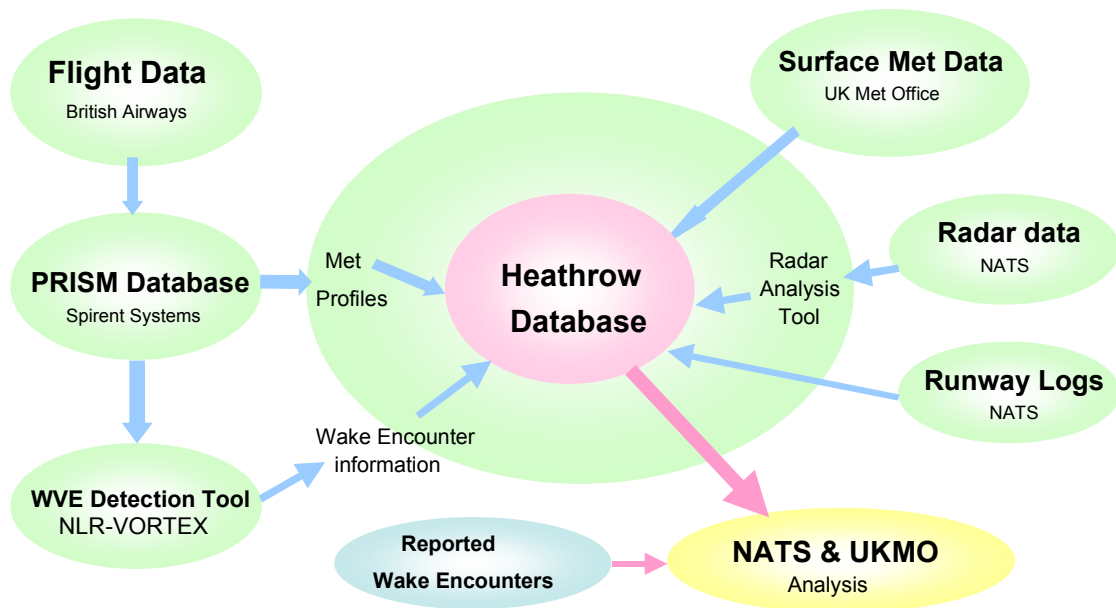


*Fig. 39    Overview of the Heathrow DataBase (HDB) data collection activities*

Unfortunately, the activities in Task 5.1 and Task 5.2.1 have faced severe technical problems. Not only did the collection of data on the PRISM system prove to be a highly technical challenge, but also the development of a robust FDR processing algorithm (NLR-VORTEX) proved very difficult. For example, the FDR data-formats changed during the data-collection, requiring regular adaptation of the code interface. Also, essential parameters were often missing from the input FDR data or were in error. *Considerable resource was expended in addressing these problems*. Due to these technical problems, the volume of flight data that could successfully be collected and processed was significantly smaller than originally anticipated. Furthermore, a close inspection of the NLR-VORTEX outputs during the analysis phase suggests that some of the events identified as a WVE may actually have been due to other causes (e.g. atmospheric turbulence). Therefore the WVE results collected in the HDB have to be considered as preliminary.

Nevertheless, in the final phase of WP5 statistical analyses were conducted by NATS using the HDB database to investigate relationships between vortex encounter parameters and situational parameters such as time separation and wind vector. The UK Met Office also undertook a detailed analysis of the large set of detailed meteorological data from the processed FDR traces and from the ground based METAR data in the HDB.

As an example of the preliminary WVE results, figure 40 shows a plan-view of the London
Heathrow area (covering all four approach corridors) with the locations of the WVEs detected
by NLR-VORTEX. The radar tracking locations of the WVE aircraft are shown as well.
Clearly, WVEs occur both along the ILS flight path and along flight segments joining onto the
ILS flight path.
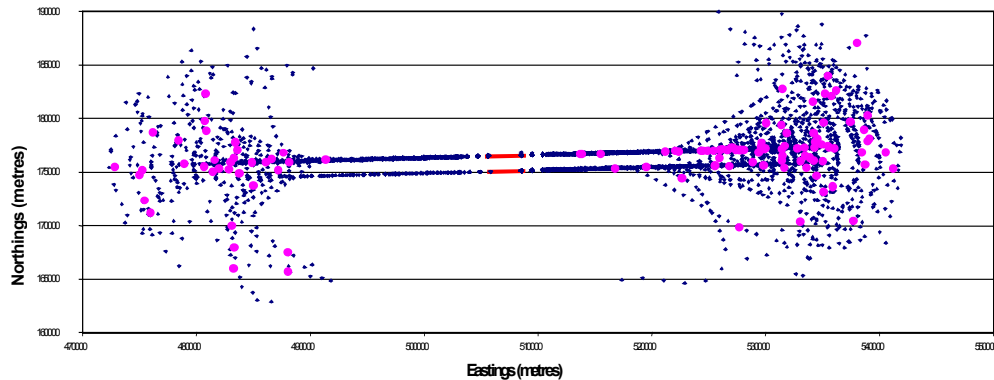


*Fig. 40 Top view of the London Heathrow area, with radar flight tracking and WVE positions
detected by NLR-VORTEX from FDR data analysis (preliminary result)*

Similarly it is also possible to show the heights of the detected WVEs along the glide slope.
Figure 41 shows preliminary results for the height of detected WVEs against the distance from
touchdown (data from all four approach corridors are shown in one plot). The nominal ILS track
is shown for reference. The majority of the detected WVEs occur below the ILS flight path. A
substantial number of WVEs occurs near a height of 4000 ft, where many aircraft intercept
horizontally with the ILS.
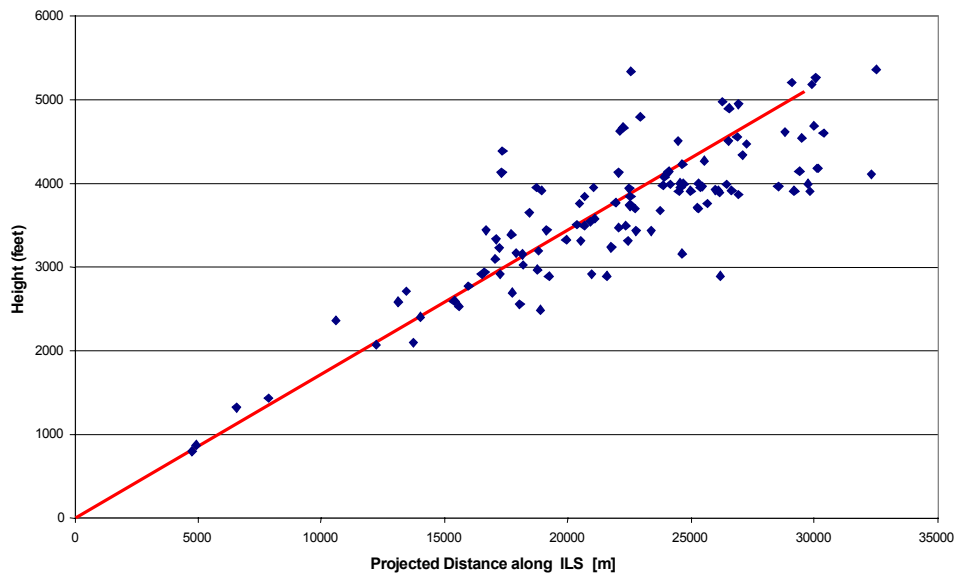


*Fig. 41 Height versus distance from touch down, for the WVEs detected by NLR-
VORTEX from FDR data analysis (preliminary result)*

The height distribution of WVEs reported by pilots (not shown here) shows a similar pattern as those detected by NLR-VORTEX, except there is also a noticeable set of encounters reported close to ground level. It should be noted that the data, such as that shown in figures 40-41, have only become available due to the work in S-Wake WP5, combining WVE detection, radar tracking and the correlation of the data in the HDB.

Further investigation of the output from NLR-VORTEX suggested that some of the identified encounters might be due to causes other than wake vortex (e.g. atmospheric turbulence). Therefore, the statistical analysis of WVEs further concentrated on data from NATS database of voluntary pilot reports.

### Analysis of voluntary pilot reports

The additional analysis of voluntary pilot reports for WVEs was insufficient for WP5 to successfully meet one of its main objectives, which was the intended validation of WP4 with data from WP5. However, the analysis did produce two interesting results:

- The rate of WVEs appears to increase rapidly (see Fig. 42) when aircraft are spaced more than 10 to 15 seconds below the separation minimum. This suggests that the current separations (expressed in terms of time) have been set at appropriate levels, at least for the meteorological conditions in which WVE are reported. However, this does not exclude the possibility that significantly smaller (but safe) separations are possible under certain weather conditions (see next bullet for example).

- For leader and follower aircraft established on the glide slope, the rate of WVEs is considerably reduced when the crosswind is above a critical level (about 6 to 8 knots). Figure 43 shows the distributions of crosswinds at encounter and also the overall crosswind climatology at Heathrow, as derived from the FDR data.
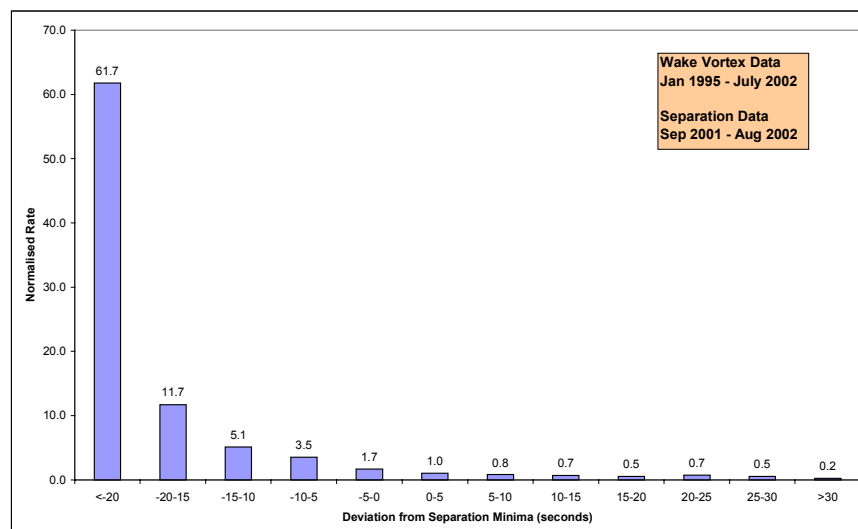


Fig. 42    Relative WVE Rates (WVE rate for nominal separations normalised to 1) for Voluntary Reported Encounters
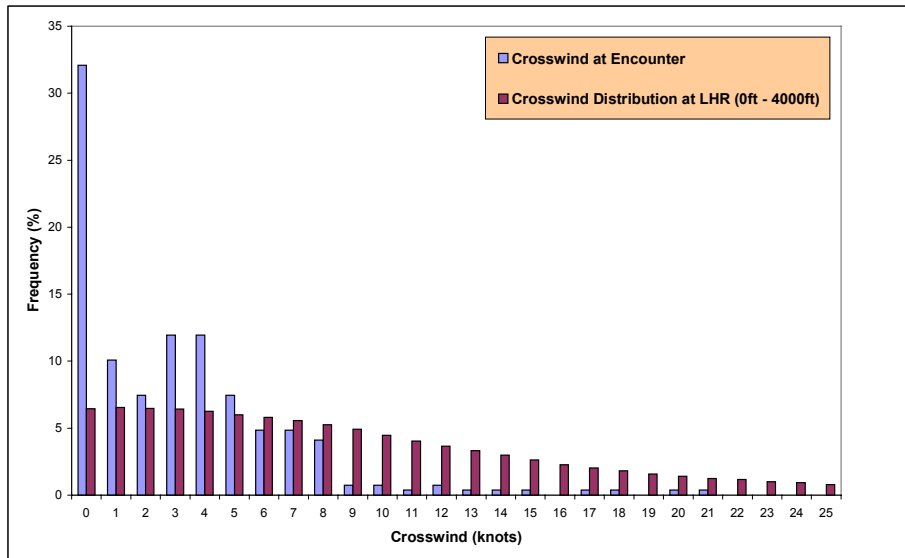
*Fig. 43    Crosswind Distribution for Voluntary Reported Encounters
compared with the London-Heathrow crosswind climatology*

The main focus of the work performed by the UK Met Office was to compare the HDB with forecasts made by the Met Office Site Specific Forecast Model (SSFM) and to investigate the skill of forecasts of the Wake Vortex Behaviour Class (WVBC) that were defined in WP1. The two key results from this analysis are:

- The majority of meteorological data in the HDB were found to be consistent with the SSFM across a range of heights and these can thus be used with confidence.

- The skill of the SSFM in forecasting WVBCs ('*Turbulence*' and '*Cross Wind*') was evaluated. This showed that the *Cross Wind* class is well predicted with a detection rate of 83 % and a false alarm rate of 17 %.  The *Turbulence* class is less well predicted.

These results suggest that there is potential to reduce wake vortex separations in specific wind conditions. This possibility has been confirmed by other work performed in WP1 of the S-Wake project.


The activity in WP5 has shown that it is possible, in principle, to obtain statistical data on WVEs in an automatic manner. Clearly, however, improvements to the data processing/collection are still needed but any system developed could become very useful (if not essential) in a decision making process if a change in wake separation methodology has to be tested in the future.

## 5 Conclusions

**Wake vortex modelling in the atmosphere, modelling and validation**
- The parametric numerical simulations of wake vortex behaviour in the atmosphere have led to an increased understanding on the decay mechanisms. A good summary of this is given in refernce 8.
- The outcomes of the numerical simulations and LIDAR observations contributed to the development of two-phase decay models, both by CERFACS (Refs. 6) and by DLR (Refs. 7 and 39-41). These models were however not yet used in the modelling activities for S-Wake.
- A Wake Vortex transport and decay model has been developed for implementation in the flight simulators. Either an analytical model or a numerical model can be used. In the latter case any wind field can be delivered to the flight simulator.
- A wake vortex transport and decay model was developed for Monte-Carlo type simulations in WP4. Input parameters characterising the turbulence and the stability of the atmosphere are drawn from stochastic distributions.
- Wake Vortex Behaviour Classes (WVBC) have been defined and their forecasting (a necessary requirement for usage in an operational ATM system) has been evaluated. It was concluded that crosswind conditions can be relatively well predicted and offer a potential for reduced minimum wake vortex separations.
- An airport WVBC climatology study was made for the busiest European airports. This revealed that crosswind conditions occur for a significant portion of time and may therefore be used with advantage for reduced wake vortex separations.
- Detailed analysis of the Memphis database with LIDAR measurements reveals that under standard ICAO separations a substantial amount of vortices will still be alive. It is therefore concluded that a significant part of today's safety level is due to transport of the vortices out of the flight corridors and not to their decay.

**Aerodynamic models for wake vortex encounter**
- Two different Aerodynamic Interaction Models (AIMs) for computing the aerodynamic forces and moments during a wake encounter were developed and validated. The first model, developed by ONERA, is based on a Strip Method (SM). The second model, developed by TU-Berlin, is based on a Lifting Surface Method (LSM) and is more advanced but requires more computational effort.
- The strip model and the lifting surface method were incorporated in a portable Wake Vortex Encounter (WVE) software package that was implemented in the flight simulators.
- Both aerodynamic interaction models were validated against WVE wind tunnel tests.

- Both aerodynamic interaction models were also mutually compared against each other for a large number of wake intercept conditions. It was concluded that both methods yield roughly equivalent results, though the LSM seems to offer some advantages with respect to accuracy.
- Both models predict the prime important parameters with sufficient accuracy and can therefore be used for wake encounter simulations in piloted WVE simulations or in off-line WVE simulations (with a pilot reaction model).
- The strip model requires less computational effort and is therefore more suited for probabilistic WVE simulations that require large number of simulations.
- Some attempts were made to model fuselage effects, but this was underestimated and could not be completed. It was conjectured that for small wake intercept angles these effects are of minor importance only. At larger wake interception angles however, fuselage effects can probably no longer be neglected.

**Wake Vortex Encounter flight tests**
- Certification of the smoke generator mounted on the wing of the VFW 614 ATTAS aircraft of DLR required much effort and caused significant delays in the planned wake vortex encounter flight tests.
- These problems were ultimately solved and successful flight tests were made with the Dornier Certification of the smoke generator mounted on the wing of the VFW614 ATTAS aircraft of 128 aircraft of IFF/TU-Braunschweig and with the Cessna Citation II of NLR. A unique WVE flight test database was created.
- Both wake penetrating aircraft were equipped with flow sensors in order to measure the wake characteristics during the highly dynamic passage of the aircraft through the wake vortex field. The Do 128 aircraft was equipped with four flow sensors: at its wing tips, at the nose of the fuselage and at the top of the vertical tail. The Cessna Citation was equipped with only one flow sensor at its nose-boom.
- The properties of the wake flow field behind the ATTAS could successfully be reconstructed by fitting analytical models to the flow measurement data using Parameter IDentification techniques. The use of four flow sensors proved advantageous for the quality of the fitting process.
- Vortex circulation strength, core radius and lateral distance between the vortices could be determined by fitting either to a Lamb-Oseen or a Burnham-Hallock vortex pair. The latter model performed slightly better for the fitting.
- A suitable method for measuring the vortex characteristics, at altitudes hitherto not reachable by LIDAR-measurements, was thus demonstrated.
- The Aerodynamic Interaction Models were successfully applied to compute the wake vortex induced angular and lateral movements and accelerations. These results were

compared with the actual measured values and showed a satisfactorily agreement, particular for the most important parameter (roll).

**Wake vortex encounter simulations**

- A portable WVE software module was successfully implemented in four flight simulators.
- An implementation problem (called "kinematic problem") was discovered and solved. Its impact on the hazard criteria was estimated to be negligible.
- A simplified pilot/WVE model was developed and was used in the high-fidelity off-line simulation model as well as in the probabilistic simulations for WP4.
- A total of 1623 WVE flight simulations were flown with airline and test pilots

The following general conclusions can be drawn from the piloted flight simulation tests:

- All tests showed the important influence of height above ground on the wake hazard perceived by the pilots.
- All partners identified bank angle, roll rate and ILS glide slope deviation as well-suited hazard metrics.
- Application of the bank angle criterion (illustrated in a height/ bank-angle diagram) that was previously used by NASA delivered acceptable results.
- Each partner developed GA prediction criteria (pilot decision models), which predict GA or NOGA based on objective aircraft response data. These criteria had better prediction performance than the simple bank angle criterion.
- Motion influence seems to exist, but though a clear relation could not be identified, it was concluded that motion seems to have no strong effect on the results.

**Probabilistic safety assessment**

The WP4 study comprises a quantitative safety assessment of wake vortex induced risk related to single runway approaches under ICAO flight regulations. A probabilistic approach has been followed to evaluate wake vortex induced risk related to different separation distances between landing aircraft on a single runway. The Wake Vortex Induced Risk assessment (WAVIR) methodology is based on a stochastic framework that incorporates sub models for wake vortex evolution, wake encounter, and flight path evolution, and relates severity of encounters to possible risk events (incidents/accidents).

- A sensitivity analysis was carried out with the initial WAVIR methodology at the beginning of the project, in order to give early modelling feedback to the other WPs and to identify those factors that contribute most to wake turbulence incident/accident risk.
- The WAVIR methodology has then been upgraded with improved wake evolution and wake encounter models (from WP1, WP2, and WP3), and a flight path evolution model.

- Subsequently, the extended WAVIR method has been applied to assess the risk related to four different follower aircraft, landing behind a Large Jumbo Jet (like Boeing 747-400) and a Medium Jet (like Airbus A320) on a single runway. Appropriate separation distances for different operational and weather and wind conditions were derived, using a method with proposed risk requirements based on historical wake encounter incident data collected at Heathrow airport.

- The proposed risk management framework (consisting of risk metrics for defined incident/accident risk events and associated risk requirements based on the Target Level of Safety (TLS) approach) has been externally reviewed by FAA and Eurocontrol within the frame of their Action Plan 3 "Air Traffic Modelling for Separation Standards".

- The impact of weather and wind conditions (atmospheric turbulence, stratification effects, crosswind, headwind/tailwind conditions) and ATM procedural aspects (different glide slope intercept altitudes, navigation performance, glide path angles) was investigated.

- It was shown that the largest runway capacity improvements might be achieved through exploiting favourable wind conditions. In particular crosswind and strong headwind conditions appear favourable and might allow reduced separation minima.

- It was also shown that ATM procedural changes further away from the threshold are not effective in reducing wake vortex induced risk. Weather based prediction, monitoring and warning systems should focus on weather and wind conditions near the runway threshold where wake vortex risk mitigation measures are most effective.

- A study of new systems and ATM procedures combined with an initial assessment of airport capacity gains (with a runway capacity model from ONERA) suggests that in principle substantial gains in airport capacity can be obtained.


**Safety assessment from Flight Data Recording data for Heathrow airport and from voluntary pilot reporting**

- An algorithm (NLR-VORTEX) which detects and classifies WVEs from aircraft flight data has been developed and initially validated;

- The algorithm has been applied to approximately 30,000 FDR segments. Visual inspection suggests that 210 of the detected events were WVEs but more work is required to confirm these preliminary results;

- An extensive database (the HDB) was created with information relating to arrivals at Heathrow over the period from September 2001 until August 2002. The database includes runway logs, radar-tracking information and ground based meteorological data. It also contains meteorological data along the glide-paths from the processing of the 30,000 FDR segments, together with detailed information on the 210 WVEs identified by NLR-VORTEX;

- An analysis of the meteorological data along the glide-paths showed that this data was largely consistent with forecast data from the Met Office SSFM. This analysis also showed that the *Cross Wind* WVBC is well predicted by the SSFM;
- A preliminary analysis of the WVE data was performed, and then supplemented with results from the NATS voluntary pilot reporting scheme. The rate of WVEs appears to increase rapidly when aircraft are spaced more than 10 to 15 seconds below the separation minimum. This suggests that the current separations (expressed in terms of time) have been set at appropriate levels (at least for the meteorological conditions in which WVEs are reported). However, this does not exclude the possibility that significantly smaller (but safe) separations are possible under certain weather conditions (see next bullet for example).
- The analysis of reported WVEs concluded that crosswind conditions (above 6-8 knots) lead to a decrease in WVE rates for aircraft established on the glide slope.

**Concluding remarks**

The S-Wake project experienced several unforeseen technical problems that needed extensive (unplanned) actions by some of the partners and in some cases led to significant delays. The following items are specifically noted:

- Problems with certification of the smoke generator to be installed on DLR-ATTAS for the wake encounter flight tests.
- This delay also caused problems with the planning of the Citation flight tests (aircraft not available in the possible testing period).
- Quality and reliability of the FDR data were less than expected.
- The problems with the FDR data also caused problems with the validation of the NLR-VORTEX algorithm.

Despite these problems most of the original goals of the S-Wake project could be achieved and the work has significantly contributed to the strategic goals mentioned in section 2.
In total 63 Technical Notes were produced during the project. Results are being further used in e.g. the ATC-Wake project.

# 6  Recommendations

**Wake vortex modelling in the atmosphere, modelling and validation**
- Further CFD simulations of WVs In Ground Effect (IGE) are needed under various crosswind and shear situations in order to improve and validate parametric models. This is especially needed, because the situation close to the ground is most dangerous during a wake encounter.

- A validated parametric WV-shear layer interaction model is still missing.
- A further refinement of the WVBC Rapid Decay is needed in order to allow for safe separation reductions.
- Further validation of the WVBC concept by using additional databases (e.g. Dallas databases).
- The prospects of two-phase wake decay models should be further investigated.
- Tactical usage of a crosswind and headwind WVBC for reduced separations should be further investigated.
- Weather forecast tools have to be adjusted and improved to provide robust, reliable and tailored predictions of WV impact variables for an operational WVPMS system. This includes methods to provide probabilistic predictions of meteorological variables, which consider the temporal and spatial variability of those variables. Furthermore, robust forecast tools have to be extended such that they are able to assimilate locally measured data. The predictability of turbulence needs to be improved.

**Aerodynamic models for wake vortex encounter**
- Further research should be directed to improve the encounter models. This concerns mainly the fuselage and perhaps inclusion of unsteady aerodynamic effects (e.g. employing a Küssner's function approach). The improved models would probably be more appropriate for larger wake intercept angles.
- It is recommended to undertake additional static and dynamic wind tunnel measurements of wake encounters using realistic aircraft models for further detailed validation of the aerodynamic interaction models.
- The flight simulation capabilities created can equally well be applied to other problems of practical interest, e.g. aircraft encounters with heavy turbulence or windshear. Only the wake vortex model needs then to be replaced by a suitable windfield.

**Wake Vortex Encounter flight tests**
- The data collected from the flight tests are a valuable database that can be used for model validation in future extensions of this work.
- Further flight tests, using follower aircraft with a swept wing geometry, could be very valuable because wing sweep will have a more pronounced effect on pitching moments during a wake encounter.
- The produced smoke trail was insufficient under low temperature conditions, therefore test periods during summer time should be preferred.
- For better visibility of the smoke trail, special coloured smoke oil should be tested.

- Wake vortex measurements during wake penetrations can give additional detailed information on the wake characteristics. Such measurements may be combined with lidar test campaigns to give an additional source of information.

**Wake vortex encounter simulations**
- For future WVE simulations it is recommended to use the high fidelity offline model prior to the piloted simulation in order to evaluate the most interesting critical conditions and thus improve the efficiency of the piloted simulations.
- The modified WVE software interfacing with the flight simulators should be used in future flight simulations.

**Probabilistic safety assessment**
From a safety and capacity perspective, it is of importance to locate those factors that contribute most to the incident/accident risk related to wake turbulence. For this reason, a sensitivity analysis has been carried out, and the major findings are:
- The highest wake vortex induced risk is clearly located near the runway threshold. This implies that – to reduce the risk – weather based prediction, monitoring and warning systems should focus on weather and wind effects near the runway threshold.
- The risk is most sensitive to wind conditions. This implies that an increase of runway capacity might be possible if reliable and stable predictions of wind conditions over a time period of 20 minutes or more (necessary from operational point of view to allow scheduling for approach with prescribed separation minima) can be made. In this respect, crosswind and strong headwinds are most favourable to increase runway capacity.

With respect to validation, it is recommended to analyse the data collected within the Heathrow Data Base (HDB) in more detail. Also, in support of the acceptance of the WAVIR methodology, it will be necessary to closely co-ordinate the application with European interest groups responsible for the safety of operation (besides the EC also including Eurocontrol groups).

**Safety assessment from Flight Data Recording data for Heathrow airport and from voluntary pilot reporting**
In order to improve the performance of the WVE detection algorithm NLR-VORTEX, and to identify a higher proportion of genuine WVEs when it is applied, it is recommended that:
- The algorithm is fine-tuned in order to avoid classifying flight data affected by data dropouts (and other data errors) as WVEs. Attention should focus to the effect of smoothing when applied to these data errors, and correct identification of changes to control variables such as landing gear status.

- The algorithm is amended to reject encounters due to clear air or convective turbulence, and turbulence due to buildings on the ground.
- A further full validation of the algorithm is performed, which should include an analysis of the discrepancy in the number of WVEs reported close to ground level and those detected by NLR-VORTEX.
- Further work is performed to assess the validity of the severity parameters produced by the algorithm.
- The algorithm is re-programmed to allow more flexible use.

In order to improve the usefulness of the data collection it is recommended that:
- The NLR-VORTEX algorithm is applied directly to FDR data when it is originally processed. The algorithm could, for example, be added to the software tools that British Airways already uses to analyse FDR data.
- Improved hardware is used in any further FDR data collection exercise.
- The collected FDR data are maintained to enable future re-processing with an improved NLR-VORTEX algorithm.
- The data collection exercise is continued in some form.

In order to get the most benefit out of the activity of WP5 it is recommended that detailed analysis of the 210 WVEs identified in WP5 is performed. In particular, it is suggested that further analysis be done to look at the effect of crosswind on encounter rates and to examine the severity of the identified encounters. Also a correlation between the tracks of generating and encountering aircraft is recommended to improve the understanding of the conditions under which WVEs occur.

**Possible application of the results for reduced aircraft separations**
Probabilistic safety assessment results and analysis of reported and detected wake vortex encounter rates at Heathrow airport indicate a reduced wake encounter rate in crosswind conditions. Crosswind conditions effectively transport the wake vortices out of the flight corridor (as demonstrated by analysis of the Memphis data). At the same time airport climatology studies show that crosswind conditions occur for significant periods of time at many major European airports, but also that crosswinds can be reasonably well predicted. Therefore, in the short-term, the *Cross Wind* WVBC and situations with strong headwind seem good candidates for allowing (tactically) reduced aircraft separations. Further investigation is however needed.

## 7 Acknowledgements

Acknowledgements are made to:

## 8 Glossary

| | |
|---|---|
| Airbus-D | Airbus-Deutschland, GmbH. |
| AM | Aerospatiale Matra |
| ATC-Wake | 5th Framework project proposal under Information Society Technologies Programme |
| ATM | Air Traffic Management |
| ATTAS | VFW614 aircraft of DLR, used as wake generating aircraft for wake encounter flight tests in WP2 of S-Wake |
| AVOSS | Aircraft Vortex Spacing System developed by NASA |
| AVOSS data | Data bases with wake vortex tracking data measured at Dallas/Fort-Worth (1997, 1999 and 2000) |
| AWIATOR | 5th Framework EU project for flight tests including wake measurements with wake alleviation devices on the wing |
| BA | British Airways |
| CATS | Certified Airline Training Simulator (here: A330 simulator of TUB) |
| CERFACS | Centre Europeen de Recherche et de Formation Avancee en Calcul Scientifique |
| CTS | Certified Training Simulator (here: Do128 simulator of Simtec) |

| | |
|---|---|
| C-Wake | 5th Framework RTD project on Wake Vortex Characterisation and Control |
| DFS | Deutsche Flugsicherung |
| DFW | Dallas/Fort Worth, AVOSS test campaigns |
| DLC | Direct Lift Control (DLR-ATTAS aircraft is equipped with DLC flaps) |
| DLR | Deutsches Zentrum für Luft- und Raumfahrt |
| DTOP | Dual Threshold OPeration (Frankfurt Airport) |
| ETWIRL | European Turbulent Wake Incidence Reporting Log |
| FAA | Federal Aviation Authority |
| FDR | Flight Data Recording data |
| GA | Go Around |
| HALS | High Approach Landing System (Frankfurt Airport) |
| HDB | Heathrow Data Base, used in WP5 to store and correlate radar, meteorological and wake vortex encounter data |
| IFF/TU Bs | Institut für Flugführung, Technische Universität Braunschweig |
| IST | Instituto Superior Técnico |
| I-Wake | 5th Framework EU project for onboard wake vortex detection and warning |
| LHR | London Heathrow Airport |
| LIDAR | LIght Detection And Ranging |
| LSM | Lifting Surface Method (from TUB) for aerodynamic forces and moments |
| Memphis | Data-base with wake vortex tracking data measured at Memphis airport in 1995 |
| MF | Météo-France |
| MO | Meteorological Office |
| NATS | National Air Traffic Services Ltd |
| NLR | National Aerospace Laboratory, the Netherlands |
| NLR-VORTEX | Wake vortex encounter detection and classification algorithm developed by NLR for analysing FDR data in WP5 |
| NOGA | NO Go Around |
| ONERA | Office National d'Etudes et de Recherches Aérospatiales |
| P2P | Probabilistic 2 Phase model for wake prediction, developed by DLR |
| RFS | Research Flight Simulator of NLR used for Citation and F100 tests |
| SWIM | Simple aircraft geometry for which wake encounter tests have been performed by NLR (in WAVENC project) |
| SSFM | Site Specific (weather) Forecast Model |
| SYAGE | French national research project on wake vortex evolution and prediction |
| THOR | Development simulator of Airbus |
| TUB | Technische Universität Berlin |

| | |
|---|---|
| VORTEX | A simple engineering method from CERFACS to compute wake vortex trajectories and decay |
| WakeNet | Thematic Network Wake Vortices |
| WAKE-OP | Test campaign with multiple LIDARs at Langen Airport (C-Wake). |
| WAVENC | WAke Vortex Evolution and WAke Vortex ENCounter (1998-1999) |
| WAVIR | Probabilistic Wake Vortex Induced Risk model of NLR |
| WP | Work Package |
| WV | Wake Vortex |
| WVE | Wake Vortex Encounter |
| WVPMS | Wake Vortex Prediction and Monitoring System, developed in ATC-Wake |

## 9    References

### 9.1 S-Wake Reports

1.  Moet, H.L.C.; *S-Wake Final Report for Work Package 1, Wake Vortex behaviour in the atmosphere, modelling and validation*, SWAKE-WP1R, February 2003.

2.  Krag, B.; *S-Wake Final Report for Work Package 2, Aerodynamic Models for Wake Vortex Encounter*, SWAKE-WP2R (DLR IB111-2002/13), September 2002.

3.  Luckner, R.; *S-Wake Final Report for Work Package 3, Flight Simulations*, SWAKE-WP3R (Airbus TN-EYCDD/007/02), February 2003.

4.  Speijker, L.J.P.; *S-Wake Final Report for Work Package 4, Probabilistic Safety Assessment*, SWAKE-WP4R (NLR-CR-2003-248), March 2003.

5.  Mason, S.M.; Engel, C.; Ogden D.; Haverdings, H.; *S-Wake Final Report for Work Package 5, Safety Assessment from Flight Data Collection*, SWAKE-WP5R (NATS SA PT 0303), March 2003.

### 9.2 Publications and presentations resulting from S-Wake

6.  Moet, H.L.C.; Darracq, D.; Corjon, A.*; Development of a decay model for vortices interacting with turbulence*, AIAA-2001-0545, 39th AIAA Aerospace Science Meeting Conference and Exhibit, Reno (NV), January 8-11, 2001

7.  Frech, M.; Holzäpfel, F.; *A probabilistic prediction scheme for wake vortex evolution in a convective boundary layer*, Air Traffic Control Quarterly, Vol 10, pp 23-42, 2002.

8.  Holzäpfel, F.; Hofbauer, Th.; Darracq, D.; Moet, H.L.C.; Garnier, F.; Ferreire Gago, C.; *Analysis of wake vortex decay mechanisms in the atmosphere*, accepted for publication in Journal of Aerospace Sciences.

9.  Frech, M.; Zinner, T.; *Wake vortex behaviour classes and their initial validation*, presented at Euromech Colloqium 433, Dynamics of trailing vortices, Aachen, Germany, March 20-22, 2002.

10. Gerz, T.; *Trailing wake vortices in the Atmosphere, presented at Euromech Colloqium 433, Dynamics of trailing vortices*, Aachen, Germany, March 20-22, 2002.

11. Gerz, Thomas (DLR); *Wake vortex prediction and observation: Towards an Operational system*, presented at 3rd ONERA-DLR Aerospace Symposium, Paris, June 20-22, 2001.

12  Agnew, P.; Lunnon, B.; Hoad, D.J.; Frech, M.; Gerz, Th.; Carriere, J.-M.; Bruin, A.C. de; *Wake vortex alleviation strategies focus on influence of weather on vortex behaviour,* ICAO-Journal, Vol 56, No. 7, 2001 (http: //www.icao.int/icao/en/jr/5607.pdf).

13. Heyman, S.; Scott, T.: *Helping to control air traffic*, Article for NWP Gazette, June 2002, http://www.metoffice.com/research/nwp/publications/nwp_gazette/jun02/index.html.

14. Agnew, P.; Hoad, D.J.; *Climatology study of World airports in the context of wake vortex behaviour class*, article for American Met. Soc, 10<sup>th</sup> Conference on Aviation, Portland USA, May 2002.

15. Bauer, T.; *Full-scale Wake Vortex Encounter Flight Tests: Induced Velocity measurements and Modelling of Aircraft reaction*, presented at DGLR Jahrestagung, October 2002, Stuttgart.

16. Fischenberg, D.; *Full-scale Wake Vortex Encounter Flight Tests*, presented at DGLR Jahrestagung, October 2002, Stuttgart.

17. Campos, L.M.B.C.; Marques, J.M.G.*; On wake vortex response for several combinations of leading and following aircraft*, ICAS 2002 Conference, Toronto, September 2002.

18. Kos, J.; Blom, H.A.P.; Speijker, L.J.P.; Klompstra, M.B.; Bakker; G.J.; *Probabilistic wake vortex induced accident risk assessment*, NLR TP-2000-280, presented at the 3<sup>rd</sup> USA/European Air Traffic Management R&D Seminar, Naples, Italy, 13-16 June 2000.

19. Speijker, L.J.P.; Kos, J.; Blom, H.A.P.; Baren, G.B. van; *Probabilistic wake vortex safety assessment to evaluate separation distances for ATM operations*, NLR TP-2000-326, presented at the 22<sup>nd</sup> International Congress on Aeronautical Sciences (ICAS 2000), Harrogate UK, 27 August–1 September 2000.

20. Konopka, J.; *The wake vortex turbulence problem: Capacity and Safety*, presented at 3<sup>rd</sup> ONERA-DLR Aerospace Symposium, Paris, June 20-22, 2001.

21. Bruin, A.C. de (with input from partners); *S-Wake: Assessment of wake vortex safety*. Project overview presented at the Aeronautics Days Hamburg, January 2001.

22. Bruin, A.C. de; *S-Wake: Assessment of of wake vortex safety*, presented at EUROCONTROL Headquarters, 28 August, 2001.

23. Bruin, A.C. de; Baren G.B. van; Speijker, L.J.P.; *An assessment of wake vortex safety aspects with a probabilistic approach, as part of the S-Wake project*, presented at the Conference on Capacity and Wake Vortices, Imperial College, London, 11-14 September 2001.

24. Baren, G.B. van; Speijker, L.J.P.; Bruin, A.C. de; *Wake vortex safety evaluation of single runway approaches under different weather and operational conditions*, NLR TP-2002-077, presented at PSAM6 Conference, Puerto Rico, 23-28 June 2002.

**9.3 Background References**

25. Hinton, D.A.; Charnock J.K.; Bagnell D.R.; *Design of an aircraft vortex spacing system for airport capacity improvement*, AIAA Conf. Proc. 2000-062, 2000.

26. Riddick, S. E.; Hinton, D.A.; *An initial study of the sensitivity of Aircraft Vortex Spacing System (AVOSS) spacing sensitivity to weather and configuration input parameters*, NASA/TM-2000-209849, Jan 2000.

27. Anon.: *HALS/DTOP system and procedures*, in Aeronautical Information Circulars, AIC IFR 7/99, May 6, 1999 and AIC IFR 9/01, May 17, 2001.

28. Nicolaon, J.-P.; *On-Going FAA-EUROCONTROL Action Plan on Wake Vortex*, presented at meeting at European Commission, 18 December 2001.

29. Bruin, A.C. de; *WAVENC, Wake Vortex Evolution and Wake Vortex Encounter, Synthesis Report*, NLR-TR-2000-079, 2000.

30. Campbell, S.D.; Dasey, T.J.; Freehart, R.E.; Heinrichs, R.M.; Matthews, M.P.; Perras, G.H.;Rowe, G.S.; *Wake Vortex Field measurements program at Memphis, TN Data Guide*, Project report NASA/L-2, Lincoln Lab., MIT, 1997.

31. Liot, D.; *Flight simulation of wake vortex encounter, WAVENC Report, R9*, Aerospatiale, February 2000.

32. Burnham, D.C.; *Analysis of UK encounters 1982-1990*, presented at AGARD Conference The characterisation & modification of wakes from lifting vehicles in fluids, Trondheim, May 1996.

33. Marren, K.; *An analysis of wake vortex encounters reported during 2001*, NATS R&D Report 0217 (NATS-IN-CONFIDENCE Report), July 2002.

34. Woodfield, A.A.; *Automatic identification of Wake Vortex encounters from Flight data Records*, WAR Report No. 9804, September 1998.

35. Haverdings, H.; *Specification of the WINDGRAD algorithm.* NLR-CR-2000-143. March 2000.

36. Haverdings, H.; *Updated specification of the WINDGRAD algorithm.* NLR-TR-2000-623. November 2000.

37. *Anon.;Quotation from Federal Register*, Vol. 63, No. 37, Febr. 25, 1998/Notices, FAA Policy Statement number ANM-98-1.

38. Vaughan J.M.; Brown, D.W.; Constant, G.; Eacock, J.R.; Foord, R.; *Structure, Trajectories and Strength of B747 Aircraft Wake Vortices measured by laser*, Proceeding of the AGARD FDP Symposium on The Characterization and Modification of Wakes from Lifting Vehicles in Fluid, 1996.

39. Zinner, T.; *Analyse und Modellierung des Verhaltens von Flugzeugwirbel-schleppen in der Atmosphare*, Diplomarbeit, Meteorologisches Institut, Ludwig-Maximilians Universität, Munchen, 2001.

40. Frech, M.; *VORTEX-TDM, a parameterized wake vortex transport and decay model and its meteorological input data base*, DFS Technical Report, 2001.

41. Holzapfel, F.; *A probabilistic two-phase wake vortex decay and transport model*, paper submitted to Journal of Aircraft.

42. Hinze, J.; *Turbulence*, McGraw-Hill, New York, 1959.

43. Greene G.; *An approximate model of vortex decay in the atmosphere*, J. of Aircraft, Vol. 23, July 1986, pp. 566-573.

44. Corjon, A.; Poinsot, T.; *VORTEX: a complete tool to define aircraft separations due to wake vortex encounter*, TR/CFD/94/11, CERFACS, 1994.

45. Crow, S.C.; *Stability theory for a pair of trailing vortices*, AIAA Journal, Vol. **8**, 1970.

46. Sarpkaya, T.; *Trailing vortices in homogeneous and density-stratified media*, J. of Fluid Mechanics, Vol. 36, pp. 85-109, 1983.

47. Sarpkaya T.; *A new model for vortex decay in the atmosphere*, AIAA 99-0761, 37th AIAA Aerospace Sciences Meeting, Reno (NV), 1999.

48. Burnham, D.C.; Hallock, J.N.; *Monostatic Acoustic Vortex Sensor System*, Report No. DOT-TSC--FAA-79-103.IV, July 1982, pp. 206 [Available from NTIS].

49. Winckelmans, G.; Jeanmart, H.; *VLES of Aircraft Wake Vortices in a Turbulent Atmosphere: A Study of Decay*, ECCOMAS Computational Fluid Dynamics Conference 2001, 4-7 September, Swansea, Wales (UK).

50. Stewart, E.C.; *A piloted simulation study of wake turbulence on final approach*; AIAA Paper 98-4339.

51. Nieuwpoort, A.M.H.; *Analysis of Fokker 100 wake encounter*, NLR-Memorandum LV-2001-010, May 2001.

52. Tatnall, C.R.; *A proposed methodology for determining wake-vortex imposed aircraft separation constraints*, MSc. Thesis, The school of Engineering and Applied science of the George Washington University, August 1995.

53. Privett, R.; Sunderland, M.: *Case studies and statistical analysis of wake vortex encounters based on data from the European turbulent wake incident reporting log (ETWIRL)*, WAVENC Technical Note, December 2000.

54. Privett, R.: *Tackling turbulence (ETWIRL, a pan-European Wake Vortex Reporting System)*, Air Traffic Management, Vol 7, No 6, Nov 1998, p.26-27.

55. Anon.: *Wake Turbulence Encounters, Aviation Safety Reporting System (ASRS) Database Report set*, Update 8, December 6, 2002.

**9.4 Presentations by S-Wake members at WakeNet workshops**

56. Ronig, S.; *Do-128 In-Flight Measurement System for Wake Vortex Fields*, 3rd WakeNet Workshop on 'Measurement Techniques for Vortex Wakes', May 22nd-23rd, 2000. DERA, Malvern, UK.

57. Fischenberg, D.; *Determination of vortex characteristics from vortex encounter flights*, 4th WakeNet Workshop "Wake Vortex Encounter", October 16-17, 2000, Amsterdam.

58. Luckner, R.; *Flight simulator preparation for the investigation of wake vortex encounters*, 4th WakeNet Workshop "Wake Vortex Encounter", October 16-17, 2000, Amsterdam.

59. Mason, S.M*.; Wake vortex safety assessment using aircraft measurements*, presented at 5th WakeNet Workshop, Langen, April 2&3, 2001.

60. Haverdings, H.; *Analysis of wake vortex encounters on the basis of flight data recorder traces*, presented at 5th WakeNet Workshop, Langen, April 2&3, 2001.

61. Hoad, D.J.; *Validation of wake vortex behaviour class forecasts with aircraft measurements*, presented at 5th WakeNet Workshop, Langen, April 2&3, 2001.

62. Darracq, D.; *SYAGE: Ground based measurements at Toulouse Blagnac airport*, presented at 5th WakeNet Workshop, Langen, April 2&3, 2001.

63. Frech, M.; *Wake vortex modelling aspects for HALS*, presented at 5th WakeNet Workshop, Langen, April 2&3, 2001.

64. Baren, G.B. van; *Simulations for probabilistic safety assessment*, presented at 5th WakeNet Workshop, Langen, April 2&3, 2001.

65. Campos, L.M.B.; *On the calculation of safe separation distances between aircraft due to wake effects*, presented at 5th WakeNet Workshop, Langen, April 2&3, 2001.

66. Escande, B.; *Flight mechanics: Basic parameters, encounter modelling and validation*, presented at 6th Wakenet Workshop, June 17-18, Thales Toulouse.

67. Davies, H.; Speijker, L.J.P.; *Incident reporting: Incident reporting scheme's, automatic encounter detection and safety assessment*, presented at 6th Wakenet Workshop, June 17-18, THALES, Toulouse.

68. Speijker, L.J.P.; *Introduction to ATC-Wake*, presented at 6th WakeNet Workshop, June 17-18, THALES, Toulouse.

Table 5  Brief description of the role of the S-Wake partners

| partner | WP | Brief description of the role of the partner in the different Work packages |
|---|---|---|
| NLR | 0 | Project co-ordination. |
| | 1 | Validation of VORTEX against Memphis database. Development and application of a probabilistic wake evolution model. |
| | 2 | Participation in wake encounter flight test with NLR Citation II aircraft. |
| | 3 | Preparation of the NLR Research Flight Simulator (RFS). Wake encounter flight simulations with F100 and Citation. Analysis of the flight simulation results. Development and application of a probabilistic wake encounter model. |
| | 4 | Co-ordination of Work Package 4 (probabilistic safety assessment). Application of existing NLR probabilistic wake vortex safety assessment method (WAVIR) in a sensitivity study Extension of existing WAVIR method with improved probabilistic wake evolution, flight path and wake encounter models. Application of the extended WAVIR method to assess safe separation distances for several pairs of landing aircraft types and investigation of the influence of weather parameters (especially head and tailwinds). |
| | 5 | Development of a method to detect and classify wake vortex encounters from routine flight data recordings of commercial aircraft. |
| DFS | 4 | Technical and operational feedback and support (including review of deliverables). |
| Airbus | 1 | Definition of requirements and specification of code interfaces for the wake evolution model to be used in the flight simulators. |
| | 2 | Definition of requirements for the wake vortex aerodynamic interaction model to be used in the flight simulators. |
| | 3 | Management of Work Package 3 (flight simulations). Preparation of the THOR flight simulator . Wake encounter flight simulations with VFW614. Analysis of the flight simulation results. Development of a high fidelity off-line wake encounter simulation model. Development and application of a worst case wake encounter search method. Improvement of the wake encounter simulation software. |
| DLR | 1 | Numerical simulations of wake vortex evolution in the atmosphere. Development of an interface to the Memphis database. Definition and further development of Wake Vortex Behavior Classes (WVBC). Definition of probability probabilities for the WVBCs. |
| | 2 | Management of Work package 2 (Development of aerodynamic interaction models and wake encounter flight tests). Preparation of the wake generating aircraft ATTAS (including the mounting of a smoke generator). Planning of and participation in the wake encounter flight tests with VFW614 ATTAS. Analysis of the wake encounter flight tests and reporting of the results. |
| | 4 | Review of the evaluation of safe separation distances and definition of new ATM procedures that might allow reduced separation distances. |
| IFF/TUBs | 2 | Participation in the wake encounter flight tests with the Do128 aircraft |
| ONERA | 2 | Improvement and modification of a wake encounter model based on a strip method. Validation of the improved strip method. |
| | 3 | Assistance with the implementation of the strip method in the flight simulators |
| | 4 | Assessment of the impact of modified ATM procedures on runway capacity |
| CERFACS | 1 | Management of Work Package 1 (wake vortex evolution in the atmosphere). Numerical simulations of wake vortex evolution in the atmosphere. Improvement of the VORTEX method. Adaptation of the VORTEX method for implementation in flight simulators. |

| partner | WP | Brief description of the role of the partner in the different Work packages |
|---|---|---|
|  | 3 | Assistance with the implementation of the VORTEX model in the flight simulators. |
| MF | 1 | Assistance with the definition of Wake Vortex Behavior Classes (WVBCs). Validation of the WVBCs and their usage in a practical environment by investigating the predictability of the WVBCs with Numerical Weather Predictions. |
| IST | 3 | Development and application of simplified methods for assessing wake encounter properties, including the assessment of safe separation distances. |
| TUB | 2 | Improvement and modification of an existing lifting surface method for the calculation of aerodynamic forces and moments due to a known wake vortex disturbed velocity field. Assistance of DLR with the validation of the lifting surface method against the wake encounter flight test data. |
|  | 3 | Preparation of the A330-300 Certified training simulator of TUB. Preparation and supervision of the Do228 flight simulator of Simtec. Wake encounter flight simulations with VFW614 and Do228. Analysis of the flight simulation results. |
| NATS | 4 | Assessment of safety requirements for the risk management framework. Assistance with the validation of the probabilistic safety assessments. |
|  | 5 | Management of Work Package 5 (Safety assessment from FDR data collection). Validation of the wake encounter detection algorithm developed by NLR. Development of the Heathrow Database (HDB). Analysis of the HDB. |
| Spirent | 5 | Processing of the FDR data and technical assistance. |
| BA | 5 | Provision of the FDR data and technical assistance. |
| MO | 1 | Airport climatology study o0f WVBCs for large airports. Assessment of the forecasting of WVBCs. |
|  | 5 | Analysis of weather related data in the HDB. |

Table 6  List with main points of contact after finishing the S-Wake project.

| Name | Organisation | fax | Tel | E-mail |
|---|---|---|---|---|
| **Anton de Bruin** | NLR (AE) | +31-527248210 | +31-527248659 | Bruina@nlr.nl |
| Lennaert Speijker | NLR (IW) | +31-205113210 | +31-205113654 | Speijker@nlr.nl |
| **Jens Konopka** | DFS | +49-6103705741 | +49-6103705792 | jens.konopka@dfs.de |
| **Robert Luckner** | Airbus-D | +49-4074374183 | +49-4074375689 | Robert.luckner@airbus.com |
| Dietrich Fischenberg | DLR-FT | +49-5312952845 | +49-5312952657 | Dietrich.Fischenberg@dlr.de |
| Michael Frech | DLR-PA | +49-8153281841 | +49-8153281263 | Michael.frech@dlr.de |
| **Manfred Swolinsky** | IFF/TU-BS | +49-5313919804 | +49-5313919805 | M.Swolinsky@tu-bs.de |
| Tobias Bauer | IFF/TU-BS | +49-5313919804 | +49-5313919817 | T.Bauer@tu-bs.de |
| **Nicole Imbert** | ONERA | +33-562252564 | +33-562252786 | Imbert@cert.fr |
| **Henri Moet** | CERFACS | +33-561193000 | +33-561193085 | Moet@cerfacs.fr |
| **Christine LeBot** | Météo France | +33-561078209 | +33-561078234 | christine.lebot@meteo.fr |
| **Luis Campos** | IST | +351-21817539 | +351-218417267 | lmbcampos.aero@popsrv.ist.utl.pt |
| **Andreas Reinke** | TU-Berlin | +49-3031426958 | +49-3031421248 | andreas.reinke@tu-berlin.de |
| Prof. Thorbeck | TU-Berlin | +49-3031422955 | +49-3031422873 | Juergen.Thorbeck@tu-berlin.de |
| **Haf Davies** | NATS | +44-2078326225 | +44-2078325956 | haf.davies@nats.co.uk |
| Simon Mason | NATS | +44-2078326225 | +44-2078326424 | Simon.mason@nats.co.uk |
| **Cliff Engel** | Spirent Systems | +44-2089905901 | +44-2089905947 | cliff.engel@spirent.com |
| Peter Clapp | Spirent Systems | +44-2089905901 | +44-2087593455 | peter.clapp@flightdata.co.uk |
| **Robert Smith** | BA | +44-2085628869 | +44-2085620508 | robert.L.smith@britishairways.com |
| Graham Thrower | BA | +44-1815628242 | +44-1815622643 | graham.1.thrower@britishairways.com |
| **Robert Lunnon** | Met Office | +44-1344854412 | +44-1344856423 | rwlunnon@metoffice.com |
| Deborah Hoad | Met Office | +44-1344854412 | +44-1344854114 | djhoad@metoffice.com |
| Paul Agnew | Met Office | +44-1344854412 | +44-1344854534 | paul.agnew@metoffice.com |