Wake Vortex Research Needs
for
“Improved Wake Vortex
Separation Ruling”
and
“Reduced Wake Signatures”

Part II

Specialist’s Reports

This document has been prepared by the partners of the European Thematic Network ‘WakeNet2-Europe’ in collaboration with ‘WakeNet-USA’
The Research Needs document is the final deliverable of the Thematic Network WakeNet2-Europe, as part of the Sixth Framework Programme (contract number G4RT-CT-2002-05115).

The expertise of WakeNet2-Europe partners covers the whole spectrum of wake turbulence related issues including e.g.
- research how vortices are created by a lifting wing
- measurement and modelling of the important meteorological influence on the vortex dynamics
- implementation in a true operational environment.

While the phenomenon under consideration is very complex the basic question is what level of detail is required to master the challenging operational wake turbulence related problems. In particular the approval of new procedures based on a formal safety assessment plays a crucial role here.

This document describes the ‘Research Needs’ in the area of wake turbulence as perceived by a group of experts, basically the WakeNet2-Europe partners with valuable input from some external parties (e.g. WakeNet-USA).

Part I provides an overview of the wake vortex problem, a problem characterized by a balance between the risk of wake vortex encounters and airport and airspace capacity. Some of the schemes (CONOPS) to improve capacity without loss of safety are presented followed by a discussion of the research needed to improve the methods to assess the safety issues.

In Part II more detailed information is presented to clarify why specific research is needed in various areas. It will be in particular useful for those that are interested to pursue further research in their area of knowledge.

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Co-ordinator WakeNet2-Europe
On the Thematic Network WakeNet2-Europe

WakeNet2-Europe, further on abbreviated as WN2E, is a thematic network for Aircraft Wake Turbulence sponsored by the European Commission in the 6th Framework Programme (contract number G4RT-CT-2002-05115). It relates to Key Action 4.4 “Improving Operational Capability and Safety of Aircraft”.

The mission is described as: “WakeNet2-Europe will promote multidisciplinary contacts and information exchange between specialists active in the field of wake turbulence and end-users of this knowledge in the operational airport environment.”

WN2E has the following partners:

NLR, IFALPA, DLR, THALES-AVIONICS, DFS, UCL, NATS En-route Ltd, EUROCONTROL, AIRBUS-DEUTSCHLAND, MET OFFICE, QinetiQ, ONERA.

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WN2E has an active site, maintained by ONERA:

http://www.e-onecert.fr/projets/WakeNet2-Europe/

where information can be found on the WN2E activities and copies of presentations of WN2E workshops can be downloaded.

WN2E is organized in various ‘working groups’ and ‘links’ that exchange information, organize specialists’ meetings and keep contacts. The present document is the result of a combined activity of all partners and constitutes the ‘Final Deliverable’.

Since WN2E ran for 3 years, its activities have come to an end February 28, 2006. It is the intention to continue the activities as part of the 7th Framework Programme (to start early 2007). In the mean time, the EUROCONTROL Experimental Centre will act as a focal point for the wake vortex activities in Europe.
Acknowledgements

In a Thematic Network ideas are carried by people and they should have the full credit for what has been achieved. The ideas expressed in this ‘Research Needs Document’ are the result of numerous discussions between the partners of WakeNet2-Europe within working groups, during workshops or otherwise. This is specifically true for Part I: although written by the co-ordinator, it was done so with the intention to give a kind of collective view on what all partners in the Network believe what has to be done. The authors of the various sections in Part II of the Research Needs Documents are mentioned in their respective section.

Those that contributed to all these activities should be acknowledged and their names are given below:

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Bram Elsenaar, co-ordinator WakeNet2-Europe
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Section 1
Introduction and Overview

The document ‘Wake Vortex Research Needs’ has emerged from the activities of Wakenet2-Europe, a European sponsored Thematic Network that has been active between 2003 and 2006. Over a much longer period, research in the area of wake vortices has been stimulated by the European Commission by co-financing many European research programs. The interest in wake vortices stems from the fact that airport capacity is becoming increasingly a bottle neck for the air transportation system. Also, the introduction of the A380 has stimulated research to find out if and how wake vortex signatures can be reduced.

The document has two parts, Part I and Part II.

This Part II contains the detailed specialist’s reports as written by the WakeNet2-Europe (WN2E) partners, each in their specific area of competence. Although WN2E was organised in a number of ‘Working Groups’ and ‘Links’ the sections of this report were organised slightly differently, as a result of discussions within WN2E. Information from the various Working Groups was used as well. Under the heading of each particular section you can find the names of those who contributed to that section.

The Workshops organised by WakeNet2-Europe are listed at the end of this report. The presentations for these workshops can be found on the WakeNet2-Europe InterNet Site, together with the Technical Evaluator Report of that meeting.

Part I of this report finally summarizes the sections of this Specialist’s Report. It lists the specific recommendations and adds some comments relevant for the relations between the various themes.
Section 2  
CONOP studies

Antoine Vidal (Eurocontrol Experimental Centre) and Wayne Bryant (NASA)

2.1 Introduction

Airport capacity will become an increasingly constraining factor in tomorrow’s ATM landscape. Large increases in airspace capacity over the past decade have put more and more pressure on airport capacity, especially during peak periods. The situation is aggravated by the operation of hubs that condense traffic into arrival and departure banks.

One of the limiting factors to increase runway capacity is the standard separation imposed by ICAO during landing and take-off phases. The separations were implemented to ensure that an aircraft does not enter into an unsafe situation due to the wake turbulence of a preceding aircraft. These separation distances are often over conservative as they deal with worse-case scenarios and so in most cases unnecessarily reduce capacity.

Changes can be done through the introduction of new operational concepts. Operational Concepts are a high-level description of a set of defined ATM components and the manner in which they are organized and operated to meet a given set of high-level user requirements.

Operational concepts are applied through Concept of Operations. Concepts of Operations are detailed description of how an operational concept is applied. They identify the functions and processes, and their corresponding interactions and information flows; concerned actors, their roles and responsibilities.

This paper will describe the:
- Past and/or implemented applications
- Schemes currently in study
- Future developments
- Available validations of models and tools

2.2 Past proposed and/or implemented applications

2.2.1 WSWS: Wirbelschleppen-Warnsystem (Wake Vortex Warning System)

The WSWS has been initiated by DFS in the 1980’s for Frankfurt airport. The aim is to provide a warning system to prevent WV hazards for operations on parallel runways that can not be operated independently because WV may be advected to the adjacent runway. The WSWS uses data from a wind line, a statistical wind forecast,
and a vortex decay and transport model to predict minimum non-hazard times for the
two runways.
There are four approach procedures, which have been contemplated to take advantage of this system:

- Staggered approach
- Modified staggered approach 25L
- Modified staggered approach 25R
- Single runway approach

WVWS only uses surface winds for its measurements, and uses no real time verification of wake behavior. WSWS works for the lowest 80 m above ground. A vertical extension to cover the whole glide path is under development before starting operations using WSWS.

The originally proposed warning system was not accepted by the pilots since it was mainly based on weather and wake vortex information close to the ground. A re-introduction didn’t materialize so far since the safety case (in an absolute sense!) could as yet not be proven.

2.2.2 HALS/DTOP : High Altitude Landing System/ Dual Threshold Operations

The procedure HALS /DTOP has been implemented for trials at Frankfurt airport. HALS/DTOP also aims at using two closely spaced parallel runways independently:

Two aircraft, on radar separation, make an approach on the parallel runways along two glide paths separated by 80 m vertically and 518 m laterally.

The aircraft on the higher path lands at a runway with a staggered threshold installed 1500 m behind the original threshold. By using this displaced approach path, wake turbulence separation can be disregarded. Thus a Heavy aircraft can approach the northern runway followed by a Medium aircraft using the HALS procedure to the southern runway by applying radar separation minima only.

Here the safety case was made, based on a relative stochastic risk assessment.
2.2.3 SOIA: Simultaneous Offset Instrument Approach
SOIA refers to simultaneous approaches for a set of parallel runways utilizing a straight-in ILS approach for one runway and an offset Localizer type Directional Aid (LDA) with a displaced glide slope instrument approach for the other runway. A visual segment of the LDA approach is established between the LDA missed approach points (MAP) and the runway threshold, permitting aircraft in the LDA track to be in visual conditions to be aligned with the runway and be stabilized by 500 feet above the touchdown zone elevation.
After accepting a clearance for an LDA PRM approach, pilots remain on the LDA course until passing the LDA MAP prior to alignment with the runway centerline. If ATCO advises that there is traffic on the adjacent ILS, pilots are authorized to continue past the LDA MAP to align with runway centerline if the other traffic:
- is in sight,
- is expected to remain in sight,
- ATCO has been advised the runway environment is in sight.
Between the LDA MAP and the runway threshold, pilots of the LDA aircraft are responsible for separating themselves visually from traffic on the ILS approach, which means maneuvering the aircraft as necessary to avoid the ILS traffic until landing, and providing wake turbulence avoidance.

2.3 Scheme’s currently in study

2.3.1 ATC-Wake:
The operational concept described a wake vortex prediction/detection system that enables airports to operate tactical reduced separations, for arrival and departures, under the appropriate meteorological conditions and under different runway configurations (single RWY, parallel RWY).
The Concept of Operations defined the procedures and working methods for en-route, approach controllers and sequence managers, as well as the tools and information to be integrated in a platform and displayed to the controllers. The system enables ATCOs to apply new weather based dynamic aircraft separation (Reduced Separations or Standard ICAO separations) based on the wake vortex prediction/detection.

One of the subsystems is the Separation Mode Planner (SMP) that is responsible for the advice to the ATC supervisor, with respect to safe and adequate separation minima to be applied by the air traffic controllers.

A subsystem predicts for individual aircraft the WV behavior and detects its position, and strength, in the pre-defined arrival or departure area(s) (displayed by a “vortex vector” on the radar screen). At the end, in case of a problem an alert is given if:

- significant deviation between WV detection and WV prediction information which raises the risk of WV encounter
- failure of one or several WV components

To assess the operational feasibility of the ATC-Wake operational concepts, procedures and requirements, fast-time simulations were conducted.

A scenario with standard separation mode was compared with different scenarios (reduced separation modes, transition between standard and reduced separation modes).

Potential benefits were found but the application of reduced separations were highly dependent on the traffic distribution and the airport environment.

### 2.3.2 Time Based Separations:

The operational concept defined the possibilities of preventing loss of runway capacity against strong headwinds while maintaining required level of safety in assessing a new concept of separation based on time interval instead of distance.

Both these approaches are highly beneficial to hub traffic sequence and chronically congested airports.

To apply this operational concept, the concept of operations led to a description of specific tools:

- Intelligent Time Vector (ITV) that shows the forecast position of a following aircraft for a time corresponding to the required time separation to be applied from the leading aircraft. This point is linked to the following aircraft.
• Target Trailing Position (TTP) that indicates the point behind a leading aircraft that would correspond to the required position of the following aircraft according to the required time separation. This point is linked to the leading aircraft.

An improved knowledge of wind behavior by using forecasting and nowcasting models is also needed.

The ITV and the TTP were tested, by ATCOs, during rapid prototyping simulations. The ATCOs preferred to use ITV before capture of the ILS (i.e. whilst the aircraft were in the maneuvering area) as they found it helpful when adjusting the position of successive aircraft. TTP, however, was the preferred representation after capture of the localizer as it gave a limiting position for any following aircraft. TTP was found more helpful from a safety viewpoint for the final phase of the flight.

During the Rapid prototyping exercises, it was observed that the main objective - recovery of the loss of capacity – was therefore seen to have been achieved.

A preliminary safety assessment of TBS with respect to the risk of WV encounter in the case of medium-medium WV category pairs of aircraft has been undertaken, using a meteorological database for Frankfurt Airport as a basis for investigation.

The use of a time-based separation minimum appears to offer significant capacity benefits without increasing the risk of WV encounter in headwind conditions, with the following recommendations:

1. An assessment of other WV category pairs needs to be made. For instance, Medium category aircraft following a Heavy, etc.
2. An assessment should be made of anticipated, non-routine approach conditions and other sensitivity tests should be performed.
3. The influence of the calculated meteorological conditions at Frankfurt Airport should be examined to determine if, and under what conditions, these results for Frankfurt can be generalized to other European airports.
4. A full safety assessment of the TBS proposal should be performed. Such a safety assessment would include recommendations 1 to 3 and, in addition, would address other safety aspects of the time-based separation operational concept.
2.3.3 St Louis trials
The detailed concept of operations supports a modification to the 2500 foot rule for CSPR for aircraft types large and below. For STL, the concept is for 1 ½ mile diagonal separation during IMC when a large or small class aircraft lead. Based on wake behaviour data collected over a period of 15 months, a safety argument for relaxing the 2500 foot rule will be modified for STL having 1300 foot separation. This requires only changes to existing operating procedures or their application. Thus, they can yield “near-term” airport capacity enhancements without extensive infrastructure development delays. No changes in airborne or ground systems will be required. In the case of STL, initial studies indicated that the airport IFR arrival rate could be increased to ~ 40 per hour (presently ~30 per hour) in conditions requiring wake dependent approaches. This study also indicated that the increase could be achieved without impact to departures.

2.3.4 WSVBS: Wake Vortex Prediction and Monitoring System
The WSVBS (Wirbelschleppenvorhersage- und beobachtungssystem) aims at dynamically adjusting aircraft separations in a weather dependent way for approaches to single and closely-spaced parallel runways based on predicted wake vortex behavior and related hazard areas. The system is in development as part of the DLR project “Wirbelschleppen”, launched in 1999. The WSVBS consists of the components NOWVIV (prediction of relevant weather parameters), P2P (probabilistic wake vortex prediction), SHAPe (predicts the area around the wake vortices which must be avoided for safe approaches), pulsed Lidar (monitoring of predicted wake vortex evolution), and a system for the utilization of suggested temporal aircraft separations within an Arrival Manager (AMAN). WSVBS shall demonstrate its functionality during a measurement campaign at Frankfurt airport in fall 2006.

2.4 Future developments envisaged

2.4.1 CREDOS: Crosswind Reduced Separations for Departure Operations
The operational concept will undertake specific research to show the feasibility of the use of reduced separations for departures under certain specific meteorological conditions. Current knowledge of the wake vortex phenomenon suggests that considerable reductions of the current separation standards could be achieved under crosswind conditions but this needs to be confirmed through data collection and modeling.

The concept of operations will investigate and defined the procedures, working methods and tools needed to apply reduced separations between departures in crosswind conditions.

2.4.2 ATC-Wake2:
The operational concept will be based on the results of the project ATC-Wake. It will aim at the implementation of the ATC-Wake platform (SMP, prediction, detection, monitoring and alert) at given airports.
The concept of operations will investigate all flight operations (arrivals and departures).
For this purpose, shadow mode field trials and flight testing will have to be done.

2.4.3 WakeVAS:
The FAA and NASA are pursuing an integrated plan to develop a viable set of wake vortex avoidance solutions meeting the needs of the aviation community (aircraft operators, FAA, airports, manufacturers, unions) in mitigating the impact of wake turbulence for airport arrivals and departures. The joint program is planned to accomplish the required research to meet a phased series of desired implementation outcomes. The Operational Concept and the Concept of Operations for each of the three phases are described below:

- **Near-term (2006 – 2007) operational concept:** Improve capacity through site specific procedural changes to current arrival operations based on long-term observations of wake behaviour.
  - Support implementation of various wake turbulence procedure modifications at STL, DTW, CLE and similar CSPR airports.
  - Develop a set of wake avoidance procedures for an airport with CSPR and a displaced threshold.

- **Mid-term outcome:** Enhance capacity through weather sensitive procedural alternatives
  - Develop a set of procedures/tools that will factor in crosswind predictions to allow wake-independent approaches and departures on CSPR for all classes of aircraft, including aircraft in the 757 and heavy classifications
  - Develop a set of procedures/tools that will factor in crosswind predictions to allow wake-independent departures on single runways for all classes of aircraft following aircraft in the 757 and heavy classifications

- **Far-term outcome:** Enhance capacity by providing active solutions for wake turbulence avoidance
  - Evaluate pilot and controller based options
  - Expand the results of the mid-term research to include additional weather variables, eventually leading to a dynamic spacing tool.
  - Evaluate aircraft design changes that mitigate/reduce generated wake
  - Define an acceptable level of wake encounter

A successful Near-term research outcome will achieve only a part of the potential National Airspace System (NAS) capacity benefit from safely reducing wake turbulence aircraft separations. The joint research program’s Mid-term and Far-term components explores the best approach for utilizing technology for more fully mitigating the impacts of aircraft wake and thus obtaining the remaining benefit of more efficiently utilizing existing airport runways for arrivals and departures. Success in the Mid-term and Far-term outcomes would allow the separation distance between aircraft either arriving or departing an airport to be dictated only by collision risk safety margins. To achieve this efficiency, the following improvements are needed:

- **Better knowledge of the movement and decay of aircraft wakes through improved monitoring and forecasting of terminal winds and other meteorological parameters**
• Reduced total system error for aircraft navigating on arrival and departure paths
• Better monitoring of wake and aircraft positions through monitoring and alerting decision support tools for pilots and controllers and through cost effective, accurate, and timely reporting of aircraft position information for arriving and departing aircraft.

For the execution of this integrated plan, the primary focus of the FAA efforts is on the Near-term outcome along with developing the Mid-term concept of wind dependent departures on CSPR. The primary focus of NASA is in developing the operational concepts and associated application for the Mid-term and Far-term outcomes. FAA and NASA will share research tools, data, analysis results, and resources in pursuit of all three outcomes.

As part of this on-going cooperative program, the FAA and NASA have established St. Louis, MO as a prime wake vortex data collection airport. Extensive instrumentation has been installed with a total investment in equipment alone of over $8M; these instruments are presently collecting data for the near-term focus and for cross-wind based CSPR departures. At some future time, these instruments will be relocated to focus on the arrival mid-term solutions that depend on crosswinds to transport the wake vortex out of the way of following aircraft for closely spaced parallel runways.

2.5 Available validations of model and tools

To validate the operational concepts and Concepts of Operations, a panel of experts is needed to obtain operational advices. Then, validation is also achieved by using Fast-Time and Real-Time Simulators.

The Fast-Time Simulators allows the concept of operations identification with quicker results and better cost efficiencies.

The Real-Time Simulators allows simulation of real situations, with fundamental aspects as well as not foreseen events.

The experts analyse results of simulations and can give quantitative and qualitative advices on concepts.

2.5.1 Fast-Time Simulators

Here are listed the main fast-time simulators which can simulate different airports configurations.

2.5.1.1 TAAM : Total Airspace and Airport Modeller

TAAM, developed by PRESTON Aviation, is a fast-time simulator widely used by airport community. TAAM is able to model:

• Airspace
• Aircraft
• Airport.

It can be used to conduct simulations aimed at:

• Improving airspace capacity with no detriment to safety
• Identifying solutions to complex airport ground capacity problems
• Planning for optimal future infrastructure developments
• Supporting tactical decision-making in air traffic management

Even though TAAM is able to model en-route phase, it is more appropriate for studies around and on airports. In particular, it gives accurate results on the airport by:
• Managing the runway, taxiways and gates use
• Taking into account use rules for taxiways and gates

To set up a simulation, TAAM needs many data to be input and validated:
• Airspace (centres, sectors, restricted areas, nav aids, routes…)
• Flights (callsign, aircraft type, departure time, gate, flight plan, RFL,…)
• SIDs and/or STARs
• Airport elements characteristics: gate usage (by airline, aircraft type,…), taxiways usage (by departure/arrival, aircraft type,…)
• Conflict resolution rules
• Holdstacks

TAAM generates a few huge output files: all information describing flight life is recorded every “n” seconds as set during the simulation run, “n” being 0.03s, 0.1s, 0.3s, 1s, 3s or 6s.

2.5.1.2 SIMMOD: Simulation Model
SIMMOD is an event-step simulation model, developed by ATAC Corporation, that traces the movement of individual aircraft and simulated ATC actions required to ensure aircraft operate within procedural rules. SIMMOD computes the impact on aircraft delay and fuel consumption and uses a wide variety of parameters.

SIMMOD inputs include
• traffic demand and fleet mix,
• route structures (both in the airspace and on the airport surface), airspace sectorization, and runway configurations,
• separation rules and control procedures,
• aircraft performance characteristics,
• interaction among multiple airports,
• and weather conditions.

SIMMOD uses a node-link structure to represent the gate/taxiway and runway/airspace route system. Input parameters depending on aircraft type include: permissible airborne speed ranges for use by ATC, runway occupancy times, safety separations, landing roll and declaration characteristics, taxi speeds, and runway/taxiway utilization. Gate utilization depends on aircraft type and airline

SIMMOD output consists of reports which provide statistics describing aircraft delay, travel time, and fuel consumption.

SIMMOD also has a post-processing animation system which shows the movement of aircraft on the airfield and in the airspace.

2.5.1.3 VAST: Virtual Airspace Simulation Technologies
The Virtual Airspace Simulation Technologies (VAST) support NASA’s Virtual Airspace Modeling and Simulation Project’s objective of developing and benchmarking a set of analytical models to assess air transportation operational concepts. VAST is both a non-real-time modeling environment for system-wide
assessments and a real-time modeling environment for specific human performance assessments. Components of the VAST of specific interest to WakeVAS are described below and are used individually or in combination as required.

2.5.1.4 LMINET3: A Queuing network model (from Logistics Management Institute, Inc.) of the National Airspace System (NAS) used to investigate delay reduction for estimated future demand. Delays recorded include:

- Departure Queue
- Arrival Queue
- Departure Taxi Queue
- Arrival Taxi Queue
- Ground Hold
- Wait for Aircraft (aircraft not available for departure)
- Total Delay (sum of the above)

2.5.1.5 ACES: Airspace Concept Evaluation System
This is a modeling and simulation environment for the air transportation system. This capability captures the key feedback response mechanism of the National Airspace System. The agent-based modeling approach used represents the individual behaviors of the airspace participants (e.g., aircraft crew, controllers and airlines) and captures the critical ripple effect of the user’s actions on other system participants. This modeling approach isolates the individual models so they can be enhanced, improved, and modified to represent new concepts with low development impact on the overall simulation system.

ACES features relevant to WakeVAS:
- Individual Runway Identification and Aircraft Spacing Matrices
- Site-specific VFR and IFR configuration models for each airport based on current airport designs
- Representative set of Terminal Areas (currently only ORD, EWR)
- International Flights
- Tail # connectivity feature keeps track of individual aircraft within ACES

Comparison between ACES and LMINET Delay Reduction due to Phase III WakeVAS:
- ACES annualized delay reduction ~ 163,929hrs
- LMINET annualized delay reduction ~ 67,340 hrs
- Average Delay Reduction per Airport LMINET ~ 5,600 hrs
- Average Delay Reduction per Airport ACES ~ 7,300hrs

2.5.1.6 RAMS Plus: Reorganized ATC Mathematical Simulator
Developed for EUROCONTROL, RAMS Plus is a simulation model providing decision support as applied in the design, analysis, and planning of ATM systems. RAMS Plus simulates traffic from a macro-to-micro level (gate-to-gate movements), where a single scenario can contain as many flights, sectors, and airports as needed, from a local to global level, to provide insights into the ATM system being studied. RAMS+ helps answer a spectrum of questions about ATM system, from airspace
design, capacity, working procedures, & safety concerns, to airport movements, capacity and delay.

RAMS Plus Benefits:
- Measure proposed changes to existing ATM systems (e.g. sectorisation)
- Study impacts of new ATM elements (e.g. new runway or airspace restricted zones)
- Propose changes to increase airspace capacity
- Classical controller workload analysis.
- Unlimited “What If?” perspectives on any ATM system.
- Save Time And Money

Primary RAMS Plus objectives are:
- Model & Study Wide Range of ATC System & Concepts In Fast-Time
- Provide Gate-to-Gate Operations
- Unlimited Number Of Flights & Sectors
- Intuitive and Quick Data Preparation
- Geographic Independence (local To global view)
- Rapid Comparative Analysis
- Macro-To-Micro View (fully data driven scalability)
- Provide Meaningful Views (reports) of Simulation Outputs

2.5.2 Real-Time Simulators
This section describes the main Real-Time Tower simulators, enabling Controller’s functions in the Loop.

2.5.2.1 DSNA (SDER): PEGASE/TAMATA
Platform for Experimentations on Ground and Air Systems Environments -Tower and Approach Man-machine interfaces Applied studies based on new Technology and Advanced cooperative principles.

The PEGASE/TAMATA is a complete R&D ATC Human-In-The-Loop simulator, fully controlled by DSNA (Direction des Services de la Navigation Aérienne) and capable to host Human-in-the-loop simulation ranging from Enroute to LOCal controller (runway management).

Its traffic generator, MASS provides realistic aircraft behaviour. It also allows integrating a wind model, into radar tracks, enabling 4D scenario.

Several tools are made available to the controllers on the TAMATA CWP:
- ADAGIO : stack manager and coordination tool
- AMAN : arrival manager
- TBS : Time Based Separation assistance tools (ITV and Target Trailing Position)

Those tools were used during Rapid Prototyping exercises for TBS in 2004. A new set of Real-Time simulations will take place to improve and validate the conclusions of the first Real-Time simulations.

2.5.2.2 NLR : Tower Research Simulator (TRS)
The National Aerospace Laboratory NLR of the Netherlands operates a real-time Tower Research Simulator (TRS) for advanced research and development on airport control tower operations and systems under a variety of meteorological conditions.
The TRS is capable of simulating Tower Control and Apron Control activities at airports under nearly realistic operational conditions, with air traffic controllers and pilots in the control loop. The TRS is well suited for applications where the human aspect plays an essential role, such as the following:

- Validation of Surface Movement Guidance and Control Systems (SMGCS), including strategic and tactical support tools and associated controller procedures;
- Validation of Human Machine Interfaces for controller working position design;
- System integration studies on industrial SMGCS equipment, reducing implementation risk;
- Studies of airport capacity, safety and efficiency under dense traffic and marginal visibility;
- Testing and optimisation of future tower procedures and airport infrastructures, including legislation and safety assessment;
- Development and validation of ATM automation tools, including data link applications, by Collaborative Decision Making (CDM) and Gate-to-Gate operations;
- Studies and training of airport emergency situations, including rescue operations;
- Safety critical runway operations, for example taxiway/runway crossings with heavy traffic and low visibility.

2.5.2.3 Others: ATS (Apron and Tower Simulator) from DLR and TOSIM (TOwer SIMulator) from DFS.

2.5.2.4 USA: NASA FutureFlight Central

A U.S. ATC/ATM test facility dedicated to solving the present and emerging capacity problems of the U.S. airports. The two-story facility offers a 360-degree full-scale, real-time simulation of an airport, where controllers, pilots, and airport personnel can interact to optimize operating procedures and test out new technologies. NASA FutureFlight Central is the first environment where airport planning can be conducted and airport teams can be immersed into a live simulation of specific airports.

Features of FutureFlight Central

- Real-time peak traffic simulation supporting the most complex airport operations
- The world’s only “live action” simulation supporting all interacting positions: TRACON, tower, ramp, and pilots
- Customizable to specific airports, towers, fleet mixes, and specific operating procedures
- 360-degree out-the-window view of a highly realistic 3D representation of specific airport
- Full-scale cab tower configurable as any FAA or ramp tower
- Comprehensive aircraft performance modeling includes control of 75 parameters
- Built-in digital and programmable radio/voice communications system
- Video/audio record and playback from controller, ramp tower, or pilot viewpoints
- Precise controls for weather, time-of-day, cloud coverage, and lighting

2.6 Recommendations

It is recommended:

- To improve Stakeholder (air traffic controllers, pilots, airports, airlines, ANSPs, industry and ICAO) involvement.
- To collect data for validation and safety assessment. Data collection from LIDAR, but also from wake vortex incidents reports are vital.
- To assess Safety and Risk that are the key element in getting operational changes approved.
- To increase European / US Co-operation to complete the wake-physics and to develop the operational applications.

2.7 References

(NB authors named in the text; here listed alphabetically)

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Section 3
Regulatory framework and means of compliance

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3.1 Introduction

This chapter discusses a number of issues related to the regulatory framework pertaining to wake vortex separation minima, and in particular the steps required to introduce new systems and procedures that would allow reductions of these separation minima.

In this context it has to be first established what is actually meant with the term “regulatory framework”. A short description is given of the organisations involved in regulation and their responsibilities. Subsequently the actual regulatory framework (standards and recommended practices) in so far as relevant to wake vortex separation minima and related safety requirements are described. Further the mechanisms of approval or certification of new systems or procedures, particular in the wake vortex area, are elucidated. Finally it is indicated what tools currently are available to support the approval process, and what are the essential research needs to be carried out to qualify these tools as acceptable means of compliance.

3.2 Regulatory framework and aviation authorities

General definitions
In general a regulatory framework in the area of aviation has the following functions:

- To set the minimum admission standards for entry into the aviation system;
- To define the responsibilities of all the participants within the civil aviation system;
- To provide effective sanctions for non-compliance with safety rules;

The main functions of a civil aviation regulator are:

- Rulemaking; i.e. to provide standards for the different sectors of the civil aviation system;
- Certification, approval and licensing; i.e. to perform entry control by means of licensing, approving or certificating new entrants into the system;
• Oversight and enforcement; i.e. to perform functional supervision by means of surveillance, support and corrective actions;

Based on these definitions it is shortly addressed how the regulatory framework and the responsible authorities are organized, globally, and on a European and national scale as well, with particular emphasis on Air Navigation Service provision. Also some future developments are shortly addressed.

On a global scale the regulatory framework has been established by ICAO.

**ICAO**
ICAO was established in 1944 with the signing of the Convention on International Civil Aviation in Chicago. Today ICAO has 185 contracting States, including all European states. Usually it is the civil aviation authority that represents the State in ICAO. The Convention and its 18 technical Annexes are comparable to international law. The Convention and the Annexes can be considered multi-lateral agreements between States, essential for the regulation of international aviation. It is a contract between States, and that is why the 185 member States are called contracting States in the ICAO vocabulary.
The Annexes contain international Standards and Recommended Practices (SARPS). States implement the Standards, and endeavor to implement the Recommended Practices in their national legislation and regulations. In practice there are instances in which states may deviate from the Standards for particular reasons. In such cases the state has to inform ICAO of such deviations by means of a formal Notification of Difference. There is no requirement to inform ICAO concerning deviations from Recommended Practices. Normally, the ICAO regulatory framework is considered minimum requirements to be implemented in each State. However, there are areas, where developed States may be expected to go above the minimum ICAO requirements.

Despite the fact that the global regulatory framework is established by ICAO, ICAO can not be regarded as a global civil aviation authority. This is because ICAO is functioning primarily at the rulemaking level. It is not responsible for either certification/approval or for supervision/enforcements. These functions are strictly the competence of national aviation authorities.
The consequence of this is that it may lead different interpretations of the regulations, and to varying methods and processes for approval and certification at national level.

**Eurocontrol**
Within Europe EUROCONTROL (comprising today 35 states) has assumed responsibility with respect to safety related rulemaking and publications of standards on European Level for the domains of ANS and ATM (ground part and some airborne elements).
In 1998 Eurocontrol established a Safety Regulation Commission (SRC), which main objective is to harmonise safety regulation and safety initiatives within the Eurocontrol Member States.
The formal rulemaking function, i.e. the taking of decisions that bind EUROCONTROL’s Member States is the preserve of EUROCONTROL’s Permanent Commission.
The harmonised framework for ATM safety regulation is currently embodied in the EUROCONTROL Safety Regulatory Requirements (ESARR). According to the “Single European Sky” regulations, these ESARRs are to be progressively translated into the Community legislation.

The concern with EUROCONTROL’s regulatory function is that it suffers to a certain extent from a similar drawback as ICAO. Eurocontrol is not a regulator which is directly able to transfer rules into binding legislation. It needs the adoption of rules into national or Community legislation to make them binding. Also it does not have the authority within Europe to certify or approve systems and to supervise and -if required- enforce the implementation of the regulations. It is still the national authority that has this competence. As a result difference exists in the implementation of ESARRs among the Member States of Eurocontrol [1].

**National authorities**

As mentioned above the regulatory framework has its roots in international rulemaking. However, the main regulatory functions are still the responsibility of national authorities. For this reason the introduction of any new system or procedure in a certain country needs approval at national level. This means that any country can decide which interpretation of the international standards and practices are acceptable. Also the acceptable means to show compliance are agreed on a national level. This is specifically true in the area of ANS and ATM. In other areas of the aviation system, such as airworthiness, operations and maintenance, international harmonisation of rules and standardisation of approval processes has largely been accomplished within (first) JAA and (now formally) within EASA.

**Future Developments**

The problems arising from the non-harmonised regulatory framework, and non-uniform implementing rules, in the area of ATM, ANS and airports have been recognised at the European level by the European Commission. For this reason the EC is now preparing a new directive that will transfer in the near future (around 2010) the regulatory competences in mentioned domains to EASA. It is of importance to realise here that an approval or certification of wake vortex advisory systems within Europe most probably will not materialize before the regulatory competences in the field of ATM have been transferred to EASA. So, it must be expected that such future systems will most likely be approved under the authority of EASA, against the safety requirements that are adopted by EASA at that time. Evidently, it is as yet not clear how such framework look like. It is likely that it will be based to some extent on the current ESARRs, but at the same time it may be expected that EASA will adopt a total aviation system approach, and will apply experiences and processes from other domains (airworthiness, operations) in the approval of ATM systems and procedures.
3.3 Wake turbulence regulations

In the context of wake turbulence regulations it is first and for all important to establish which Standards and Recommended Practices are in force in this area. Quite surprisingly it has to be concluded that within the international regulatory framework of the ICAO SARPS and Eurocontrol ESARRs the specific subject of wake turbulence separation minima is in fact barely addressed.

Wake separation minima
Annex 14 – Aerodromes – is the only regulatory standard document that mentions the issue of wake vortex separation minima, as part of a recommendation concerning the minimum distance between two parallel runways, by referring to the so-called PANS-ATM (Doc 4444), see text below.

ICAO Annex 14, Aerodromes, par. 3.1.10

Note.— Procedures for wake turbulence categorization of aircraft and wake turbulence separation minima are contained in the Procedures for Air Navigation Services — Air Traffic Management (PANS-ATM), Doc 4444, Part V, Section 16.

Inspection of the PANS-ATM shows that in fact in the following sections the guidelines for wake turbulence separation minima are laid down:
- chapter 4.9: Wake turbulence categories
- chapter 5.8: Non-radar wake turbulence longitudinal separation minima
- chapter 8.7.4: Radar separation minima

For details on these well-known criteria is referred to the PANS-ATM itself [2]. The PANS-ATM is however not an ICAO standard. This means that states in general will endeavor to comply with the requirements of the PANS-ATM, but it is no binding requirement. To avoid misunderstandings, most states do follow the requirements scrupulously and will not deviate without good reason and motivation.

However, in the present context it is however interesting to note that there are various states that use deviant radar separation minima. For instance within the US, a different definition of the weight categories is used, and in addition the Boeing B757 is categorized as a “heavy” aircraft, whereas based on it’s actual max. take-off weight it would be categorized as “medium” weight aircraft. Within the UK (CAP 943) a set of criteria is used, that is based on another definition of the weight categories. CAP 943 specifies 4 categories, i.e. heavy (> 136000 kg), medium (between 136000 and 40000 kg), light (between 40000 kg and 17000 kg) and small(< 17000 kg). Further, in addition to the Boeing 757, a number of other aircraft (DC8, B707, IL62 or VC10) are also categorized as “heavy” aircraft in so far these aircraft are leading aircraft in the separation of aircraft pairs.

The reasons for these deviations from the ICAO criteria are known to be based on national experience and reported incidents. Therefore, they are –safety-wise– most probably a sound initiative of mentioned states.
This is a clear illustration that the regulatory framework inherently incorporates substantial freedom for the various states to tailor criteria and requirements to local circumstances.

**Requirements for Wake Vortex Advisory Systems (WVAS)**

Similar to the wake vortex separation minima there is also substantial freedom for any state to introduce new systems that might enable a relaxation of the wake vortex separation minima. As indicated the approval of such systems is currently a national responsibility and the set of applicable requirements and associated procedures (in the absence of applicable ICAO standards) needs to be defined at a national level.

This current practice invokes however a certain dilemma. Despite their formal responsibilities as the local authority in charge, many states lack the resources and the expert knowledge to define the set of requirements and the acceptable means of compliance for new and complex systems, such as for instance a wake vortex advisory system. For that reason there is a strong urge to pool resources at an international level, and to come to common sets of requirements and implementation rules. Usually, this occurs on a voluntary base.

However, all these initiatives have as yet not materialized either into a common agreed set of wake turbulence separation minima or a uniform set of requirements for wake vortex advisory systems.

This is a serious bottleneck for the introduction of such systems, because without a clear definition of requirements, and the associated acceptable means of compliance to show that the system will meet these requirements, it is not possible design any system that would be accepted for practical application.

For this reason it is of essential importance to define such standards, and acceptable means of compliance, if we want such systems ever to become reality. This would require direct consultation with approving authorities (national and international) and user communities.

### 3.4 Acceptance requirements and means of compliance

**Prescriptive and analytic requirements**

When reflecting on how requirements and the associated means of compliance could look like, there basically are two approaches.

One option is that the authorities prescribe exactly the performance and safety requirements (reliability, integrity, availability), and propose the means of compliance at system and sub-system level. To put it simplistically, the manufacturers in that case basically would have to build the system in conformance with the requirements specification, and tick-off the means of compliance checklist to obtain approval. This could be called a prescriptive approach to system certification. Many aircraft systems are more or less build and certified in this way, by submitting the design to extensive and rigorous certification specifications, including guidance material, means of compliance and Technical Standard Orders (TSO). The notion “acceptably” safe is then inherent to compliance with the certification specifications.
Another option is that the authority would leave the design and the associated design requirements largely to the applicant (manufacturer or service provider) and would approve the system on the basis that it can be proven that the system or procedure would meet a certain pre-defined and agreed target level of safety. This could be called an analytic approach towards obtaining certification approval. The main advantage of this approach is that the authority does not have to prepare detailed set of requirements and that the applicant is not limited in his design freedom. The consequence is that the authority must have the expert knowledge to comprehend and analyse the system design and to rightfully judge the safety documentation required for approval. In this case the notion “acceptably” safe is now directly determined by comparing the established safety level with the target level of safety. Both approaches (and mixes thereof) are in general acceptable to authorities.

Practical approach towards approval of wake vortex advisory systems

If we would now focus on the introduction wake vortex advisory systems, the question is how such a system could be approved or certified for a practical application.

It appears that there are currently very few prescriptive requirements for such a system and its components, embedded within the current regulatory framework. Some requirements can be found in ICAO Doc 9426 [4], see box below.

**ICAO Doc 9426, Part II, Chapter 3, Appendix A:**

[..] a wake vortex avoidance system should meet the following requirements:

a) replace fixed wake vortex separation minima with separations adapted to individual cases, thus optimizing traffic flow;

b) detect the presence of a vortex hazard and generate information necessary to avoid it;

c) make the system ground-based. No additional avionics should be required to obtain the use of the system;

d) **use** a modular system design, tailoring the system capabilities and cost to specific requirements;

e) use a complement of ground instrumentation to ensure uniform system performance independent of site constraints;

f) design the system for maximum independence from other **ATS** systems to ensure maximum system reliability

g) use of the system shall not place any additional burden on air traffic controllers or pilots.

It is evident that such a set of requirements would fall short as a sufficient basis for approval. Moreover they would unnecessarily limit the design freedom of the applicant, for instance by specifying that the system should not require airborne components (see c).

Clearly a large effort would be required to develop and verify the required certification specifications to a similar level as for instance is currently in place for windshear detection and guidance systems (see e.g. TSO-C117 and AC25-12).
Therefore, it seems most practical to use an analytical approach towards achieving system approval. The basic requirements for such an analytic approach are laid down in ESARR4 [11]. Moreover guidance material for the application of ESARR4 is available and safety assessment methods (such as SAM) have been defined to conduct the safety analysis. Nevertheless application of ESARR4 is not without difficulty.

3.5 Acceptable risk models and research outlook

Absolute safety assessments
Application of ESARR4 requires first of all specification of the required safety target of the system in an absolute sense. This safety target has to be derived from the risk classification scheme as presented in ESARR4. This scheme presents the maximum tolerable probability of the overall ATM contribution to accidents as $1.55 \times 10^{-8}$ per flight hour. A fraction of this number has to be apportioned to the system in question, representing the overall safety design requirement for the system.

Research would be needed to determine a reasonable value for this design requirement. It would comprise an analysis of the contribution of the currently applied separation minima to the overall ATM related accident rate in order to establish a baseline safety requirement. Some of this research has already been conducted in the past, but results have to be verified and agreed to be a valid base for the system design.

Further, it is necessary that models are constructed that enable a sufficiently accurate estimate of the actual risk involved in the application of the system. It is of essential importance to the approval process that it can be satisfactorily proven that these models provide trustworthy and valid results, because the results of model simulations factually determine the acceptability of the system in question. This means that the applicable models will have to be subjected to a rigorous validation process, before they can be accepted as an acceptable means of compliance.

We know the elaborate scale of such validation efforts from -amongst others- aircraft autoland system certification processes. As an illustration it is shown here what is required to be delivered for certification approval of such system (JAR-AWO [5]):

- A specification of the airborne equipment;
- Evidence that the equipment and its installation comply with the applicable standards;
- A failure analysis and an assessment of system safety
- A performance analysis demonstrating compliance with the applicable performance criteria;
- Flight test results including validation of any simulation;
- Limitations on the use of the system and description of crew procedures;
- Evidence that the crew work-load is acceptable;
- Inspection and maintenance procedures shown to be necessary by the system safety assessment
It should be added to this that the performance and safety analysis of a wake vortex advisory system would require a much more complex model than required for autoland certification. This stems from the fact that simulation of the wake vortex advisory system would have to include the properties of various aircraft types, ground equipment, meteorological conditions and prediction thereof, wake-vortex prediction, and human performance. Development and validation of all these model elements will require a tremendous effort, depending on the required accuracy.

It may even be expected that a complete simulation model of WVAS operation to a similar fidelity as autoland certification simulations might prove to be beyond current technological feasibility. One should think of Monte Carlo type of simulations with a representative number of real (qualified, non-linear, 6 degrees-of-freedom) aircraft models, 3D encounter models, wake vortex measurement and prediction, weather and weather prediction, and human interaction. Therefore it is clear that actual simulation models require substantial simplifications. The effects of such simplifications on the accuracy need to be carefully analysed, and it has to be established whether the resulting accuracy will be sufficient for the analysis at hand. Therefore, further research will be needed to establish and validate which model approximations would be acceptable.

**Relative safety assessments**

A possible outcome of mentioned research might be that an absolute estimation of the actual risk can not be performed with sufficient accuracy, to support approval decisions based on a comparison with a specified (absolute) risk level.

Therefore, alternative methods should be investigated that reduce the effects of model simplifications. Such an alternative is the relative risk assessment. It is known that relative estimates have smaller ranges of uncertainty, and thus are less susceptible to model simplifications. In this respect it should be noted that currently there is not any requirement or standard that would preclude system approval on a relative basis. The basic reasoning is that current ATM procedures and/or systems are each contributing to the currently accepted level of safety (or rather unsafety), as f.i. specified in ESARR4, although the actual quantitative contribution might not be exactly known. If it can be proven that new systems or procedures are at least equally safe as the ones they replace, the overall safety level would not be affected and therefore would satisfy the required target level of safety. The acceptability of such an approach should be further investigated. In particular, agreement should be reached concerning baseline scenarios that would represent current standard practices, and concerning the judgment that these scenarios are considered acceptably safe. Also it would have to be established which model simplifications are allowable in a relative comparison. It is essential that models do not lead to bias effects when comparing the safety of two systems.

**Introducing new systems**

It should be realized that the outcome of any safety assessment (relative or absolute, qualitative or quantitative) will inherently encompass certain levels of uncertainty, due modeling inaccuracies, assumptions and simplifications. Therefore methods should be found that reduce these uncertainties to acceptable levels before the new
systems or procedures are fully applied in practical operation. A common procedure is to define a specific introduction phase for the system at hand. A good example of such approach is the autoland system. After the initial approval, based on the safety assessment results, the system is first required to demonstrate a certain number of actual autolands in service before weather limits, under which the system can be operated, are gradually lowered. Clearly such a phased introduction builds confidence in the system and the associated safety assessments. This enables a gradual and controlled transition from the standard operation to the full operational application of the system. **In the context wake vortex advisory systems it is therefore prudent to conduct further research to specify a suitable introduction phase for such systems.**

*Simulation models and validation*

Evidently, there is wide array of safety methodologies that can be used for safety assessments, both qualitative and quantitative. It is beyond the scope of the present chapter to address all of these (qualitative and quantitative) methods. However, in light of the anticipated application of ESARR4 requirements for performing risk assessments, simulation models that are able to estimate the risk level in a quantitative (probabilistic) way are of particular interest here. These models are further addressed in the following.

In general there are two basic requirements that would have to be satisfied by any of such models. That is that they have to be:

- validated as a sufficiently accurate representation of the operation under study, and…
- able to estimate the actual risk level involved in the operation

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**Figure 1: Wake vortex safety assessment model (WAVIR)**
Presently, there are three simulation models that are potential candidates to meet these requirements, viz.

- WAVIR (NLR)
- WakeScene (DLR)/VESA (AIRBUS)
- ASAT (FAA Standards Development Branch, AFS-420, which subcontracted development to Air Traffic Simulation Inc. (ATSI))

WAVIR (Wake Vortex Induced Risk) is a stand-alone risk assessment method, based on a modular approach. Risk assessment process employed by WAVIR is depicted in the figure 1.

Basically it is a three step approach. First evolution of the generated wake vortex by a leading aircraft is calculated at a given number of gates along the approach or departure path. From this the relative position and strength of the wake vortex can be determined at the time that a following aircraft passes the defined gates. Secondly, the effect of the wake on the passing (i.e. follower) aircraft is determined. Depending on the aircraft model used this is expressed either in a single disturbance parameter (induced roll angle) or a combination of disturbances (in the lateral and vertical axes). Finally these disturbances are translated to a certain hazard category. The set-up of the model allows Monte Carlo simulations, with varying meteorological conditions, aircraft types, etc. to estimate frequencies of certain risk events in a certain scenario. This can than be compared with a certain target level of safety in order to establish the anticipated acceptability of the operation.

Figure 2: Development of wake vortices visualized by circles in 13 gates from final approach fix (gate 1) to threshold (gate 25). Dimensions in meters. Wake-generating aircraft has already landed, follower aircraft (magenta) at about 2.5 NM before touch-down. Due to changes of wind directions wake vortices are transported in opposite directions at different heights.
The WakeScene (Wake Vortex Scenarios Simulation) Package allows assessing the relative encounter probability behind different wake vortex generating aircraft within a domain ranging from the final approach fix to threshold. An example of a result of WAKESCENE is shown in figure 2.

In cases with potential wake encounters all relevant parameters (encounter conditions) can be provided to VESA (Vortex Encounter Severity Assessment) which subsequently performs an assessment of the wake vortex encounter severity.

The modeling environment supports Monte-Carlo Simulation as well as prescribed parameter variations and generates statistical evaluations. The package consists of elements that model traffic mix, aircraft trajectories, meteorological conditions, wake vortex evolution, and potential hazard area. The Aircraft-Speed Model provides time, speed, and mass of generator and follower aircraft at the different gate positions, using point-mass aircraft models, based on the BADA database [6]. From this the Flight-Path Deviation Model computes random deviations from nominal glide path which are derived from measured flight path deviations [7]. The Meteorological Data Base comprises a one-year statistics of meteorological conditions (more than $1.3 \cdot 10^6$ vertical profiles) for the Frankfurt terminal area which were produced with the weather forecast model system NOWVIV [8]. Based on vertical profiles of environmental conditions and aircraft parameters, the Probabilistic Two-Phase Wake Vortex Decay and Transport Model [9] simulates the development of wake vortex trajectories, circulation, vortex core radius, and attitude of wake vortex axes. The module Hazard-Area Model computes the distance between wake vortex and follower aircraft. The severity of the potential encounter is then computed by VESA.

![WVE Flight Simulation Diagram](image)

**Figure 3: High-fidelity wake vortex encounter simulation of VESA**

VESAs is based on fast-time, high-fidelity aircraft simulations that are embedded in a MOPS/Matlab environment (see figure 3). The wake vortex encounter simulation consists of four main elements: the wake vortex encounter software package, the 6 DOF flight simulation of the follower aircraft, a pilot model and severity criteria. The wake vortex encounter software package consists of the model of the wake vortex velocity profile (generator aircraft) and the aerodynamic interaction model (AIM, follower aircraft). The AIM uses the strip method to compute the forces and moments
that the velocity field of the wake vortices induce at the follower aircraft. These forces and moments are the input of the flight simulation of the follower aircraft. Depending on the application of the WVE simulation, the follower aircraft is controlled by a pilot (simulator tests), an autopilot or a pilot model (offline simulations). The vortex-induced aircraft responses are finally assessed with the help of a severity criteria which correlate the objective aircraft parameters with the subjective assessment of pilots that is known from piloted simulator tests. VESA’s environment allows Monte Carlo Simulations, single case studies, sensitivity analyses and worst-case search.

ASAT (Airspace Simulation and Analysis for TERPS) is a collection of models and simulations that can be used to analyze safety and risk factors for a large range of aviation scenarios. As opposed to WAVIR and WAKESCENE/VESA it has not been specifically designed as a wake vortex risk assessment model. In fact it is a generic simulation package that can be used for many applications, of which wake vortex safety assessment is one.

The heart of the system consists of the high fidelity engineering flight dynamics models of three Boeing aircraft (737, 767, and 747) against which the lesser models normally used in the high speed simulations are frequently checked. Model performance is also driven by empirical data collected in flight simulators and flight tests. In addition to these aircraft simulation models ASAT comprises models of aircraft avionics (FMS, autopilot, etc.) based on real equipment, models of ground navigation aids, etc. In this respect the simulation models resemble the models as for instance used in autoland certification.

For its wake vortex applications it uses airport models, models that emulate aircraft trajectories, a pilot model to control the aircraft trajectory and a module that provides wake vortex trajectory evolution and decay. If the distance between a vortex and the follower aircraft is smaller than a conservative threshold value, an encounter is detected/counted.

With these models ASAT is well suited to determine the probability of potential encounters. Similar to WakeScene, ASAT has an interface to VESA that permits subsequent wake vortex encounter severity assessment.

Validation issues and research outlook
The simulation models described above have some generic resemblance, but at the same time they differ essentially at the level of sub-models employed and the calculation processes used. A recent validation of sub-models within WAVIR and WakeScene [10] has revealed several differences at sub-model level. For instance wake-vortex evolution in ground-effect showed significant discrepancies. Also the flight-path evolution and wake vortex encounter models are modeled differently. It is presently unknown how the various model assumptions and model simplifications in the mentioned models affect the final risk assessment results. However, in light of the anticipated application of the models in future approval processes, it is undesirable if the outcome (in terms of risk estimates) of the various models would differ significantly from each other.

Therefore, as part of a future research outlook it is recommended to direct efforts into a comparison of the available models and validation of the employed sub-models. This would provide an indication which simplifications would be allowable, and where the models would be sensitive to the modeling structure and parameters.
The outcome of this research could provide a baseline for modeling requirements that would be acceptable as a means of compliance in future approval (or certification) processes. How this research should be mechanized is an issue that needs to be agreed internationally. **An effective proposal could be to define a benchmark scenario and apply the various models to conduct a risk assessment for this scenario.** This would give an indication of the level of differences between the models and could identify the required accuracy of sub-models to equalize differences to an acceptable level.

### 3.6 References

Section 4
Probabilistic prediction of wake position and strength

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Wake vortex physics is in general well, though not completely, understood. A recent assessment can be found in [1]. It can be concluded from existing data that, under certain circumstances, wakes persist longer than the applicable longitudinal separation standards. Nevertheless, there is a general consensus, based on the empirical evidence, that the present ICAO rules with respect to (IFR) wake vortex separations are acceptably safe; there is however no rigorous proof of that. Also, available field data indicate that wake vortex behaviour (transport and decay) is very sensitive to the weather conditions and to the ground proximity conditions. Both points illustrate that a probabilistic approach is essential in support of any new ruling.

Abnormal behaviour (long lived vortices, rising vortices) are still very much of concern and its relation with specific atmospheric effects is still not completely understood. Another issue is the more or less stochastic nature of the occurrence of strong thermals that cause complex large scale deformations of the vortices and enhanced decay. The prediction (transport and decay) under these highly turbulent conditions can still be done, by taking into account the increased RMS value of the ambient turbulence. Another important factor is the ground proximity (near ground effects (NGE) and in ground effects (IGE)), which is also often combined with wind and wind shear: those affect vortex wakes in a complex manner, both for transport and decay: e.g. rebounding vortices IGE, tilting of the vortex system by the wind shear, eventually resulting, when IGE, in one vortex interacting strongly with the ground while the other one rises and gets advected by the wind. The accuracy of predicting the advection of wakes due to wind and wind gradients for parallel runways approaches (in and out of ground effect) and for take-off situations is also of high importance.

Operational models are available, that predict the global transport of each wake vortex and its global decay (e.g., in terms of $\Gamma_{5-15}$) [3-11, 13-14,16-17]. They result from many years of studies and developments; and they are still continuously being further enhanced. The “validation” of such models always was, and still is, a most critical issue. Clearly, this validation can only be done, and should only be done, in a statistical way. Indeed, there is a significant stochastic element on the “input data
As well as on the “predictive model side” (the models being parameterized and real-time, they are necessarily much simplified compared to the reality; they are based on sound physics, yet they have “coefficients” that need to be determined, etc.). The models have already been calibrated and (partially) validated on the basis of the existing databases and large-scale 3D simulations (large-eddy simulations, LES). Some models are however better calibrated and validated, also because of access to more recent data that are not (yet) available to all groups. Efforts have also been made to categorize the weather conditions in particular “weather classes”: those are also useful for validations. All this being, it is also important to recognize, and accept, that a complete validation is out of reach. It is also not necessary, given the fact that the predictions are made probabilistically. The obtained distributions can be used to obtain valid PDF (probability density function) fits which, in turn, can be used to provide probability estimates. Obviously, PDFs also contain tails: the part beyond the predictions and/or the finite number of available experimental measurements. The statistical significance of those tails is however limited. The obtained PDFs are likely to provide probability estimates that are sufficient for “relative risk assessments” studies (i.e., studies aimed at showing that a new proposed procedure is better than a baseline procedure).

It is important that the existing databases be used for validation; for that, it is also important that they be made available as much as possible to the community. As to further campaigns, the relation between what needs to be measured and what is required for further model validation should be established first. It is equally important in the analysis to determine what type of information and detail is actually needed on the weather side (profiles, spatial coverage, time-averaging, etc.) as it relates to wake vortex behaviour prediction.

We now further consider the models that are used for wake vortex behaviour prediction. The primary objective of a parametric wake vortex model is to reliably predict vortex positions and strengths, in real-time, in order to guide a safe readjustment of aircraft separations. For this purpose, the model should consider all effects of the first (leading) order impact parameters: aircraft configuration (span, weight, velocity, trajectory), wind (cross and head components), wind shear, turbulence (also that associated with wind shear or thermals), temperature stratification, and proximity of the ground. It is also to be noted that the prediction is needed at varying height, along the complete flight path. There is no doubt that the prediction of the (sufficiently) detailed weather conditions is a most important issue in itself, and that it merits a whole section in this document.

To take into account the stochastic characteristics of wake vortex behaviour, the model should predict a deterministic (mean) evolution together with envelopes for vortex trajectories and strengths, combined with specified probabilities. From the number of proposed wake vortex models, only a few comply with most of the listed requirements. In the following, two models, the “Vortex Forecast System” (VFS) [8,12,13,16] together with its probabilistic version (P-VFS) [2,14,17], and the “Probabilistic Two-Phase wake vortex decay and transport model” (P2P) [2-7,17],
will be introduced to illustrate capabilities, validation activities, and prospects connected to current real-time wake vortex modelling.

The VFS is a deterministic predictor based on the method of discrete vortices (discrete “vortex particles”): those are used to model the “primary” wake vortices (those generated by the aircraft) as well as the “secondary” vortices (those generated near the ground when IGE). It was developed by an international team (SABIGO of Russia, Oracle Telecomputing Inc. and M. Yaras of Canada, and G. Winckelmans of UCL, Belgium), in the framework of “Wake Vortex Project” funded by Transport Canada (TC) from 1994 to 2000 [8,12], and since further developed by UCL [13-16]. Its latest version has physical models that use all the wake-vortex impact parameters listed above. The physical models are implemented using an “accumulated damage” approach, so as to capture the variations with altitude of the input weather profiles. Two decay models are implemented (EDR-based decay model, also further calibrated based on LES, and TKE-based model, used when EDR is not available). A “two-phase” decay approach is also implemented, following an approach similar to that in [3,4]. The NGE effects are modelled using image vortices. The viscous IGE effects are modelled using additional (secondary) vortex particles that are produced near the ground at the location of the dynamically evaluated separating boundary layers, also taking into account the cross wind effects: the vortex particle method is indeed capable, even with a moderate number of secondary particles generated (typically 100 total) to capture sufficiently well the vorticity flux emanating from the ground and the vorticity leaving the ground to interact with the primary vortices; this, in turn, allows to obtain the enhanced decay effects IGE. An original wind shear effect model was also developed and implemented to account for tilting of the wake vortex system under wind shear conditions [8,12]: its determines both the shear-induced vortex circulation variation and vertical displacement variation (through an added velocity). When IGE, this model also allows to properly capture the asymmetry on the port and starboard vortex behaviours under crosswind, and its associated wind shear, see [14]: for instance, one vortex interacting strongly with the ground while the other one rises and gets advected by the wind. Finally, an original two-equation model was recently developed and added, to capture stratification effects [16]: it determines both the stratification-induced vortex circulation decay and vertical velocity variation (through acceleration).

A further note concerning winds shear effects: based on the physics [8,12], one finds that modelling the rate of change of vortex circulation and vertical velocity, requires using the second derivative of the cross-wind profile (i.e., the first derivative of the wind vorticity profile). However, the net integrated effect on a vortex system going through a shear region (e.g., its net tilting) is only sensitive to the first derivative of the wind: this lessens the requirements on the wind profile. Basically, shear effects on wakes are significant when the wind variation over a distance scaled by vortex spacing is significant compared to the wake-induced descent velocity (i.e., when the dimensionless “shear parameter” is high enough).

The physical models used in the VFS are already quite mature, and their calibration (using experimental databases and LES) is also well advanced, though not completed. The VFS already allows to realistically capture, and thus predict, complex wake vortex behaviours.
Recognizing that probabilistic modelling and assessment of wake vortices is clearly what is required, an upper software layer was also developed by UCL, for “Probabilistic use of the VFS” (P-VFS). The P-VFS tool is based on Monte Carlo simulations (themselves using the deterministic VFS as a subtool) that use the uncertainties/variations of the input impact parameters (aircraft and weather profiles) and of some of the VFS physical model coefficients (those less well determined/calibrated). Typically, the P-VFS uses one thousand to ten thousand VFS runs, depending on applications. The output of the P-VFS is the obtained distribution (the “empirical” PDF) of predicted wake vortex behaviours (transport and decay). Eventually, a mathematical PDF shape is further assumed and is fitted to the empirical distribution. In either case, the PDF provides the mean predicted behaviour as well as the envelopes for probabilities. An example of prediction results is shown in Fig. 1. The provided envelopes of $2\sigma$ (95.4%) and $3\sigma$ (99.7%) were here based on assuming a Gauss normal distribution.

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Fig. 1: Wake vortex behaviour as observed at the Dallas Fort-Worth test campaign (case DFW 2021) and compared with calculations using P-VFS by UCL. The symbols denote the actually measured values (+ for starboard vortex and o for port vortex). The lines represent the predictions: red and blue lines denote mean behaviour of the port and starboard vortex respectively; green and light blue lines envelopes for 95.4% and 99.7% probabilities. The figure right below indicates the weather conditions that are used as input: vertical profiles of wind (mean profile in solid black and uncertainty bounds in dash-doted black) and temperature (green).
The P2P also considers all of the wake-vortex impact parameters listed above. Recently, the ground proximity model has been adapted to wake-vortex measurement data acquired at Frankfurt airport [7]: apparently, relatively simple modifications improve prediction skill noticeably, see Fig. 2. Since the impact of ambient turbulence and crosswind on vortex decay turns out to be weak, it appears sufficient to employ an average ground effect decay rate (realised by an effective viscosity) as soon as the vortices reach the lowest altitude above ground. On the other hand, the impact of crosswind on vortex rebound characteristics is very strong. The observed asymmetry is here modelled by adjusting the strength and generation time of the secondary vortices, see Fig. 2.

Fig. 2: Example of P2P model output. Measured (symbols) and predicted (lines) evolution of normalized vertical and lateral positions and circulation in ground proximity. Red and blue lines denote deterministic behaviour; green and light blue lines envelopes for probabilities of 95.4% and 99.7%, respectively. Right below: vertical profiles of normalized environmental data.

So far P2P has been validated against in ground and out of ground effect measurement data of two US and four European field measurement campaigns [3-7]. To evaluate deterministic model performance a scoring procedure has been applied to data of five
campaigns. The scoring indicates that deviations between measurement and prediction continuously have been reduced which reflects progresses in prediction, measurement, and data analysis techniques.

Of major interest for the introduction of operational wake-vortex advisory systems, however, are unusual and safety relevant cases like long-lived vortices and rebounding vortices caused by turbulence, stratified atmosphere, wind gradients, thermal activities, and ground proximity. With the exception of rebounds caused by stratification and ground proximity, which are directly parameterized, all these influences are addressed within P2P by its probabilistic components.

In the first instance, the increased scatter of vortices in turbulent and convective environments is modelled by the assumption that the RMS value of ambient turbulence serve as superimposed propagation velocity which widens the predicted envelopes [3]. If wake vortices encounter a pronounced shear layer, a normalized shear velocity is employed to expand the envelopes for vortex transport in a similar way as it is done for turbulence [6]: P2P detects regions with a critical amount of shear (regions with “shear parameter” above a threshold) and widens the probabilistic envelopes accordingly.

These measures address the average increase of scatter caused by environmental conditions. The unusual cases which deviate most from the mean behaviour can in a first step be estimated and in a second step be modelled based on statistics of vortex measurements [6]. The described method is applicable to probabilistic model output of any wake-vortex model.

![Figure 3](image)

**Fig. 3:** Probability density distributions of measured lateral position, vertical position, and circulation of wake vortices normalised with respect to the uncertainty bounds predicted by P2P. Fits of respective PDFs denoted by dotted lines.

For this purpose a preferably large number of measurement data is related to the predicted probabilistic bounds such that values of zero and one denote measurements situated on lower and upper bounds of vortex predictions, respectively. As an
example, the resulting statistics of 110 vortex evolutions in ground proximity is shown in Fig. 3. Clearly, the unusual cases are situated in the tails of the distributions. The second step is to fit a mathematical PDF to the empirical distributions (dotted lines in Fig. 3). The validity of the fits is assessed by Kolmogorov-Smirnov goodness-of-fit tests at a significance level 0.05.

Valid PDF fits are likely to provide probability estimates that can be extrapolated beyond the range of the finite number of the so far available experimental measurements; at least up to some extent. Based on these PDFs, the model output can be adjusted to a required degree of probability, at least up to some extent. Figure 2 exemplarily shows envelopes with probabilities of $2\sigma$ (95.4%) and $3\sigma$ (99.7%). This approach, of course, primarily considers unusual behaviour that is contained in the employed database (with a certain extrapolation given by the fit). This also highlights that a large number of measurement data must be available in order to establish statistics which are adequate for validation of operational wake vortex predictions.

![Fig. 4: Example of danger volume prediction by the ATC-Wake Predictor tool with wake vortex measurements (here case WakeTO419). The ATC-Wake Predictor uses both the P2P and the P-VFS (respectively dashed lines and solid lines) and merges the results; this also increases the reliability of the prediction. The green area is the ICAO corridor tolerance. Right below: vertical profiles of temperature (dashed) and crosswind (mean profile in solid and uncertainties in dash-dot).]

It is also worth mentioning that both the P-VFS and P2P predictors have been implemented in the Virtual Integrated Platform (IP) of the project ATC-Wake [2,15,17]. The prediction system handles probabilistic simulations and assessments
for all computational gates corresponding to all aircraft in the airport area (the gates being created dynamically every 6 seconds). The proper reconstruction (3-D space and time) of the complete wake vortex situation provides the time evolution of the “danger volumes” (the volumes in which wake vortices could be found). These are the usable results for the ATC-Wake Predictor system. An example of danger zone evolution is shown in Fig. 4.

Concerning the future developments of the models, we note the following:

- More measurement data is needed to increase the validity of the statistical basis used for probabilistic predictions.
- The P2P and the P-VFS will still be further validated and improved for wake vortex behaviour IGE, also as part of the ongoing project FAR-Wake on “Fundamental Research on Aircraft Wake Phenomena” (within WP3 on “wake evolution near the ground”, T3.3 on “assessment and real-time modelling”).
- It must be verified that the wake vortex models are adequate for take-off, as it is planned in the project CREDOS on “Crosswind-Reduced Separations for Departure Operations” recently accepted by the EC. The models must be adapted to take-off conditions where required.
- A clearer relation between the spatial and temporal resolution and the accuracy of measured or predicted environmental parameters and wake-prediction skill would be very helpful to design optimum wake-vortex advisory systems. However, this is a difficult and time-consuming task. Maybe that part of such systematic investigation could be done theoretically (e.g., by running simulations of P-VFS with detailed local weather models). But, if we want to answer these questions completely, we also need to cover all the possibilities for real vortex behaviours.
- Parameterizations of the orientation and curvature of vortex axes might turn out to be decisive to model the weak impact of long-lived and strongly deformed vortices on encountering aircraft.
- An important question is still whether the remaining uncertainty on the PDFs (the tails) is low enough to give acceptable uncertainty numbers for a probability-based safety analysis of specific procedures with respect to wake encounters? Even without further knowledge about the tails, the obtained PDFs already provide probability estimates that appear sufficient for “relative risk assessments” studies (i.e., studies aimed at showing that a new proposed procedure is better than a baseline procedure). What quality is required of the PDFs for “absolute risk assessment” studies” remains to be investigated.
- The only way to further assess the quality of PDFs is to check their validity against other, independent, measurements. So far, the results are promising. The number of measurements needed is still an open question.
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Section 5
Wake Vortex Encounter Assessment

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5.1 The state of the art

The survey of the state of the art comprises relevant references and available validations of models and tools. Most work in the area of wake vortex encounter research has been and is done in Europe and USA [1]. A comprehensive overview on wake vortex research for transport aircraft during the 20th century is given in [2] and also in [36].

5.1.1 Analytical Studies
Several studies investigate wake vortex encounters with analytical means [45], [46]. A NASA study investigated parallel wake vortex encounter in terms of wake vortex-induced accelerations [20]. Roll and vertical accelerations were identified as dominant.

5.1.2 Offline Simulation
Numerical offline simulations offer the possibility to perform systematically parameter studies with repeatable constraints. Some basic parameters for the uncontrolled and automatic controlled aircraft in a wake vortex encounter situation were investigated in Ref [30]. Flight path deviations and bank angle response were used to assess the effect of parameter variation.

Numerical wake vortex encounter offline simulations with an autopiloted B737-100 behind a B727 were performed to develop boundaries for wake vortex encounters with a tolerable severity [35]. The strip method was used as aerodynamic interaction model. The required control power to counteract the wake and the maximum bank angle turned out to be a suitable criterion [34].

Most wake vortex models describe straight vortices. Ref. [13],[14] report about investigations in a Boeing 737-300 flight simulator where perturbed vortices were encountered with activated autopilot. The results show a significant reduction in the maximum bank angle and a continuous reduction in the level of upset as the vortices become increasingly wavy and ultimately break up into rings (Crow instability).

Early studies considering wake vortex encounter improvement with automatic control feasible are [48], [49]. Encounter simulations using an autopilot based on model following control (designed for ILS approaches) were conducted at DLR. Although this autopilot was not specifically designed for wake vortex encounters the aircraft
response was generally improved. Encounter simulations suggest that a value of 0.3 for the required roll control ratio (wake vortex induced rolling moment related to encounter aircraft roll control power) is acceptable. This assures tolerable automatically controlled wake vortex encounters in terms of flight state and flight path deviations [3]. Even better aircraft behaviour was achieved with a special feed-forward controller for wake vortex disturbance compensation [44]. The latter concept requires knowledge of the flow field ahead of the aircraft.

In [23] a nonlinear lifting line method has been implemented to calculate the wake vortex induced forces and moments on an encountering aircraft opposed to the widely used strip method. Unsteady effects have been incorporated to provide a more realistic aircraft reaction which is generally weaker [24]. It is expected that this effect is more significant for strong encounters and that there is only a minor influence on flight path deviations.

5.1.3 Pilot-in-the-loop Simulation

Piloted wake vortex encounter simulations with the goal to develop hazard criteria for wake vortex encounters were conducted by NASA using the strip method as a wake vortex encounter/aerodynamic interaction model (landing approach with target flight path through one vortex core). Realistic reproduction of wake vortex encounters with a Learjet 23 was confirmed by experienced pilots [42]. In this preliminary study with 5 pilots and more than 200 simulated wake vortex encounters the maximum bank angle was found to correlate best with pilot hazard ratings. A follow-on study was carried out on a higher-fidelity simulator with Learjet 23 and B707/720 as encounter aircraft and tentative hazard boundaries were developed for VFR and IFR conditions based on encounter altitude and maximum bank angle during the encounter [43], [47]. The relationship between bank angle and altitude turned out to be of high significance for pilot’s encounter perception, which was confirmed by later studies.

Summarizing piloted encounter simulations from the 1970ies [42],[43] and other sources it is concluded that the roll-induced wake vortex interaction is of most concern, especially for parallel encounters (also based on flight tests) and estimated that a required roll control ratio (wake vortex induced rolling moment related to encounter aircraft roll control power) of less than 0.5 results in acceptable wake vortex encounters [39].

A NASA research flight simulator study has been conducted to provide a means to estimate the effects of different levels of wake turbulence on final approach [21]. Fourteen airline pilots of various experience levels flew in total almost 1000 wake vortex encounters (encounter aircraft model Boeing 737-100) giving ratings for the wake vortex disturbance. The study concludes that a normalized vortex strength (wake vortex induced rolling moment related to encounter aircraft roll control power) of 0.2 or 0.3 could be an appropriate limit for acceptable wake vortex encounters. In general the roll acceleration due to the vortex was found to be the primary determinant of the subjective disturbance ratings.

Wake vortex encounter simulations have been undertaken with delta wing follower aircraft offline and with pilot-in-the-loop simulations applying a panel method [25]. Load factor peak values and roll amplitudes are in good agreement with data found in
flight tests with similar aircraft. Pilots have judged observed visual responses to be realistic.

Lufthansa Flight Training has wake vortex encounter simulation available on its full flight simulators, using simplified models [37]. Fine tuning of the models is done subjectively with pilot comments [38]. However as no training requirements exist, wake vortex encounter simulation is not used for pilot training.

Piloted wake vortex encounter simulations have been carried out at Technical University Berlin in an A340 full flight simulator during a national German research project [28]. The lifting surface theory is used as a wake vortex encounter/aerodynamic interaction model and a modified OSEEN vortex velocity distribution after HEINTSCH [30].

Within the European project WAVENC offline and piloted encounter simulations have been conducted at NLR and Aerospatiale with an A319 like trailing aircraft [11]. The strip method was used as a wake vortex encounter/aerodynamic interaction model and the LAMB-OSEEN vortex velocity distribution. Maximum bank angles of 15 deg or more generally resulted in go-arounds [29].

Within the European project S-WAKE piloted encounter studies were conducted with five different aircraft types in order to identify severity metrics and develop hazard criteria [17], [18]. It was found that the encounter severity that is perceived by pilots is depending on the altitude. Parameters for hazard metrics were identified to be bank angle, roll rate, glide slope deviation, and roll control ratio. Different go-around prediction criteria were developed (prediction accuracies of 70% and higher were achieved).

The feasibility of integration of Large Eddy Simulation (LES) data sets (opposed to analytical wake vortex models) into real-time flight simulations is demonstrated in [22]. Using the strip theory as a wake vortex encounter/aerodynamic interaction models, preliminary proof-of-concept simulations were compared with the analytical LAMB-OSEEN model, but no validation has been carried out.

5.1.4 Wind Tunnel Studies
Wind tunnel measurements of the wake vortex velocity distribution and the induced rolling moment on wings behind two transport aircraft were carried out by NASA [32]. Both transport aircraft were found to produce comparable wake vortices also with respect to vortex alleviation.

Static and free flight wind tunnel tests were conducted with a B737 and a business jet model by NASA. The induced rolling moment and the required control power to counteract the wake were measured [33].

Within the European project WAVENC wind tunnel measurements have been conducted with a simple encounter aircraft ("SWIM model"). In addition to the wake vortex velocity distribution the wake vortex induced forces and moments were measured to validate different wake vortex encounter/aerodynamic interaction models with satisfactory results [11].
5.1.5 Flight Test

Flight tests for wake vortex encounter assessment were conducted in the 50s/60s in the USA with smoke visualisation of the wake vortices [55]. B747 wake vortices were investigated with encounter flight tests in 1969 by Boeing for a comparison with B707 vortices [56]. Flight tests were continued in the USA throughout the 70s to study vortex attenuation [58], for example in 1974 Boeing and NASA performed encounter flight tests to study vortex alleviation for a B747 with different flap settings [57]. In general different methods were successful in attenuating vortices but were found to be impractical for operational usage [58].

In 1995/97 NASA performed flight tests with a B737 and a North-American Rockwell OV-10A behind a Lockheed Martin C130. A database was created (about 230 wake encounters) for wake vortex development under different atmospheric conditions including wake velocity data which can be used for validation of wake vortex models [40], [33]. According to [41] considerable effort remains to reduce B737 wake encounter flight data into a usable database.

Wake vortex encounter flight tests with a highly instrumented B737 behind a B727 with smoke generators (for wake vortex visualisation) were carried out by NTSB/FAA in 1995 associated with the investigations of the USAir Flight 427 accident on September 8, 1994 [26],[27]. Over 160 wake vortex encounters were accomplished and simulator tests were performed in addition. A thorough evaluation of the data is not available, however a need for further refinement of B737 simulations was found.

Wake vortex velocity distribution models which describe the spatial distribution of the wake vortex induced velocities are used for wake vortex encounter simulations. The analytical tangential velocity models of BURNHAM-HALLOCK [4] (based on ROSENHEAD [5]) and LAMB-OSEEN [16] were validated with on-board measurements from flight tests within the EU project S-WAKE (Dornier 128-6 and Cessna Citation behind a VFW614). Both velocity models yields good results for wake vortex encounters, BURNHAM-HALLOCK being slightly better than the LAMB-OSEEN model [6],[7].

For the consideration of the effect of wake vortex flow phenomenon on aircraft dynamics aerodynamic interaction models are needed. These models calculate the vortex-induced forces and moments acting on the encounter aircraft. The strip method [10] subdivides the lift generating surfaces into sections for which the vortex influence is determined and integrated over the aircraft [8]. This method was verified against wind tunnel tests in [9], [11] and validated with flight test data in [12] and [7]. The lifting surface method was validated with flight test data and compared with the strip method. Both methods yield good results, with the strip method being less complex and requiring less input data [31].

The concept of Simplified Hazard Areas (SHA) has been developed by the DLR Institute of Flight Systems [3]. Avoiding these zones allows safe and undisturbed flight operations. The definition of the hazard areas is based on the required roll control ratio. The limit for this value must be chosen carefully to ensure that outside the hazard area all wake vortex effects are noncritical. In order to identify such a limit offline simulations, full flight simulator studies and in-flight simulations were
conducted. The hazard area dimensions for a specific roll control limit are derived with the "Simplified Hazard Area Prediction" method (SHApe). Parameterization of the input parameters makes this method universally applicable to different aircraft types. Piloted wake vortex encounters were conducted with a full flight simulator and in a flight test (in-flight simulation – IFS), where the real test aircraft reacts as if it encounters a wake vortex, which is only simulated. Pilot ratings and objective parameters are used to derive a limit for the definition of the SHA [15].

5.2 Applications and Tools

Airbus and DLR have developed several tools that can be used for wake vortex encounter safety assessment: WakeScene and VESA. WakeScene (Wake Vortex Scenarios Simulation, DLR) is an airspace simulation that models traffic mix, aircraft trajectories, meteorological conditions and wake-vortex evolution [19]. WakeScene determines the probability to hit a vortex of certain strength and the encounter conditions (e.g. how the vortex is hit).

WakeScene does not compute the effect of the vortex on the trailing aircraft. This is done by VESA (Vortex Encounter Severity Assessment, Airbus) that is a high-fidelity wake vortex encounter flight simulation [17]. VESA computes the response of the follower aircraft during a wake vortex encounter and, using VESA for statistical evaluations, it determines the probability of severe encounters. For the severity assessment different criteria are available which comprise aircraft parameters such as bank angle, sink rate, glide slope deviation, etc. VESA has interfaces to WakeScene and WAME (WAke Model at Encounter time, Airbus) so that computations can be performed based on simulated encounter conditions. WAME contains models to compute the wake vortex transport and decay. The output can either be the vortex strength as a function of distance behind the generator aircraft or the parameters of different wake vortex velocity profiles. WAME and VESA as well as WakeScene and VESA have been used to evaluate the encounter severity for different scenarios and for comparative wake vortex encounter safety assessments.

The wake vortex simulation capabilities of the U.S. tool ASAT (Airspace Simulation and Analysis for TERPS (Terminal Procedures)), a computer tool for aviation related simulations and safety evaluations, are similar to WakeScene [50], [51]. ASAT has been developed by ATSI (Air Traffic Simulation, Inc.) and was used in studies for FAA.

The Aircraft VOrtex Spacing System (AVOSS) by NASA [52] has been demonstrated at Dallas/Fort Worth International Airport in July 2000 and is considered to increase airport throughput [61]. According to [59] vortex severity is described with a limit for the circulation strength. Based on this project a Wake Vortex Advisory System (WakeVAS) is developed with the goal to minimise the impact of aircraft wakes on operations [53].

WAVIR (WAke Vortex Induced Risk assessment, NLR) is a stand-alone probabilistic risk assessment method comprising three steps: vortex evolution, encounter classification and risk evaluation. Encounter severity is mainly classified based on
altitude dependent bank angle boundaries [54]. The WAVIR method is used for the
determination of reduced separation minima with the Separation Mode Planner (SMP)
within the EU project ATC-Wake.

Transport Canada coordinated the further development and evaluation of a Vortex
Forecast System (VFS) for use by air traffic controllers and pilots during takeoff and
landing in order to reduce separation distances. The major components are wake
modelling and "danger evaluation". For encounter severity evaluation an "admissible
rolling moment as a function of aircraft speed and altitude" is recommended [63].

The Wake Vortex Warning System by DFS (Deutsche Flugsicherung) is technically
completed [62], but an operational use would not give enough benefit in terms of
capacity. A problem is that the meteorological conditions cannot be forecasted
accurately enough with current technology [60].

5.3 Future Developments

5.3.1 Wake Vortex Encounter Safety Assessment
The wake vortex encounter safety assessment is considered as a key element of wake
vortex research. In general a safety assessment is a statistical procedure to evaluate
the risk of a usually rare phenomenon. The evaluation of the risk must take into
account the likelihood of the event and the severity, i.e. the likelihood to encounter a
vortex and the effect of the vortex on the follower a/c.

In connection with wake vortex encounters the terms safety and hazard are frequently
used. This suggests that there can be a clear and unambiguous boundary drawn
between safety and hazard and that there exists a common understanding of these
terms. But it has to be noted that meaning can be very different depending on the
respective application. The term hazard covers the range from a fatal accident to an
undesired go-around. The envelope of a safe wake vortex encounter reaches from go-
around (which is a safe standard flight procedure) to the requirement of undisturbed
flight operations without adverse effects resulting from wake vortices (operationally
safe). Reliable definitions of (non-)hazard criteria (levels) are urgently required
based on a common and clear understanding of what is the respective purpose.
This is the major aspect of any encounter safety assessment. To solve this problem
extensive pilot-in-the-loop wake vortex encounter severity investigations have to
be executed.

5.3.2 Extension of Models and Tools
Most investigations that were carried out in the past focused on approach and landing
as this flight phase was identified as most critical due to the ground proximity.
However, wake encounters can occur during all phases of flight so that it is necessary
to extend the wake vortex encounter simulation and risk assessment capabilities to all
other flight phases (take-off, departure, cruise and landing approach). It is important
that all sub models of the simulations are validated so that they are acceptable
for all stakeholders, i.e. authorities, pilot organisations, ATC.
With a focus on a reclassification of separation standards, it is necessary to take into account all ICAO weight categories. As the current list of high fidelity offline wake vortex encounter simulations does not cover all categories it is desirable to supplement especially an aircraft of the ICAO “light” category and a frequently used aircraft of the regional jet class. As a complete flight mechanical simulation with all aerodynamic derivatives is necessary to set up such a high-fidelity offline wake vortex encounter flight simulation, an organisation is needed, which has access to the aircraft data and which can develop, validate and maintain such models.

For offline severity assessment of manually controlled flights wake vortex encounter pilot models are necessary and have been developed for the approach situation in S-Wake. But for other flight phases like departure models are lacking. The development of such models requires many simulator tests with sufficiently numerous airline pilots.

Aerodynamic interaction models are necessary for the determination of the wake vortex induced forces and moments. However, an assessment of developed aerodynamic interaction models in S-Wake has shown that the representation of the side forces and the yaw motion was found to be less good as for the other axes since the strip method neglected the fuselage effects – a modification of the strip method towards a better consideration of the fuselage effects is an important point for future improvements.

5.3.3 Validation of Models and Tools
The validation of tools and models and an agreement on their validity among all stakeholders such as authorities, pilot organisations, ATC, etc. is necessary and has to be pursued in the future.

For wake vortex encounter simulations a simple one-to-one comparison with flight test data is not feasible because flight tests cannot be performed close to ground for safety reasons, the exact encounter geometry can hardly be controlled during flight test, flight tests always cover specific meteorological conditions and flight tests for a statistical validation are beyond the scope of any project. As a consequence, a sub model validation in conjunction with plausibility checks that ensure correct interaction between the sub models is the only suitable means to validate such a methodology.

Much validation work has been performed within the frame of wake vortex-related European research projects, such as S-Wake, WAVENC, AWIATOR, etc. For example the validation performed in S-Wake has shown that aerodynamic interaction models (strip method and lifting surface method) are valid for the Do128 and the Citation and give a high quality for the vertical acceleration, roll rate and bank angle and moderate quality for the pitch motion. S-Wake did not demonstrate by flight tests if the strip method is valid for a larger transport aircraft with sweep angle and wing twist. Therefore, research work is encouraged, in which aerodynamic interaction models (including fuselage effects) for transport aircraft are validated by flight test results.
5.3.4 Application of models and tools
When wake vortex encounter simulation models and severity criteria are sufficiently validated and accepted by all stakeholders, they can be used for means that allow safety improvements and increase of capacity. For example, a tool for the prediction of reduced (possibly dynamic) wake vortex separations (distances/times) could be developed (including predictions of meteorology & wake vortex behaviour), in order to contribute to airport capacity increase on the air traffic management level.

Another possibility are systems for pilot assistance such as wake vortex warning and avoidance systems that prevent trailing aircraft from encountering wake vortices by early detection and prediction, i.e. priory information is used to evade wakes. On-board wake vortex detection and avoidance systems have been addressed in the European project I-Wake. The benefit of such a system could be demonstrated in piloted simulator tests. Different human-machine interface concepts have been developed and tested. The investigated concepts were based on on-board Lidar sensors that were used to detect the vortex in front of the aircraft. While system integration and the development of an operational human-machine interface is considered as straightforward work, the development of onboard sensors (e.g. Lidar or radar) that are capable of detecting vortices 3 to 6 NM in front of the aircraft under all weather condition is a serious technological challenge. Based on the know-how of I-Wake, studies on wake vortex detection and warning systems are continued within the frame of the Flysafe project.

5.3.5 Improved Flight Control Systems
Flight control systems that are capable of an improved compensation of vortex-induced effects have the potential to improve safety and comfort. Applying the same severity criteria that are established for manual control it can be expected that automatic controllers can cope with stronger wake vortices. It is important to note that it is not intended to fly deliberately into a wake vortex. Research in this area should also focus on the reduction of vortex-induced lateral and vertical accelerations. Especially the lateral load factor is considered to be a contributor to injuries on board after wake vortex encounters in cruise flight when flight attendants and passengers are not buckled. On-board wake vortex detection systems could provide valuable inputs to such flight control functions.

5.3.6 Wake Vortex Encounter Data Collection
A possibility to increase the data base for piloted wake vortex encounters and therefore of the data base for the development and improvement of pilot models and severity criteria is to include wake vortex encounters in regular training simulators of major airlines. The airlines would benefit from having a realistic wake vortex encounter simulation. In return airlines would convey anonymous time histories and pilot comments from those pilots who have agreed to this process. The gathered data would fulfil the requirements of authorities such as level D motion base simulators, airline pilots, consideration of surprise effect, etc. Severity criteria that rely on such data are expected to have a better chance of being accepted by the stakeholders, especially airline pilot organisation, air traffic service providers and authorities.
The capability of identifying wake vortex encounter conditions from FDR (flight data recorder) data is important with regard to a monitoring of wake vortex encounters. Monitoring of wake vortex encounters will become necessary in case of the introduction of new or revised separation standards and in case of the introduction of new aircraft that are larger than those in service. Only a monitoring can finally assure that such changes of the air traffic system meet the required safety level. Seen from another perspective, the results of the monitoring represent the final validation of the safety assessment methodology because only so all combinations of meteorological conditions, ATC scenarios, airports, aircraft pairings, trajectory variations, etc. can be considered. **Apart from establishing a wake vortex encounter monitoring, there is a need to set up a reliable process for identifying the wake vortex encounter conditions based on FDR data.** This process shall allow distinguishing between wake vortex encounter incidents and aircraft reactions that were caused by atmospheric disturbances such as clear air turbulence or wind shear. Within the frame of S-Wake, NLR has started to work on such a process, WAVENDA (WAke Vortex ENcounter Detection Algorithm). A further possibility is to develop a wake vortex encounter identification process based on a high-fidelity wake vortex encounter simulation. Both approaches are considered as promising candidates to develop a mature and reliable process for wake vortex encounter identification based on flight data.

### 5.4 References


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Section 6
Weather prediction, monitoring and statistics

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6.1 Introduction

The following report lists recent achievements and requirements concerning the observation and forecast of meteorological parameters for aircraft wake-vortex advisory. A series of next steps to follow is proposed in order to come up with a dedicated operational weather forecasting and monitoring system to enable safe reductions in current wake-separation distances for aircraft arrivals and departures (Gerz et al. 2005). So far such a system, which covers the terminal area or at least the glide paths of an airport, has been established nowhere.

The following meteorological parameters influence transport and decay of wake vortices:

- mean wind (all three wind components),
- variability of the wind,
- turbulence,
- virtual potential temperature,
- and vertical wind shear.

These quantities in principle need to be known as profiles of altitude and time at various locations covering the terminal manoeuvring area of an airport. However, some of these parameters are difficult or impossible to forecast or even to measure. Therefore, one might tailor specific solutions for specific applications. For example, a cross-wind nowcasting system for aircraft departures requires to observe and to forecast only a minimum set of parameters, such as the horizontal wind components and associated temporal and spatial variability, for a short time horizon on the order of 10 minutes. Another approach relies on observation combined with statistics collected at the airfield where the quantity of the measured parameter is assumed to persist (or to vary slowly) in time with growing uncertainty allowances as the forecast lead time proceeds. The time horizon for that method is maximum 1 hour. For larger forecast horizons, numerical weather prediction is prerequisite. It is evident though that deterministic weather and wake forecasts cannot meet the requirements as the processes in the atmospheric boundary layer, especially at small scales, which are relevant for wake vortices, evolve stochastically by nature. Hence, only forecasts on a
probabilistic basis may succeed with the advantage that the dependency of the result on the parameters as listed above is attenuated.

6.2 Requirements

Before discussing existing systems and model approaches it is necessary to recall the operational requirements of a wake vortex advisory system such as reliability, safety, accuracy, minimum work load for users, and, of course, a resulting advantage to use that system in the ATC/ATM environment. These operational needs then dictate the requirements of a weather monitoring and prediction system, such as equipment availability and reliability, temporal and spatial resolution and averages, update rates, accuracy, uncertainty allowances, availability of data in due time, etc. Some of these requirements may themselves be weather dependent. It is evident but still noteworthy that uncertainty allowances, required to meet the targeted level of safety, will have a drawback on possible capacity gains.

More specifically, a weather observation system has to provide the three wind components, temperature and turbulence (preferably as dissipation rate of turbulence kinetic energy) as function of height and time in the area of interest (i.e. along the glide paths or in the whole terminal area). The equipment should work at least under those weather conditions where the staggering of aircraft due to wake vortex is an issue. Optimum combination and positioning of sensors have to be found and airport peculiarities have to be considered (e.g. runway layout, local topography, economic constraints, etc.).

A weather prediction system aiming at forecast horizons of more than one hour is based on the numerical solution of the equations which approximate the atmospheric state (i.e., its momentum, mass, heat, water content). To this end, it must capture the local topographic, orographic, and surface type properties as well as the conditions at the boundaries of the forecast domain as provided from the standard forecasts of the national weather services. A forecast horizon of some tens of minutes can be captured by simpler techniques as the persistency forecast combined with expected variations obtained from collected data bases. In any case, the forecasts should be of high accuracy and provide minimum uncertainty allowances for all parameters of interest.

6.3 Observation Systems

There is no single instrument which can provide all the needed meteorological parameters. Therefore a combination of sensors is needed. The availability of measurements from various sensors is typically weather dependent so that complementary systems are required. An example may be LIDAR which is a fair weather tool. Under adverse weather conditions (rain & clouds) a LIDAR system may be complemented by a RADAR system. A concise overview of the applicability of various instruments is given by Sauvage et al, 2005.
Requirements for the temporal and spatial resolution of the AVOSS weather observation system are discussed by Dasey and Hinton (1999). The experience with various sensors which were deployed during the AVOSS wake vortex measurement campaigns were analysed in detail by Zak et al. (2001). Following recommendations were given for an optimum sensor combination based on the availability and reliability of the sensors:

- In-situ temperature, wind and turbulence measurements on towers (3 and 10 m) using sonic anemometer and other standard micrometeorological instruments, if possible also at higher heights (30 or 45 m).
- RADAR wind profiler with a RASS extension; typical product: all three wind components and their variability, and temperature profile as function of height.
- SODAR/RASS which has a better data availability during rain; typical product: all three wind components and their variability, and temperature profile as function of height.
- LIDAR which is a “fair” weather tool (including drizzle and haze); typical product: cross-wind, turbulence in terms eddy dissipation rate as function of height, wake and clear-air turbulence detector).

In addition, AMDAR/ACARS (meteorological data measured by commercial aircraft) is an attractive source of data as the measurements are taken along the glide path where they are needed. Their use, however, still needs to be assessed. It is foreseen to include an eddy dissipation rate estimate (realised in ACARS). Unfortunately, those EDR algorithms are not designed to quantify low EDR levels, as it would be needed for a wake prediction system.

At Frankfurt Airport, a wind & temperature profiler and a sonic anemometer chain (ten 15 metre masts) have been deployed by DFS. Data from these sensors drive the statistical cross-wind prediction, see next chapter. Whether a single profiler is sufficient to cover meteorological situation along the glide path has not been assessed so far. Depending on the outcome of such an assessment additional sensors may be required. Additional safety allowances included in the cross-wind prediction algorithm may be an alternative to account for spatial variability of the wind field.

If a sensor package is installed at an airport, the whole data acquisition, processing and quality control and data fusion first has to be optimised with respect to the operational requirements which in parts may be airport dependent. This is a major task. The data fusion may be realised using analysis methods to obtain the best-guess state of the parameter of interest. Here, measurements, which typically are not continuously available in time and space, are fused with the model forecasts employing variational methods to obtain the best guess atmospheric state which is used to initialise model forecasts. If there is a sufficient spatial and temporal coverage with measurements in the terminal area input from models may be not needed. As an example, the VERA system may have potential to provide real-time best guess fields of the atmospheric state for wake vortex prediction purposes (Steinacker et al. 2000).
An important issue is the positioning of the sensors in the terminal area. The meteorological information is needed for the volume of air in which the wake evolves. This implies the need for an optimum choice of spatial and temporal averaging which is dependent on the specific sensor. During the European wake vortex measurement campaigns (e.g. WakeOP and WakeToul of C-Wake and Flight Test 1 of AWIATOR) all weather measurements were taken as close as possible to the corridor in which the wake evolved (< 1 km). This allowed a much better characterisation and prediction of the observed wake behaviour as it was the case for data obtained at the Memphis Airport (Holzäpfel and Robins 2004), where meteorological measurements were 2 km away from the wake measurement site.

Experiences from the analysis of field data suggest that the optimum averaging time for meteorological parameters is between 2 and 10 min. These averaging windows are driven by the typical life time of the wake vortices on one hand (2 min) and the required time to obtain representative averages (5 to 10 min) on the other hand. Besides the mean values also a measure on the temporal variability of the parameter is provided. The vertical resolution should be in the order of one vortex spacing.

6.4 Prediction Systems & Statistics

In this section we discuss some of the existing forecasting systems which can be split into the categories “forecasts based on statistics” and “numerical weather forecasts”. From recent findings (Frech and Holzäpfel 2006) it may be expected that up to a time horizon of 60 minutes the forecast based on statistics provides superior results compared to the forecast by numerical weather models. Eventually a combination of both methods may yield optimum results: Tactical decisions by ATC to optimise the staggering of aircraft on the final approach are made in short terms and may rely on statistical forecasts. For the strategic planning of the air traffic by ATM larger forecast horizons are needed which may be served by the numerical forecast technique.

Statistical forecasting systems

Data from observations can be used to drive a short-term prediction system based on statistical methods (Frech et al. 2002, Cole and Winkler 2004). Depending on the sources of measurement data more or less elaborated data fusion algorithms are needed in order to obtain the best guess meteorological state. Such a best-guess field is then used to drive the statistical forecasting algorithm (see also Steinacker et al. 2000).

The wind forecast used in the Wirbelschleppen-Warnsystem (Wake Vortex Warning System) developed by DFS (Gurke and Lafferton 1997) is based on a persistency forecast technique. DFS operates a wind line and a wind & temperature profiler in order to provide local meteorological measurements. For that system, statistical cross wind forecast algorithms have been developed with the focus on the prediction of lateral wake transport (Frech et al. 2002). Out of ground effect, to a large extent the wake is considered as a passive tracer which is advected by the mean cross wind. In-ground effect, a simple wake propagation and decay model is used which is based on LIDAR observations from a dedicated measurement campaign.
The AVOSS program also focused mainly on the observation systems (Hinton et al. 2000).

Other short-term prediction systems, as the Integrated Terminal Weather System in the USA (Evans 1995) or as adapted for the Hong Kong airport (Lau 2000) also rely on an observation network combined with a smart data-fusion technique. The aim here is to nowcast the weather adverse to aviation, for example, the development of strong convection, thunderstorm, and wind shear. These systems are not explicitly designed for the wake-vortex problem.

**Numerical weather forecast**

In numerical weather prediction, non-hydrostatic mesoscale models are state-of-the-art and used by the weather services for their routine weather forecast (e.g. Lokal Model, LM of the German Weather Service, run at 7 km horizontal resolution). Those models have a temporal and spatial resolution such that mesoscale features as fronts, land/sea breezes, thunderstorms, etc. can be resolved. There is a tendency to obtain even higher resolutions in order to get a better grip on convective systems (thunderstorms combined with wind shear).

The wind nowcasting model WAFTAGE (Winds Analysed and Forecast for Tactical Aircraft Guidance over Europe) has been developed at the Meteorological Office of Great Britain. This system assimilates AMDAR observations at airports to adjust forecasts of wind and temperature produced by a numerical weather prediction model. It produces 10 minute forecasts of wind and temperature up to a couple of hours ahead and up to a height of 1100 m. It is easily adapted to produce forecasts of crosswind along the glide slope. The spatial resolution of the forecasts is identical to the resolution of the forecast field taken as input (currently from the Met Office’s Mesoscale model, about 12 km), and the vertical resolution is 300 ft (~91.5 m). In the next couple of years there are plans to improve the system by optimising the parameters within WAFTAGE for forecasting at London Heathrow and also by developing quality control software to ensure consistency in observation data assimilated into WAFTAGE.

In the USA the system called “rapid update cycle” (RUC) is operational and provides products to the aviation community (Benjamin et al. 2004a,b). It is a short-term forecasting system with an update every hour and it assimilates measurements from various sensors. The focus is on clear-air turbulence (CAT), thunderstorms, visibility, ceiling, but not on wake vortex.

The model system NOWVIV (nowcasting wake vortex impact variables) has been developed at DLR (Gerz et al. 2005, see Figure 1) and has been applied in real-time during a number of field campaigns. NOWVIV provides meteorological fields in a domain of 80 x 80 km² around the airport and in particular along the glide path (10 minute resolution, horizontal resolution 2 km, vertical resolution between 8 and 50 m in the lowest 1200 m). The core of NOWVIV is the non-hydrostatic model MM5 (Grell et al. 2000).
NOWVIV has been used to compute a 1-year data base for the Frankfurt Terminal area in order to provide realistic boundary conditions for the A380 wake vortex risk assessment within WakeScene (see also Section 3 of the Document). This one year data already covers most of the climate features at Frankfurt airport. It can be used to analyse the meteorological conditions along the glide path for various criteria (e.g. cross-wind thresholds or the variability of the wind field). Embedded in a test bed, such data also provide realistic boundary condition for testing and assessing the potential and risk of new operational concepts.

A subset of 40 days from this data base has been validated in detail against sonic, SODAR-RASS, and LIDAR measurements taken up to a height of 300 m at Frankfurt airport in autumn 2004 (Frech et al. 2006). Both forecast and observation data has further been used to assess the skill of the wake predictor P2P when using two different sources of meteorological input, namely NOWVIV forecasts and a simple wind persistence forecast based on SODAR observations (Frech and Holzäpfel 2006). The results are compared against 231 high quality wake vortex data from heavy aircraft as measured by LIDAR in a glide-path crossing plane close to the runway threshold. The study shows for the first time the achieved level of safety and the potential for reduced aircraft separations of a combined numerical weather and wake prediction system. In particular, the predicted time needed by wake vortices to leave the safety corridor has been assessed.

The main findings of these 40-days analysis are:
- The NOWVIV forecasts have almost no bias in wind and yield a RMS error of ~2 m/s for wind speed and ~45° for wind direction. The RMS errors are dominated by a few but large outliers (in occurrence with frontal passages).
- The weather forecast performance of NOWVIV is good compared to recently published results on the RUC (see above) and on other MM5 applications (Zhong et al. 2005).
- NOWVIV predictions are superior to persistency predictions based on SODAR at a lead time of about 1 hour.
- With that accuracy of the wind forecast, the combined NOWVIV weather and P2P wake predictions with 2σ safety allowances achieve 100 % safe forecasts of the time needed for the wake vortices to leave the flight corridor at a flight height of typically 60 m.
- For a time horizon of 30 (60) minutes, the SODAR persistence model coupled to P2P (again with 2σ safety allowances) provides 99 % (95 %) safe forecast.
- The frequency of reduced separations (for a potential capacity gain) is significant (several ten percent) for P2P driven by SODAR data and very small (few percent) for P2P driven by NOWVIV data. This can be attributed to a larger uncertainty of wind forecasts compared to wind measurements.

6.5 Research needs

From the facts illustrated in the previous chapters one may deduce the following list of ongoing and future research necessary to improve weather forecasts and observations for a wake-vortex advisory system.

- Assessment whether a single wind and temperature profiler at an airport is sufficient to cover the variability of meteorological parameters along the glide path. A guide-line may be obtained through high-resolution mesoscale model forecasts in which sensor locations can be simulated.
- Development and automation of a wake detection and monitoring technology (e.g. 1.5 µm LIDAR) of a significantly lower price to enable implementation of new standards.
- Development of an on-board wake-detection tool (e.g. 1.5 µm LIDAR) including HMI which is complementary to ASAS equipment.
- Development and test of algorithms for an optimum combination of observation and forecast data in order to obtain best-guess fields of meteorological parameters relevant for wake vortex prediction and monitoring.
- Developing algorithms to deduce an eddy dissipation rate estimate from various measurement sources and forecast models.
- Assessment of the potential to use of AMDAR/ACARS data within a wake vortex monitoring and prediction system.
- Use of ensemble weather forecasts to derive probabilities of the expected weather (for example what is the probability for the existence of a certain cross wind threshold at a given lead time).
• Assimilation of local measurements into NOWVIV; this should improve the overall meteorological forecast quality which reduces the uncertainty allowances and, in turn, increases the capacity potential of the NOWVIV-P2P approach.

In summary, it is obvious that each component of the weather forecasting and observation equipment has to be adapted, optimised and tested individually as general improvements in the respective technology occur. The tools which have been under consideration in this report have passed these checks according to today’s standards. Any improvement and optimisation has to be assessed in terms of the skill of the whole system which has to be tailored to a specific airport and a few applications (e.g. single/parallel runway operation).

What is necessary now is the combination and integration of the tools in a prototype system and its implementation at the airport. Tests of the system under most realistic conditions will aim at the evaluation, assessment and subsequent improvement of the system and its components. The integrated system – including observation and forecast of weather and wake vortices, the prediction of wake-encounter probability and severity, and the implementation in the ATC environment – has to be considered to meet the safety and capacity targets for which it had been designed.

6.6 References

(NB authors named in the text; here listed alphabetically)


See also http://www.mmm.ucar.edu/mm5/Publications/mm5-papers.html for recent publications.


Section 7
Collection and Analysis of Empirical Data

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7.1 Introduction

Wake turbulence separation minima have been established by ICAO in the 1970’s. Since then only a very few changes have been made compared to these standards. The majority of these changes led to increased separation between particular pairs of aircraft, e.g. B757 are frequently treated as heavy aircraft when being the leader of the pair. Only a few attempts have been made to reduce the wake turbulence separation minima.

Already from this finding we can conclude that obviously the amount and the quality of the existing information about wake turbulence is not sufficient to warrant a major change of the overall operational practice. Local solutions, i.e. systems and procedures which are used at a single airport exist (e.g. the High Approach Landing System at Frankfurt airport) but they are based on local data collections. Therefore their potential application is likely site-dependent and limited to specific conditions.

In the past decade a considerable improvement in wake vortex modelling but also wake vortex sensing technology has been recognized. Still there exist too few databases that would allow for an in-depth validation of the advanced wake vortex transport and decay models.

This section addresses the question what kind of (additional) data collection and data analysis is required to significantly improve our knowledge about the effects of wake turbulence in a real operational environment.

The content of this section should be kept on a rather high general level in order to ensure applicability to a wide class of wake turbulence related issues. Where necessary or useful, specific examples will be employed for illustration purposes.
7.2 Some general remarks

Caution about Systematic Approaches to Define New Separation Standards
A rigorous scientific but also a pseudo-scientific but still systematic approach to the wake turbulence problem may suggest that separation minima could be relaxed for some pairs of aircraft. Applying the same methodology to other pairs of aircraft may indicate larger than today separation minima between these specific types.

Once any procedure has been established to determine the separation between a specific pair of aircraft or under specific weather conditions, the same method will be used to cross-check with other pairs of aircraft.

Wake Avoidance Strategies
There are three different strategies to avoid wake encounters:
1. To wait long enough until the vortices have decayed to a sufficiently low intensity.
2. Away from the ground vortices are descending below the flight level of the generating aircraft due to mutual induction. The following aircraft in the same level is flying above the vortices.
3. In case of a crosswind the vortices will be laterally advected out of the flight corridor. (In case of no crosswind flying a few hundred meters off track yields the same result.)

Modes of Operation
Wake vortices are a factor in all phases of the flight. But since the behaviour of the wake vortices as well as the performance of the aircraft involved are changing during the flight, several modes of operations have to be distinguished:
1. Queued landings on a single runway.
2. Queued landings on closely spaced parallel runways.
3. Queued take-offs on a single runway.
4. Queued take-offs on closely spaced parallel runways.
5. In-trail flights during the en-route phase.
6. Level changes of leader and/or follower during the en-route phase.
7. Missed approaches (in particular of the leading aircraft).

The two lists above show that there is no straightforward approach to address all aspects of the wake turbulence problem at one time. The operational but also the meteorological conditions as well as their implications for advanced wake avoidance procedures differ too much between the scenarios: While a crosswind could be beneficial for single runway operations the same crosswind could inhibit landings with reduced separations on a downwind parallel runway. On the other hand calm winds would increase the risk of a wake encounter on the same runway, however the wake would never reach the parallel runway in a reasonable time.

In particular the last item of the second list has been overlooked in many studies, although a missed approach may lead to a significantly enhanced risk for the following aircraft to encounter the wake of the go-around aircraft, simply because the wake of the missed approach will be generated above the following aircraft.
7.3 Weather and Wake Behaviour

Once a wake is shed by an aircraft it evolves in the atmosphere. In a more rigid sense the turbulent structures behind an aircraft become a part of the atmosphere itself. Therefore the evolution of the wake is strongly dependent on meteorological quantities. Consequently a proper treatment of the vortex dynamics involves also the treatment of that part of the atmosphere in which the vortices are embedded. For this problem no closed form solution is known to date and approximate computation using for instance large eddy simulations require large computing resources. Henceforth such calculations can be done for a few and idealized examples only. On the other hand there exists a variety of different engineering models for simulating vortex trajectories and their decay dynamics, but it is not 100% clear whether the input parameters to these models are really the right ones to distinguish between different wake behaviour classes due to different ambient meteorological conditions. It would be certainly of utmost importance the find those meteorological quantities which exhibit strongest correlations with the fate of the wake vortices. Working in this direction one always has to bear in mind the operational character of the problem.

Recommendation 1.1: Establish a short list of meteorological quantities that strongly correlate with vortex transport and decay properties.

It is obvious that a successful identification of such kind parameters can only be done by a statistical analysis of large data sets, where wake vortices and the ambient meteorology have been measured simultaneously. Some work in this direction has already been done, but the results are not conclusive in all aspects. Even more so our knowledge about the behaviour of wake vortices is currently constrained to meteorological conditions where wake vortices can be detected using remote sensing technology. A delicate example is fog, where winds are extremely calm and which may be associated with an inversion too. Both conditions are among the candidates which may adversely affect wake decay and vertical transport. Unfortunately a lidar cannot measure the wake vortices very well (if at all) under such bad visibility conditions. Moreover even the operational practice cannot be used as an argument here since due to large ILS protection zones aircraft are separated by more than the normal ICAO wake turbulence separation minima. This example shows the need for more and longer term measurement campaigns to cover all relevant meteorological conditions.

Recommendation 1.2: Identify candidate meteorological quantities that possibly have an impact on the wake evolution. Ideally these variables should be determined through routine measurements.

Relying on routine measurements has the advantage that long term measurement campaigns can be conducted at moderate costs. Likewise it is easier to incorporate such kind of information in an operational wake avoidance system. More
sophisticated variables which require dedicated sensor technology could become subject of long-lasting certification process.

While such a variable should be correlated with wake evolution, the behaviour of the wake vortices must not change drastically within the achievable measurement accuracy and resolution. Otherwise this variable is of no use in an operational context.

Turbulence, for example, has been considered such a candidate for a long time. An application appears to be difficult to implement since there exist two different classes of parameterization of the relation between wake decay and turbulence: One class employs the eddy dissipation rate, EDR, another class uses a parametrization based on the turbulent kinetic energy, TKE.

While both quantities are related to the turbulent state of the atmosphere there is no unique transformation between TKE and EDR. Even more so in the empirical data collected so far, both TKE and EDR have not been measured in a consistent way. As a result, data from different campaigns cannot be compared easily. This concern is also corroborated by the fact that EDR shows considerable variations over short time-scales and short distances.

**Recommendation 1.3: Standardize meteorological measurements in wake vortex related measurement campaigns.**

To be able to explore the possibilities associated with combining data from various campaigns, some level of standardisation is mandatory. The standards should deal with measurement frequencies, sensor siting (in particular the height above ground seems to be crucial), required resolution and accuracy.

This might appear not feasible on a global or European scale, nevertheless any level of additional harmonization lowers the practical obstacles when combining/comparing data from different measurement campaigns. Although it is not a meteorological variable, the use of $\Gamma_{5m-15m}$ as a means to characterize vortex strength serves as a positive example for such a harmonization.

**Recommendation 1.4: Perform long-term campaigns, in which the meteorological parameters and wake trajectories and wake decay are measured in parallel.**

In addition to that, meteorology dependent wake turbulence separation procedures would only be implemented if the occurrence of favourable (meteorological) conditions is large enough to warrant a major change. Therefore also campaigns where only the meteorology has been measured can provide valuable insights when assessing the comparing the benefits of a few options for modified wake turbulence procedures at the site where the measurements were done.

Concerning the wake vortex behaviour the following relationships are of particular interest:

1. Horizontal wake transport as a function of wind.
2. Vortex decay as a function of wind, stratification and turbulence.
3. Wake descent rates out of ground effect in the presence of vertical wind, horizontal wind shear and as a function of the stratification.

These assessments shall be done on an aircraft specific basis. Any kind of scaling or grouping of different types shall only be applied after the similarity is supported by the empirical data. Maybe the a priori assumption of the existence of some scaling behaviour is one reason for the large scatter in some data sets.

Finally a remark has to be made regarding the measurement of vortex decay. Vortex lifetimes must not be limited by the imperfection of the measurement system but by the physical limitations of aircraft encountering these wakes. Therefore only such kind of sensors should be considered that are capable of detecting vortices even if they already had decayed to a level that no longer imposes a threat to trailing aircraft.

**Recommendation 1.5**: Establish (site dependent) statistics to estimate the fraction of time where wake turbulence separation can be altered in a (capacity) beneficial way.

For example, stratification is a candidate that somehow influences the vertical descent of the vortices. Therefore it would be of interest, how its probability distribution at a particular site looks like. An example is given in the figure below.

![Stratification statistics](image_url)

*Figure 1: Statistics of the vertical derivative of temperature as measured by the WTR/RASS a wind profiler located at Frankfurt am Main airport. Data includes all levels up to 5000 ft AGL and comprises the statistics of more than one year.*

Once a threshold temperature gradient can be determined, when the wake’s sink rate falls below a critical value, one can easily infer the fraction of time where stratification is a factor which might inhibit closer separations.

Figure 1 shows the distribution of the vertical derivative of the temperature. Although this graph could serve as a starting point of an in-depth discussion about this very observable, some more general comments should be which in principle apply to other observables as well:
Quite often the critical cases (as far as wake turbulence is concerned) are not found in the bulk part of the distribution. If this was the case, there would be of course only very small room for improvement. The critical cases are usually belonging to the tails of the distribution. There are two major difficulties associated with those parts of the distribution:

- They are extremely hard to model, and
- they are most vulnerable to measurement errors.

A systematic analysis of weather statistics is also recommended for the assessment of the usefulness of wake vortex (remote) sensing technology. The performance of sodars, lidars and radars that can be used to measure both – the state of the atmosphere as well as the evolution of the wake vortices – is in many cases crucially depending on the environment where they are operated.

![Figure 2: Statistics of the horizontal wind at Frankfurt airport. The plots show data that has been cumulated over more than one year. The x-axis is oriented along the runway centreline (250 and 70 true bearing, grid spacing is 10 m/s. The double-differential probability is color coded. The lines at the top and the left hand side of each graph represent the integral distributions for that wind component. Data at 15m has been measured with the Frankfurt windline, the data at the other altitudes have been obtained using the WTR/RASS of DFS.](image)

**Other Weather Related Aspects**

In the previous sections emphasis was laid on the impact of the ambient meteorology on the behaviour of the wake vortices (and the impact of the weather to measure the wake vortices and the meteorological parameters themselves.) There are however few more aspects related to the meteorological conditions that have an important influence on the performance and thus the achievable benefits of novel wake avoidance procedures.
The problem under consideration becomes most apparent for approach operations. The separation of two landing aircraft will be determined a long time before the leading aircraft is actually touching down. (Here “long” has to be understood in terms of several times the average lifetime of the vortices.) Thus some predictive element is needed in order to judge whether or not the approach path of the following aircraft will be clear of vortices. Obviously this judgement cannot be made by considering only the actual measured wind (here wind has to be understood as a synonym for the entire set of variables characterizing the state of the atmosphere and its influence on the evolution of the wake turbulence).

Therefore it is necessary to study how well the actual wind represents the wind and therefore the wake vortex behaviour in the future. In practice a forecasting scheme would be employed which is usually dubbed “nowcasting” since the scales one has to deal with are much smaller than the length- and timescales involved in conventional meteorological forecasts.

To be more precise, our primary interest is not in the changes of the meteorological parameters themselves but in the changes of the anticipated wake vortex behaviour, which – for the time being – is assumed to be connected to the ambient conditions.

**Recommendation 2.1:** Determine persistence of the ambient conditions by measuring the frequency and the magnitude of the changes of wake behaviour or ambient meteorological conditions within timescales of 5 minutes to one hour.

The lead times mentioned in Recommendation 2.1 shall be considered as some initial guidance and may be adapted according to site specific requirements.

Not only the persistence but also the (lateral) homogeneity of the ambient meteorological conditions is of practical interest. In many cases the measurement of the atmospheric state in the area where the wake vortices will evolve is not feasible for various reasons. Likely meteorological measurements will be carried out not too far away but still possibly in a few nautical miles distance.

**Recommendation 2.2:** Determine the degree of horizontal homogeneity of the atmosphere by measuring the frequency and the magnitude of differences in meteorological quantities within a distance of 4 to 20 nautical miles.

The lateral distances mentioned in Recommendation 2.2 shall be considered as some initial guidance and may be adapted according to site specific requirements.

It is unlikely to determine the differences in wake behaviour directly, because in the vicinity of an airport the aircraft operating height is strongly correlated with the distance from the airport. Meteorological parameters change significantly with height, therefore the wakes are likely to show different behaviour depending on the distance from the airport. The major fraction of the difference, however, would be due to differences in height rather than differences in lateral position.
Aircraft Related Parameters
To avoid one aircraft flying into the wake of another aircraft, it is not sufficient to predict the behaviour of the wake alone. The trajectories of both – the wake generating aircraft as well as the following aircraft – must be known. In principle the same argument as above applies to, such that not only the actual position matters but some predicted trajectories need to be employed. (In fact it is the position of the second aircraft relative to the first one compared to the wake trajectory with the leader’s trajectory as initial condition.)

For precision approaches corridors where the aircraft will operate can be derived. Nevertheless there could be variations from the nominal behaviour due to various reasons. In the case of departures a wide spread of possible trajectories need to be taken into account, since in contrast to e.g. the touchdown zone in the landing case the rotation point is not very well defined since it depends on a large number of aircraft related parameters and other operational parameters.

Nevertheless for any new wake avoidance system or procedure safety under all operational conditions has to be proven (see also the section about safety assessments).

 Recommendation 3: Perform long term campaigns in which relevant aircraft performance parameters are collected and statistically analyzed.

The following preliminary list of parameters may serve as a starting point for the setup of such like campaigns:
- Aircraft dependent final approach speeds as a function of wind and turbulence.
- Aircraft lateral deviation from ideal localizer and vertical deviation from ideal glide-path course.
- Missed approach heights.
- Rotation points.
- Adherence to predefined Standard Instrument Departure routes (SIDs).
- Really achieved navigation performance (en-route).

The last point has been added for the following reason: As aircraft are more and more tuned to fly along a given trajectory with almost arbitrary precision, the probability increases that other aircraft will follow the same track. This is of no harm as long as the aircraft are operating in different flight levels and the vortices are descending. If aircraft are however climbing or descending through another aircraft’s flight level at some place there will be a remnant of the vortex in the flight path of the other aircraft. Since both aircrafts’ trajectories are constrained to a rather narrow “tunnel” around the ideal track it could be that the probability that one aircraft encounters the other aircraft’s wake will be increased. In order to assess this question on a quantitative level the last parameter of the list above needs some attention as well.
Section 8
Incident Reporting and the Analysis of FDR Recordings

Dr Claire Pugh (National Air Traffic Services Ltd), Antoine Vidal (Eurocontrol) and Henk Haverdings (NLR)

8.1 Introduction

Wake vortex encounters are currently not systematically recorded, although the more serious encounters are captured by various (International/European/National) occurrence reporting schemes. The information in these reports gives details on those events which have been deemed by those involved to affect or potentially affect the safety of operations. There also exist a few voluntary wake vortex reporting schemes which capture a wider range of severity of encounters and as such can be a useful source of data for ascertaining factors which contribute to the more severe encounters without such an encounter occurring.

Incident reporting – general
A document describing in detail many of the incident/accident reporting schemes was written for Working Group 1 of Wakenet2 - Europe, Ref. 1. Some of these schemes are listed below (however, there have only been a few occurrences where wake vortex has led to a serious incident or accident):

• ADREP, Ref. 2, is an ICAO accident/incident reporting scheme to which member states submit reports. It provides a comprehensive database of accidents but contains less information on incidents.
• ECCAIRS is an EU reporting system which is maintained, supported and made available to EU civil aviation authorities and is used to collect incident information from the EU member states.
• National occurrence reports are filed when there has been deemed to be a threat to safety. However, whether the incident was deemed to be a threat to safety is subjective. For states which are part of Eurocontrol, these national reporting schemes should be fulfilling the ESARR (Eurocontrol Safety Assessment Regulatory Requirements). In particular ESARR 2 stipulates the reporting and assessment of safety occurrences in ATM, Ref. 3.
• Confidential reporting schemes such as ASRS (Aviation Safety Reporting System) in the US can also contain information on wake vortex encounters.
Incident reporting – wake vortex specific

A number of reporting schemes which are wake vortex specific are known to exist or have existed, however, these tend to be at the national level.

- Wake vortex database managed by NATS – this was established in 1972 and still continues today. The database contains information about the leader and follower aircraft as well as associated meteorological and radar data. About 70% of the encounters reported are at Heathrow. Data from this database is used constantly by NATS for safety monitoring purposes as well as being used in European projects such as in the S-wake project (Ref. 4).

- ETWIRL (European Turbulent Wake Incident Reporting Log) – was a wake vortex reporting database managed by the UK met office. It contained details of the leader and follower aircraft, the speed, altitude, weight of the follower aircraft, encounter parameters such as roll and meteorological data. Data from ETWIRL was used by the UK met office to try to deduce a wake turbulence predictor (Ref. 5). ETWIRL finished in 2000 with no follow-on.

- DRVSM (US)/ ASRS (US) – This Domestic RVSM reporting database has been established in the US as RVSM has been introduced into domestic airspace. The reports are submitted via the existing ASRS reporting scheme and standard reports can be obtained from the site, Ref. 6. To date, there have been few encounters reported in DRVSM airspace. Current discussions are underway in the US to establish a project that will look into developing a wake reporting system.

- RVSM (Eurocontrol) – This incident reporting scheme was established to obtain wake vortex data for inclusion in the Wake Vortex database as part of the RVSM Pre and Post Implementation Safety Cases. A standard report form was issued to European ANSPs and the data collected by Brussels, Ref. 7.

### 8.2 Incident Reporting

Data from incident reporting can be valuable in several ways, namely:

- Monitoring current operations
- Highlighting areas of increased wake vortex risk
- Monitoring new procedures
- Relative indication of wake vortex risk in proposed concepts

**Monitoring Current Operations**

Constant monitoring using an incident database can identify areas in which there is a change in the method of operation. If the monitoring is sufficiently regular, then any changes in the implementation of procedures which lead to a change in wake vortex risk can be identified.

**Highlighting Areas of Increased Risk**

Data from incident reporting, including voluntary schemes, can provide a valuable insight into areas where wake vortex encounters are occurring and hence provide
useful information to future concepts which can be designed to address these particular areas.

As an example, the graph in Figure 1 shows data from the voluntary reported wake vortex database managed by NATS which holds over 30-years of UK wake encounter data. The graph shows the percentage of reports as a function of encounter height from 2000 to 2004 and it can be seen that around one quarter of all reports are from wake encounters at less than 500ft. This peak may be expected because:

- encounters close to the ground are more severe as there is less recovery time and hence are more likely to get reported than a similar encounter at a higher altitude, and
- ground effect, reflections and interactions with buildings close to the ground can cause the wake vortex to remain in the path of the follower aircraft.

Further peaks for the inbound traffic can be seen at 3000 and 4000 ft. This aligns with the aircraft joining the ILS from below the glideslope. The graph also shows that between joining the ILS and above 500ft there is a relatively low probability of encountering wake vortex which would be expected since the vortices generally sink below the glideslope. Understanding why there are a greater number of encounters at some heights gives information for proposed concepts to mitigate these effects. Full value from such data could be obtained by analysing these encounters as functions of separation (in both distance and time), weather conditions, angle of roll etc.

![Figure 1](image_url)  
*Figure 1  Frequency of heights of reported encounters from 2000 to 2004.*

Therefore, voluntary reported data can be useful in determining areas of increased risk of wake vortex encounter in current operations and procedures could be amended if the situation warrants.

**Monitoring New Procedures**

Many of the incident databases are used to ensure that any new procedure has not increased the risk from wake vortices. For example, the Eurocontrol RVSM and US DRVSM were established to capture wake vortex encounters in the new RVSM
airspace. However, although these incident databases give details on wake vortex encounters in the new procedures they did not exist before the introduction of RVSM and hence it is not known what the background level of encounters was before the reporting scheme was promulgated. Information from the NATS database has shown a tendency for an increase in reports when new procedures are introduced as there is an increased awareness of wake vortex. For example, there was a large and statistically significant increase in reported wake vortex encounters in European airspace between FL290 and FL410 following the Early Implementation of RVSM. However, in the period following Full Implementation, the rate decreased back to a level similar to that observed prior to Early Implementation. The explanation that pilots reported wake turbulence incidents with a greater diligence in 2001 as a result of concerns over the impact of a reduced vertical separation might be backed up to some degree by the increase in reports in other parts of en-route airspace during the same period. The use of incident databases (and particularly voluntary reported ones) requires long periods of time for monitoring to establish whether there is a true trend or a fluctuation.

<table>
<thead>
<tr>
<th></th>
<th>PRE-RVSM</th>
<th>EARLY RVSM</th>
<th>FULL RVSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>RVSM Airspace</td>
<td>1.8</td>
<td>6.2</td>
<td>1.8</td>
</tr>
<tr>
<td>Other En-route</td>
<td>6.4</td>
<td>8.9</td>
<td>5.8</td>
</tr>
</tbody>
</table>

Table: Reported wake Vortex incidences for RVSM (figures as per 10^5 flight hours)

Relative indication of wake vortex risk in proposed concepts
Although incident data gives knowledge and understanding of the current wake vortex risk and can be used to highlight areas of increased risk, it can be difficult to use this data to quantify the effect on wake vortex risk in future concepts. Whether this is possible or not depends on the issue being tackled, i.e. how far removed from current operations, and the quality of any theoretical data which can be used in conjunction with the incident data to extrapolate from current procedures.

8.3 The future of incident reporting

Data from sources such as ADREP only give limited information on whether current procedures are safe, as the data is only captured after a serious incident or accident has occurred. If it was shown at the time of the incident that procedures were being followed correctly, then information within this type of database shows that the procedures were 'unsafe'. A database which captures information on all events whether serious incidents or not can build a better picture of trends within the current procedures to identify if there could be any part which could be improved before a serious incident occurred. Therefore, in order to capture the ‘less severe’ encounters some sort of alternative scheme from national occurrence reporting and ADREP must exist. Using experience gained from the database managed by NATS, only around
15% of reported encounters were considered severe enough to be filed as an occurrence report to the UK CAA, i.e. 85% of encounters would not have been filed if the voluntary reporting did not exist. However, it is not the intention of the wake vortex separations to entirely remove the possibility of a wake encounter but to reduce the probability of an encounter to an acceptably low level and to minimise the magnitude of the upset when an encounter does occur. Therefore, any mandatory reporting scheme need not contain information on those encounters which were considered acceptable. This threshold of what is an acceptable encounter is difficult to quantify. Suggestions have been made that using go-arounds as a result of perceived or actual wake vortex encounter could determine a threshold of what is acceptable, i.e. if it resulted in a go-around then clearly the encounter was not acceptable. However, the number of such occurrences on an annual basis would be small and probably too few to determine any statistical trends or safety argument. Also, other encounters which may result in a significant un-commanded roll but which do not result in a go-around need to be considered and captured in a reporting scheme. However, it is difficult to determine the amount of roll and at what height above the ground would be considered as an acceptable threshold.

Although the lower severity limit of a reportable encounter is hard to quantify, what is clear is that those encounters resulting in a knock-on effect such as a go-around or loss of separation do need to be captured.

The ‘natural’ tendency to report an encounter can be seen by looking at the data in the voluntary reporting database managed by NATS. Figure 2, shows the percentage of reported encounters from 2000 to 2004 in terms of pilot reported roll and height of encounter for all phases of flight. There are a few reports of encounters with a roll of greater than 50 degrees, then as the roll angle decreases the number of reports increases until a sharp drop for encounters with less than 10 degrees roll. This would tend to indicate that those encounters where an un-commanded roll of less than 10 degrees occurred are less likely to be reported. It is also interesting to look at the height of the encounters which shows that around one third of encounters with 0 to 20 degrees of roll are at heights of less than 500ft.

![Figure 2](image_url)

*Figure 2  Pilot reported roll angle and height of wake vortex encounters in 2000 to 2004*
8.4 FDR data

Within the incident reporting databases, some Flight Data Recorder (FDR – or more usually Quick Access Recorder (QAR) data) is also used. However, in these cases it has still required that the pilot has reported a wake vortex encounter and the FDR data analysed to determine the amount of disturbance to the attitude of the aircraft. During the S-wake project, a different approach was used where all flights of a given carrier had their FDR traces analysed to see if they had suffered a wake encounter. In these cases the NLR-VOXERT algorithm developed by NLR was used to identify from the FDR trace whether the aircraft had encountered a wake vortex, Ref. 4. This method of recording the FDR traces therefore takes out the subjectivity of reporting, but does entail more resource. It was also found that the FDR was often of poor quality making it difficult for the tool to determine if there was a wake vortex encounter or not.

In order to validate wake vortex encounters detected from the FDR data a pilot-reporting scheme is very helpful in defining the discriminatory algorithms to separate wake vortex encounters from non-wake vortex encounters. Additionally fall-back data solutions could perhaps be devised to recover FDR data in case of low-quality data drop-outs or low-quality data. However, work is underway to try to improve and validate the algorithm for future FDR work.

8.5 Future Data Collection

Ideally the best way to capture wake vortex encounters would be to have an empirical scheme (for example FDR) in conjunction with a pilot reporting scheme. This would allow the subjective (pilot report) data to be aligned with the objective (FDR) data. This type of combined data collection would provide information and parameters when following aircraft are affected by wake vortices. Achieving this could lead to several forward steps into the research and mitigation of wake vortices, namely:

- Provide data to assess new/changed procedures (currently subjective biased e.g. RVSM). Aligning the objective and subjective data when a procedure is changed would allow an increase in perception/awareness and hence increases pilot reports to be differentiated from an increase in risk which would also result in an increase in pilot reports.
- Provide data to validate safety arguments. Having access to objective data could allow more robust conclusions in safety arguments.

There are two ways of approaching a combined FDR/pilot reporting data collection scheme. The first is that if a wake encounter is reported, then the FDR data is also analysed. The second method which gives a much larger data set is to take all FDR data as was done in S-Wake. Then only a subset will have accompanying pilot reports. It was by using this second method in S-wake that it was estimated, Ref. 8, that the actual number of wake encounters is some 8 to 10 times higher than the voluntary (pilot) reported rate. The advantages of this second method however, is that it gives valuable information on what didn’t get reported, i.e. what is an acceptable encounter and under what conditions did it occur. This would be a much larger data...
source and hence maybe easier to draw conclusions from, as opposed to current reporting which leads to data in which there is a large scatter of contributory factors. Using all FDR data also has the advantage of being able to determine if there is a real increase in number of wake encounters and/or severity if a procedure is changed independent of pilot awareness which can cause an increase in encounters in a pilot reported scheme.

However, to enable such a data campaign to be successful, further work and research would be needed to better extract the relevant information from FDR recordings as mentioned in Chapter 4. The S-wake project showed that different FDR types gave variations in accuracy and ease of data extraction. Work would be required to better identify which FDR traces contain wake encounters and from these obtain the most relevant information such as roll, pitch, altitude and track deviation. Due to the poor quality of some of the FDR traces, care would be needed to filter out any spurious data which could give misleading results. For those traces where a wake vortex encounter was detected and a pilot report existed, the data gathered from the FDR would then need to be correlated with the pilot report.

Such a combined data campaign would also enable further research work as inputs into any safety arguments such as providing a basis to establish severity and hazard criteria of a wake encounter. WG5 of Wakenet2-Europe, Ref. 9 discussed that to progress work on improving procedures for wake vortex mitigation, definition of hazard criteria and classification of severity need to be addressed. This can be progressed by developing a defined rating scale of severity for wake vortex encounters for pilot reports and then aligning these with objective parameters from the FDR data.

In summary, the primary set of wake vortex encounter data which exists today is subjective, which makes it difficult to draw any solid conclusions for safety arguments but is very useful in determining scenarios where wake encounters are likely to occur. However, if this subjective data was combined with objective data such as that from FDR, then this combination can further progress the factors which affect the severity of wake vortices and would go someway to providing a basis on which to build a methodology to derive safe wake vortex separation rules.

References:

Section 9
Safety enhancement tools: Real time monitoring of wakes

Chris Hills (QinetiQ), Frederic Barbaresco (Thales), Friedrich Köpp (DLR) and Agnes Dolfi (ONERA)

We list here the main methods of vortex detection and windspeed measurement, the currently or shortly available hardware, and the most recent relevant references. We recommend that the complementarity of radar, sodar and lidar should be better understood; the performances claimed for lidar microphones and long-pulse sodars should be independently assessed; and the technical state of the art should be frequently reviewed.

9.1 Remote detection of wakes

The main methods are lidar, passive acoustic, active acoustic, and radar.

9.1.1 Lidar

Wakes can be detected from characteristic changes in the radiation transmitted into the atmosphere by a lidar. We distinguish two main lidar types:

- Doppler lidar measures the frequency shift caused by moving particles / aerosols
- Non-Doppler lidar relies on backscatter measurements. Vortices can capture or “entrain” particles so that the backscattered signal is stronger than from the surrounding air.

Recent developments and papers:

Lidar triangulation measurements of wakes at Tarbes airport were reported by DLR, QinetiQ and ONERA under C-Wake. The use of more than one scanning lidar allows consistency checks, accurate location of the vortex cores by triangulation methods, and better range and trajectory information, so that uncertainties in derived parameters such as circulation are reduced. The errors in core location increase quickly (roughly quadratically) with altitude for a single monostatic CW lidar, becoming very large above 200 m.
During several field trials, the 2 micron pulsed Doppler lidar from CTI has proved its capability for wake-vortex detection, tracking and characterisation. Köpp et al. 2004 describe a long-range capability of 400 - 1500 m combined with high spatial resolution of a few metres and a velocity precision of better than 1 m/s. The C-Wake comparison campaign is reported in Köpp et al. 2005. Airborne 2 micron lidar wake-vortex detection and characterisation have been demonstrated in I-Wake 2004 and AWIATOR 2005. CTI, recently absorbed by Lockheed Martin, sell their 2 micron system under the name WindTracer.

There is now a 1.5 micron option for monostatic lidar. QinetiQ’s CW ZephIR (see 2 below) can be configured for short-range detection and tracking of vortices, in the same way as 10 micron systems. Mitsubishi’s pulsed lidar and some vortex detections were described at the 2005 Coherent Laser Radar Conference in Japan.

Mayor and Spuler 2004 discuss a Raman-shifted eye-safe aerosol lidar. Larry Cornman notes this non-Doppler system has been upgraded with 50 Hz repetition rate (for faster scanning, i.e. re-visit time) and a depolarisation channel (which could differentiate between jet exhaust aerosols and the background). His group is developing plume detection algorithms which could be applied to wake vortex detection, if – a big question - there is sufficient enhancement of the backscatter in the vortex.

9.1.2 Passive acoustic
From the characteristic sounds they emit, wakes can be detected by either a conventional microphone array or a lidar microphone array.

Data from 2003 Denver trials are further examined by Booth and Humphreys 2005, and Fine and Kring 2005. Roughly 10% to 20% of aircraft passes produced no usable acoustic signature, although Denver airport had unusually quiet acoustic background. This failure rate is not fully explained and is worrying. Another trial was performed in Denver in late 2005; its analysis continues.

Passive acoustic sensors (with beamforming processing) sometimes provide adequate SNR and vortex localisation, but they are immature and not yet sufficiently reliable. WakeNet has seen AIAA presentations but no detailed description of the sensitivity or processing of SOCRATES, the lidar microphone promoted by Flight Safety Technologies. It measures the time-varying optical phase shift (which is linked with the acoustic pressure waves) along the lidar’s optical path. Acoustic pickup noise and atmospheric turbulence are likely problems.

9.1.3 Active acoustic
Wakes can be detected through their effect on acoustic waves transmitted through the atmosphere (for example, changes in the air density and speed of sound). Sodar systems transmit and receive sound waves. RASS systems transmit sound waves – patterns of density variations in the air – then transmit and receive radar waveforms which Bragg-reflect from these patterns.

Andrew Martin of StratoSonde (a subsidiary of Tele-IP) presented results on pulse-compression sodar (LP2C) to WakeNet and other parties and sought funding.
European experts and NASA, NCAR and NOAA remain sceptical without a detailed evaluation of LP2C results. Tele-IP intend to separate from (divest) StratoSonde.

Stuart Bradley of Auckland University has supplied a preprint (now on the WakeNet website) about linear-array sodar measurements of vortices, with near-real-time (~ 2 second) updates to permit tracking.

According to NASA/Volpe, RASS is still of interest although their main trials at JFK were not fully analysed and documented.

Airport trials of an ultrasound time-of-flight method (suggested by Durgin and Johari) are described in Rebecca Rodenhiser’s WPI thesis and forthcoming papers. The measurements at 57 kHz show successful vortex detection in good conditions.

9.1.4 Radar
Conventional radar, at longer wavelengths well suited to scanning and wet weather, can detect some vortices but with poor precision / low SNR / higher false alarm rates. THALES concluded from ATC-WAKE studies that radar reflectivity images and Doppler information from existing ATC radars can enhance wind field estimates and turbulence mapping. The weather channel of ATC primary radar detects rain clouds out to ~ 80 nmi in wet weather, and provides an atmospheric clutter map with a resolution ~ 0.5 nmi.

At shorter range, the “regularised high resolution” methods developed by Thales offer improved Doppler spectral width measurements and can help turbulence mapping and hence WV predictors. Doppler resolution may be ~ 5 times better than for standard DFT-based methods, but – as always – success depends on the match between the real physics and the assumed model (e.g. autoregressive signal with additive Gaussian white noise, commonly assumed in radar and lidar). For a given radar volume cell (range resolution + beam width in azimuth and elevation), we can estimate the relative powers detected from wet air turbulence and from a wake vortex. In rainy weather, the background return is set by the atmospheric turbulence; typically the rms random wind speed (related to spectral width) is ~ 0.5 ms-1 for low turbulence and ~ 5 ms-1 for severe turbulence. The presence of a wake vortex likewise widens the Doppler spectrum. At 2000 m range, with high-resolution processing of STAR2000 S-band radar data, and for the spectral shapes deduced from a lateral line of sight and an assumed geometric vortex model, Thales estimate a “vortex” power typically between 2% and 20% of the “air turbulence” power, and this is sufficiently high to be detectable and useful.

Several recent simulations and studies suggest that Doppler short-pulse or coded radars can detect vortices at 2-4 km (see Table 1, also Shariff and Wray 2002).

9.1.5 Summary
Our current understanding of wake vortex evolution is that accurate measurement of position and circulation, even when possible, is not enough; there is so much statistical uncertainty in evolution that the measurements must be repeated, i.e. the vortex must be monitored after initial detection.
Lidar, with its fine precision of both spatial and Doppler measurement, is the best tool available to quantify the vortex strength and position, but it has necessary drawbacks: for example, it is not suited to very fast wide-field-of-view scanning, and it dislikes wet or cloudy weather. Lidar and radar (which is usually better in bad weather) are thus complementary tools.

9.2 Wind profiling

Measurements of the wind vector at various ranges and altitudes can be used in:

- Vortex transport and decay predictions for near the airport
- Meteorological models
- Gust and turbulence warning

The main methods are lidar, sodar and radar:

Conically-scanned coherent Doppler CW lidars at 10 micron wavelength (MIT, QinetiQ, ONERA etc.) have provided short-range wind profiles at many airport trials. Raster-scanned coherent Doppler pulsed lidars at 2 microns wavelength (CTI) provide wind profiles out to several km and along the glide slope. Fast and highly resolved wind measurements can be used to derive parameters related to the atmospheric turbulence; e.g. the turbulent energy dissipation rate can be estimated with an accuracy of 15 - 20 % (Smalikho et al. 2005).

QinetiQ’s 1.5 micron Doppler CW lidar (ZephIR) is accurate and reliable for anemometry and wind profiling in near-real-time at ranges up to about 200 m (see Smith et al. 2004). This compact, eyesafe instrument is available now for near-runway measurements.

Thales calculations suggest that direct-detection UV lidars will not be eyesafe or skinsafe when operated for wind monitoring at typical ranges (see the February 2005 WG6 presentation from L Mutuel et al.). Typical window materials attenuate heavily in the UV, so the radiation would be eyesafe inside the aircraft.

Sodars are probably the commonest choice for medium-range wind monitoring (AeroVironment, Metek, Remtech). Terminal Doppler weather radars routinely provide wind information for airports.

9.3 Technology comparisons

We list some of the pros and cons of different technologies such as sodar and lidar, recognising that a direct like-for-like evaluation is important but difficult.

Relevant technologies are listed by Sauvage et al. 2005. Other reviews cited in WakeNet are by Zak 2003 and Zak et al. 2001.
The averaging of signals over space and time is a critical area for comparisons between the technologies. For example, ZephIR in conical-scan mode has processing that assumes uniform airflow at each height; the narrow beam, precise pointing and known beam focus allow this assumption to be checked if necessary. That is also true of other conical-scan lidars such as the CO2 ones fielded by ONERA and QinetiQ for C-Wake trials. Sodar processing makes the same assumption of uniform airflow, but sodars inherently average over a large air volume, and they do not allow this consistency check.

For precise probing of vortex physics, the precision (in space and frequency) of lidar measurement is not matched by any other technique. For a single measurement of the Doppler shift (line-of-sight wind speed) at a single point, or more strictly in a small volume defined by beam focus/overlap, a lidar needs a few milliseconds. Sodars do not compete. StratoSonde claim (for example) 0.3 m precision for sodar measurement of vortex core position; Sauvage et al. noted this claim, but neither they nor WG6, nor sodar researchers such as Bradley, endorse it without more validation. Precise probing in this sense is less interesting (for WakeNet end users) than airport operational measurements.

Sodars and lidars are candidates for wind profiling at low altitude near the runway. ZephIR operates up to about 150-200 m range. For a single measurement of the wind vector at a single altitude, the typical conical-scan lidar needs between 1 and 4 s to gather many separate Doppler measurements and combine them in an overall estimate under the assumption of uniform airflow. The scan pattern and sampling strategy are not usually optimised for this one task. Sodars do not seriously compete.

Beyond 200 m, there is little range discrimination for the CW lidar because the beam cannot be brought to a distinct focus. Pulsed sodars enjoy the extra range discrimination allowed by time-gating. For final approach and landing, however, the accurate and real-time wind profile up to 200 m (“low altitude”) is more important than extra information about winds above 200 m.

The ability of lidar to detect rapid turbulent variations is important. With sodar, time-averaging over many separate returns is often necessary because the sodar echoes are so weak. This averaging also leads to errors in calculating wind speeds that fluctuate over the measurement time. The use of radar-type modulations in sodars allows improvements but (as said above) there is scepticism about StratoSonde’s claims for rapid accurate LP2C measurements. The lowest value of vertical resolution quoted for sodar by Zak is 5 m for an AeroVironment minisodar. Proper comparison of achievable data rates is not easy, but in practice sodars have been much slower than lidars (minutes per measurement, rather than seconds or less) and can be upset by several environmental factors. Much care is needed to site, screen and run a sodar for high accuracy, say 1% or 2% error in wind speed; but Stuart Bradley notes that in practice his trailer-mounted AeroVironment sodar routinely collects data within 15 minutes of arrival at a fresh site, with accuracy fully adequate for airport wind profiling.

For a single measurement of a wind profile, i.e. a wind vector at each of say 5 different altitudes from 20 m to 150 m, the conical-scan lidar needs 15 to 30 s. Again
the scan pattern and sampling strategy are not usually optimised for this one task. Sodars, including pulse-compression and multiple-frequency models, begin to compete here because they extract information with a single transmission for all ranges. Coherent Doppler pulsed lidars at 1.5 microns are appearing: see Pearson et al. 2002 and remarks below on FIDELIO.

For detection and tracking of wake vortices see section 1 above. Lidar and radar are complementary. StratoSonde quote parameters for LP2C sodar measurements of wake vortices: 98 % availability; no limitations caused by weather; 99.9 % probability of vortex detection.

For glide slope surveillance and weather monitoring, pulsed lidars and conventional TDW radars are complementary. CTI (now part of Lockheed Martin) remain the market leader in 2 micron pulsed lidar but their systems are expensive to build and maintain. Mitsubishi have begun to market their 1.5 micron pulsed lidar. Europe is working in 2 micron technology (e.g. LISA Laser Products) but no comparable systems have yet been marketed.

The 2 micron pulsed lidar generates huge amounts of data for which there is no processing hardware on the European market, though CTI’s wind profiling algorithm applies to some extent to wake vortices.

The objectives of the STREP EU FP6 project FIDELIO (“Fibre laser development for next generation lidar onboard detection system”) include the development of a fibre laser MOPA (master oscillator + power amplifier) as the transmitter for an onboard wake vortex detection system. The MOPA promises the inherent advantages of fibre lasers, while meeting the two challenges of high energy and single-frequency/single-mode output. The high energy (> 1 mJ) is needed to achieve long-range detection and give the pilot ample time to respond. The single-frequency output is needed for accurate estimation of the wind speed (< 1 ms⁻¹ error).

9.4 Recommendations

Several issues need to be better understood:

- **The complementarity of radar, sodar and lidar: e.g. extending the use of ATC radars in wet conditions, when lidars are handicapped.**
- **The performance claims by the manufacturers of LP2C sodar and SOCRATES lidar. These claims should be assessed by independent parties.**
- **Passive acoustic techniques and RASS may be important, but WG6 does not have enough information to advise WakeNet.**

**The technical state of the art needs frequent review.** The tables and comparisons in e.g. Zak’s NASA reports and in Sauvage et al., and in this WG output, are snapshots that become quickly outdated.
9.5 References

(NB authors named in the text; here listed alphabetically)


[ ] L Sauvage et al., “Preparatory study of wake vortex detection technology”, TRSC52/2004 on behalf of EUROCONTROL (WakeNet-USA, March 2005).


Acknowledgement
Thanks to: Stuart Bradley, Larry Cornman, Peter Fuhrberg, Ulf Michel, Gerhard Peters, Heino Teichmann, Frank Wang.
### Table 1 Some wake vortex radar detection trials

<table>
<thead>
<tr>
<th>Company</th>
<th>Radar used</th>
<th>Trials: when? where? which aircraft?</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEC MARCONI &amp; CAA (UK)</td>
<td>DX 04 (S band : 3 GHz)</td>
<td>1992 United Kingdom HS 748 BAC 1-11</td>
<td>detection range = 2.8 km confirmed by CNRS &amp; STNA processing study</td>
</tr>
<tr>
<td>CNRS &amp; STNA (FR)</td>
<td>PROUST (L band : 961 MHz)</td>
<td>1992 France Coulommiers airport</td>
<td>detection range = 4 km</td>
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<tr>
<td>APL (USA)</td>
<td>Bistatic X band</td>
<td>1997 USA Washington airport C 130</td>
<td>detection range = 2 km</td>
</tr>
<tr>
<td>NASA (USA)</td>
<td>C band</td>
<td>1997 USA Virginia C 130</td>
<td>detection range = 1.4 km</td>
</tr>
</tbody>
</table>

Other information:
- Theodore Myers (Virginia Polytechnic PhD dissertation, 1997) developed a simulation model and compared wake vortex RCS in VHF, UHF, L and S bands.
- NASA is developing a bi-band radar X+ Ka (35 GHz).
Section 10
Safety Enhancement Tools: On Board Wake Detection

Laurence Mutuel (THALES, Aerospace Division)

10.1 State of the art

Wake vortex remote detection with onboard sensors focused primarily on the potential use of LiDAR in 1993 with the EC funded FLAME project, leading to successful ground tests in 2000 during MFLAME and the world premiere flight tests in I-WAKE in 2004. The know-how gained with these projects concerns the available technology through

- the manufacturing of lightweight mirror-based scanner,
- the building and integrating of a LiDAR demonstrator,
- its ruggedisation to go from laboratory to shelter to finally aircraft installation
- its integration with aircraft systems (Air Data and Inertial System).

In terms of system, MFLAME allowed to develop signal processing techniques that revealed efficient in detecting wake vortices from the ground down to the level of Fokker 100 wakes. I-WAKE took the challenge further to adapt the signal processing algorithms to a moving platform with an 'almost' forward looking sensor geometry, a platform flying at higher altitudes thus yielding poorer signal to noise ratios and range-dependent noise spectra.

In parallel to the flight tests, flight simulator tests allowed to propose to pilots Human Machine Interface (HMI) concepts for the Navigation Display (ND), the Primary Flight Display (PFD) and the Vertical Situation Display (VSD). Strategic and tactical information on wake vortex 3D position, including tactical alerts (caution and warning) with estimated time to encounter were reviewed until accepted by pilots.

Finally, the technology part of I-WAKE had the objectives (1) to promote the IR laser for atmospheric hazard detection as a first brick to a European LiDAR system and (2) to develop and assess automatic pattern recognition techniques. At the end of the project, a laboratory mock-up of 2μm laser was tested with satisfactory performances and pattern recognition techniques showed encouraging results on the ground based MFLAME data.

As a background task started in MFLAME, I-WAKE contributed to the system definition in terms of a end-user requirements, functional architecture with selected sensors and detection methods, use of wake vortex model in support of LiDAR including datalink requirements, potentialities of datalink for ground/ board exchange of wake data, integration of onboard system with ATM in support of reduced separation distances (result sharing with ATC-WAKE).
10.2 Available validations of models and tools

The overall system is functionally represented in Figure 1.

Figure 1: Functional Representation of Atmospheric Hazard Detection, Warning and Avoidance (DWA) System.

The research projects on instrumentation for onboard wake vortex detection focused on LiDAR+model capability for the approach and landing phases. The wake vortex model used for the onboard DWA system is the Vortex Forecast System (VFS – See Specialist Report) that has been recently benchmarked. The lidar used is in the infrared wavelength at 2µm and its detection capability has been validated in ground tests and flight tests. The detection method used is based on a rectangular field of view 12° horizontal by 3° vertical with a detection range from 800m to 2.5km ahead of the aircraft to allow for 30s caution and 15s warning alerts.

During the MFLAME ground tests, numerous aircraft wakes were detected ranging from Beluga transport aircraft to Fokker 100, thus enabling a database of lidar longitudinal wake data to be used for signal processing and training of automatic pattern recognition algorithms. Unfortunately, I-WAKE flight tests only intended two tests with A340-600, enough to validate the wake detection onboard an aircraft but not enough to form the embryo of an onboard lidar longitudinal wake data.

While the operational interest in wake detection using weather radar is clear (the lidar can only detect in clear dry air conditions), the feasibility of onboard detection has to be assessed.
10.3 Examples of applications

The onboard Atmospheric Hazard DWA system aims at preventing accidents and incidents related to

- Wake Vortices in departure, cruise, approach and landing in support of reduced separation time and/or distances and under RVSM,
- Windshear (dry and/or convective) in departure, approach and landing,
- and Clear Air Turbulence in cruise.

The I-WAKE project focused on the wake vortices, but included a first assessment of the long range detection capability of the IR 2µm lidar in view of the CAT application. The results were satisfactory as fitting the operational requirement of 5 to 10km range. The detection methods were derived for the three hazards, the windshear being easier than the wake detection because of its larger span and easier than the CAT because of the lesser range. It was not included in the flight test goals but as we unexpectedly encountered windshear layer, successful results are also available.

10.4 Future developments (needs and possibilities)

The overall results of I-WAKE can be visualised in three groups (See): system related, operations related and technology related.

![Figure 2: Dissemination of I-WAKE results.](image-url)
Research needs for lidar technology
The available technology of IR 2μm 2mJ lidar has proven to satisfy the performance requirements for wake vortex detection, while an increase in energy will undoubtedly benefit long range detection and cruise operations. The culprit lies in the volume and weight needed to host such a sensor: 2μm technology requires free space optics. Research needed in this area is twofolds:

- pursue the use of 2μm lidar improving weight and compactness
- investigate 1.5μm lidar for the potential of optical fibers

The 1.5μm is a less mature technology than the 2μm but carries the promise of easier aircraft installation since the lidar will be fibered. On the other hand, the energy that can transport an optical fiber is limited and the foreseen level of 1mJ is likely to not satisfy the detection performance requirement. The 6th FP project FIDELIO will assemble such a demonstrator for ground testing of the 1.5μm technology, direct comparisons with the MFLAME results could then be done.

Besides the wake vortex hazard, clear air turbulence detection must be addressed. I-WAKE allowed the assessment of detection range with current IR 2μm technology and proposed a suitable increase in laser energy from 2mJ to 10 or 20mJ. Such systems might be under investigation in the US but not in Europe. Ongoing development in 2μm technology started in I-WAKE must be pursued.

Finally, lidar technology is sensitive to the aircraft environment in terms of vibrations, temperature and pressure. All lidar measurements from onboard aircraft have used systems installed in the cabin, not the final sensor installation spot: the non pressurized, non temperature controlled space between the nose wheel and the radome.

Research needs for operational use
As stated before, the onboard wake DWA system was mostly evaluated for approach and landing, other flight phases like cruise and departure need to be properly addressed. The development of operational concepts for departure is one of the topics of the 6th FP proposal CREDOS, the concepts could then be used in an instrumentation driven project to validate the detection performance. Cruise operation is investigated in the 6th FP project FLYSAFE with the task of wake detection in RVSM focused on the model capability and not the sensor development. The wake vortex signal processing algorithms used in I-WAKE were running off-line and were not real-time, this will one of the tasks delegated to FIDELIO. On the pattern recognition side, training is needed on onboard longitudinal wake data and no current or proposed project is covering the data collection aspect.

For the CAT detection in cruise, the relatively short range of the lidar prevents strategic awareness of the hazard, but rather tactical warning needs to be developed: alerting logic, detection parameters, HMI…etc…part of this list will be studied in FLYSAFE.
Research needs for system aspects

The detection of wake vortices is a part of a more global system called "Integrated Surveillance System" (ISS) which fuses weather, traffic and terrain hazard information to increase pilot awareness. The architecture of such a system is at the heart of FLYSAFE where ground aspects are included in addition to the onboard detection capability. Overall topics that not only interest wake vortex will be studied like datafusion, datalink, prioritization of alerts and HMI. There will be however a gap to fill between the results of a small project like I-WAKE that concentrated the wake expertise but could not deal with the transverse surveillance aspects and the results of FLYSAFE where the transverse aspects are well addressed through the wider expertise but where the wake specifics might be lost. The best would be an Integrated Project where wake related issues both on the ground and onboard could be resolved through technology assessment and operational use.

Other research needs

Two points were not addressed so far:

- Absence of standardization and certification basis for lidar systems
- Assessment of wake detection performance using onboard weather radar

The former is partially tackled in FLYSAFE where existing standardization groups will be targeted but the set up of new groups for the lidar sensor is yet to be done. The latter is not foreseen in proposed research project of the last 6th FP calls.
Section 11

Wake vortex alleviation studies and prospects

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11.1 Introduction

This Part of the “Wake Vortex Research Needs Document” will:
- summarize the present day knowledge about alleviation of aircraft wake vortices,
- list the open issues,
- provide recommendations for future work.

Research has been conducted in the last decade within the framework of European partnership, notably as part of programmes sponsored by the European Commission like Eurowake, C-Wake and AWIATOR. Important experimental as well as numerical data were generated using complementary approaches: on the theoretical side from analytical models up to sophisticated numerical methods and experimentally from sub-scale tests in windtunnel, watertank or catapult facilities up to full-scale flight trials (each requiring the development of appropriate instrumentation).

First of all, the physical background of aircraft wake vortices will be briefly recalled before detailing the main principles and practical approaches for wake vortex alleviation. Most of the results, referred to hereafter, were presented during the WakeNet2-Europe WG7 Workshop on “Principles of wake vortex alleviation devices”, held at ONERA Toulouse, February 2005.
11.2 Wake vortex flow: characterisation and simulation

Background

The lift force generated by an aircraft wing produces generally two counter-rotating vortices that can persist for long times. The basic physics of such a single vortex pair wake is reasonably well understood. When the vortex is generated its strength $\Gamma_0$ follows from:

$$\Gamma_0 = \frac{W}{\rho U s} = \frac{1}{2} C_L U b s$$

with $W$, $b$, $AR$ and $C_L$ the weight, wing span, wing aspect ratio and lift coefficient respectively of the aircraft. $U$ and $\rho$ are the aircraft speed and air density. $s$ is a dimensionless parameter defined by the distance between the vortices divided by the wing span $b$. It depends on the wing loading and is equal to $\pi/4$ for an elliptical lift distribution.

As soon as the vortices have formed, they will move downwards (due to their mutual induction) and decay. The evolution of the wake vortex behind an aircraft is very often described versus either its distance $x$ to the aircraft, normalised by the aircraft wing span $b$, ($x^*=x/b$), or by a non-dimensional time $\tau^*$ ($=t/t_0$). Here $t_0$ is the time in which a vortex pair propagates the distance of one initial vortex spacing downwards and thus equal to $b_0/w_0$, where $b_0=b.s$, the vortex spacing and $w_0$ the initial sink speed [15,25]. In terms of aircraft parameters $t_0$ can be written as:

$$t_0 = \frac{2\pi \rho U (b.s)^3}{W} = \frac{4\pi A R b s^3}{C_L U}$$

The larger the value of $t_0$, the slower the vortex decays. The formulae above indicate that for similar aircraft of different size (similar in a mathematical sense, hence the same shape but at a different scale, the same lift coefficient), both vortex strength and decay time are proportional to the span $b$. Therefore, an aircraft with a larger aspect ratio will have a weaker vortex which persists longer [23]. These scaling rules are (believed to be) known, although it has to be noted that there is in fact no “full size” proof of the $\tau^*$ scaling (too much scatter in the ‘in flight’ data sets to discriminate between aircraft of different sizes).

During their evolution, the vortices grow in size due to diffusion and develop three-dimensional oscillations caused by flow instabilities that may lead to strong interactions between the vortices and increased dissipation. During the first stage of the decay, as long as the two vortices stay apart from each other, the vortex strength or circulation $\Gamma$ and the vortex spacing $b_0$ are essentially constant. Only in the later stages, when the two vortices interact, $\Gamma$ will decrease and $b_0$ will increase. To express the intensity of the vortex the circulation (as it is constant for quite some distance) is not a good measure and instead various quantities are used:

- $\Gamma_{5,15}$, the averaged circulation between 5 and 15m distance to the vortex core, from Lidar measurements for real aircraft applications, but usually considered to the integral between $b/12$ and $b/4$ for aircraft models,
- $E_{\text{kin}}$ the cross-flow kinetic energy (its initial value being directly related to the induced drag),
- the core radius $r_c$ (the distance of the vortex centre to the maximum tangential velocity),
- the maximum tangential velocity $V_{t,\text{max}}$ at the core radius $r_c$.

For a particular profile family of the tangential velocity, these 4 quantities can be directly related to each other [14]. Due to diffusion of vorticity, $\Gamma_{5-15}$, $E_{\text{kin}}$ and $V_{t,\text{max}}$ decrease downstream whereas $r_c$ increases. The ‘danger’ of a vortex, e.g. described as an induced rolling moment for a follower aircraft, can also be related to these quantities.

The vortex field behind the aircraft is then generally split in four regions:
- the near-wake field very close to the wing trailing edge typically of the order of the wing chord length which comprises vortex sheets and highly concentrated vortices;
- the extended near-wake field, typically $0.5 < x^* = x/b < 10 - 15$, or $0.25 < \tau^* = t/t_0 < 0.5$ in which the roll-up and merging of the vortex sheet and the vortices occurs, in most cases leading to two main counter-rotating vortices;
- the mid-wake field at a maximum distance of $\sim 100b$, or $\tau^* \sim 2.5$ where the vortex system gradually drifts downwards due to mutual interaction of the vortices and where the instabilities emerge;
- at last, the far-wake field, at a distance greater than $100b$ or $\tau^* > \sim 2.5$ is where developed instabilities result in strong interactions between these two main vortices leading to their dispersal.

Note that the given values are for quiet air. For other weather conditions with turbulence, shear or inversions these values can be considerably less.

Fig. 1 – Illustrations of wake flow fields a) Regions I & II: iso-contours of vorticity behind high-lift configurations (AWIATOR, exp. performed by TUM-AER [2]); b) & c) Regions III to IV (from [41]).
Experimental techniques: ground facilities

The wake vortex formation, as well as the roll-up phase, is reasonably well understood since many investigations have been conducted in standard facilities (wind tunnels), with appropriate measurement tools. In the mid- to far-wake field, the towing tank and the free-flight (catapult) facility are the only tools which allow such wake flow scrutinising (Fig. 2). Several tests were performed in the framework of the C-Wake project in the towing tank and catapult facility to characterize wake vortices [29,46]. Some of the test results showed anomalies that could be understood from boundary or installation effects (known as end-effects) and temperature stratification. Specific new test campaigns have been performed in the AWIATOR project, during which these effects were investigated and cross-checks were made for these two specific facilities [5,35].

![Fig. 2 – Four regions of the wake flow field as well as their dedicated facilities for investigations.](image)

End-effects were carefully monitored and observed by Airbus-Deutschland, DLR and ONERA during some dedicated tests; UCL conducted also investigations at the UCL/TERM towing tank [18]. They are the result of instabilities (travelling waves) that move up- and downstream through the vortex core and that are triggered by launching or stopping the model. They have been studied in the HSVA towing tank by accelerating and decelerating the model in various ways and in the B20 catapult facility by varying the location of the observation plane [5]. Former tests made by DLR in the WSG research-type small-size towing tank confirmed such effects. These effects led to potential discrepancies on vortex core structure (core size, velocity peak) and on circulation evolution. The instability seemed to be similar to an axial-type one which developed a travelling vortex bursting wave along the vortex core, leading to enlarged cores [1].

It appeared also that temperature stratification could be a limiting factor for towing tank investigations characterised by specific values of the Brunt-Vaïsälä $N^*$ frequency (a parameter linked to temperature gradient and vortex spacing $b_0$) [13]. It has an important effect on lateral vortex spacing and strength, the intensity of which was in rather good agreement with CFD predictions performed by CERFACS at comparable values of $N^*$. 
For investigations of high-lift wing configurations at landing conditions and without any stratification and end-effects disturbance, the validation domain could reasonably be identified as ~150b and ~100b for the larger towing tanks (HSVA, INSEAN) and the B20 catapult facility, respectively; ground effects usually alter the wake development behind these upper limits.

Thus, the combination of the afore-mentioned tools (wind tunnel/towing tank/catapult) is well suited for wake vortex identification in the near- to mid-/far-wake field. Specific instrumentation has been adapted or developed in some facilities to fully track wake vortices \[5\]. Systematic investigation could then be conducted in these sub-scale facilities, allowing evaluation of wake vortex minimisation candidates.

**Experimental techniques: flight tests**

In the far-wake field, full scale tests were successfully undertaken in the last years, notably in the framework of European projects (C-Wake and AWIATOR) \[12,27,34\]; they were complementary to some dedicated national activities \[16,17,26,27\]. Continuous CW-Lidars measure the velocity ‘somewhere’ along the light of sight (LOS) of the Lidar beam and don’t provide information on the location of the vortex along the beam. DLR, ONERA and QinetiQ were the first to show the great potential of applying a triangulation method with two Lidars for tracking wake vortices generated by two different-sized aircraft in two measuring campaigns \[34\]. As a result of this the range of observation (up to decay phase) could be increased somewhat and the error in vortex core location and circulation be reduced. DLR made rather recent developments on their 2\(\mu\)m pulsed Lidar, which is really complementary to the short range CW Lidars. Although less accurate, the pulsed Lidar allowed observation over larger distances than the CW- Lidars: the vortices could be tracked from their generation to a progressed state of vortex decay. In the AWIATOR trials, excellent agreement between the two Lidar tools was obtained. Also, the evolution of the circulation over about 200 spans behind the aircraft could be recorded. These measurements indicated a large effect of weather conditions (turbulence, stratification and shear) on wake vortex decay. But also for almost identical conditions a large scatter in the data could be observed, indicating the need for large amount of data, when applying such tools.

Thus, full-scale measurement techniques might reasonably be used to quantify the effect of aircraft wing modifications (linked of course to wake vortex alleviation purpose) on the decay. Because of the afore-mentioned observations due to weather conditions and ground proximity, on-board Lidar measurements were recently considered: a first validation exercise was successfully carried out in 2005, using the DLR pulsed Lidar, mounted in the DLR Falcon aircraft tracking the wake generated by the DLR ATTAS research aircraft (AWIATOR project). The technology will soon be applied to track larger-scale vortices.

**Numerical simulations**

Numerical simulations have also advanced significantly, resulting notably from work in the two last EC projects devoted to wake vortex characterisation and control (C-
Wake and AWIATOR). As Euler computations were applied to former test cases [12], it is now possible to do 3D RANS computations on a complete high-lift wing configuration down to 0.5 spans for both sub- and flight-scaled Reynolds numbers with different turbulence models [20,45]. Vortex methods [46] are very powerful and efficient to calculate the roll-up and vortex interactions from there on and should be considered in that respect. And further downstream, the interaction between the vortices and/or with atmospheric turbulence can be calculated with Large Eddy Simulation techniques (“LES”) like the Vortex-In-Cell (“VIC”) (results will be shown later in Fig. 14). A detailed comparison of various LES methods [20], the so called ‘bench mark study’ done in the AWIATOR program, clearly indicated the maturity of these techniques. It is to be noted that the initial conditions for vortex methods and LES simulations are very often obtained from smoothed experimental results to compute the wake flow subsequently up till ~120-150 spans. RANS results could have been used instead, as starting conditions. However, it is fair to point out that these RANS calculations are still very complex whereas great care is required to reduce mesh and artificial viscosity effects.

Finally, the stability of vortex systems has been investigated with linear stability theory. Since the vortex distance \( b_0 \) is much larger than the vortex core, linear stability theory could also be applied successfully for a set (two, four or even six) of parallel vortex filaments with weak sinusoidal perturbations of their spatial positions. This allowed a parametric investigation in search for the highest levels of amplification for several multiple-vortex systems [24,25,33].

Thus, nowadays, a complete methodology/chain has been defined with support from theory, CFD, sub-scale tests and full-scale flight tests. It was recently validated for the wake characterisation of a baseline high-lift wing aircraft configuration (AWIATOR project, [42]). One can expect that this methodology can be employed in the future for the assessment of the wake alleviation potential of modified wing configurations.

### 11.3 Wake vortex alleviation: two main strategies

Knowing that it is impossible to inhibit the generation of the aircraft wake vortices [40,41], the question that has then to be considered is: “How can we alleviate, destroy wake vortices, or at least minimise their intensity”?

Two main strategies can be pursued for wake vortex alleviation (Fig. 3):

- to act at the source, i.e. in the near-field, by either promoting small scale instabilities and increasing diffusion of vorticity or by introducing new turbulence in the vortex core, resulting in a larger but less intense core (reduction of peak vorticity and velocities) (Fig. 3b). The total circulation will not be affected, but a weaker rolling moment is expected for the following aircraft. This can be obtained by devices such as wing-tip, flap-tip ones, fences, spoilers…

- to create in the far-field a multiple-vortex system to promote long-wave instabilities and/or to trigger perturbations to obtain a premature wake collapse (Fig. 3c). This can be reached either by a passive concept leading to spanwise wing loading modification (via arrangement of flap or spoiler deflections) or by active devices such as blowing, oscillating flaps, ailerons…
Passive systems exploit the natural evolution of the instabilities modes with the highest growth rates, while active systems rely on hastening selected modes of instabilities by “forcing” the vortices. Both can be done using an existing vortex topology or by changing the vortex topology through a modification of the span load.

Vortices are characterised by a high degree of unsteadiness; several experimental tests allowed identifying the presence of both short-wave (wavelength $\sim O(r_c)$ with $r_c$, core radius) and long-wave ($\lambda \sim O(b_0)$) instabilities [36,39]. The former (of Widnall-type) controls the merging of co-rotating vortex systems and could be enhanced for aircraft applications for wing-tip/flap-tip interactions. However, it would be unable to break down the wake vortex because of its weak dynamics when compared to the dominating mechanism of the rolling-up and evolution process of the wake vortices [1]. The “classical” Crow instability ($\lambda \sim 8b_0$, and growth rate $\sim 0.8\Gamma_0/(2\pi b_0^2)$) is able to destroy a pair of two-main counter rotating vortices, but its effectiveness is not obvious because of its low growth rate. Crow himself proposed a forcing scheme using the control surfaces of a wing to hasten the development of cooperative instabilities of the vortex pair in its wake. This concept was checked in towing tank tests as well, but the development of the vortices was not long enough to check its efficiency (in [40]).

Instabilities are much more powerful for multiple vortex system. This can be realised by a modification of the wing span loading (either producing additional co- or counter rotating vortex pairs) possibly enhanced by Horizontal Tail Plane (H.T.P.), normally providing negative loading and hence a counter rotating vortex pair. The counter rotating vortices can produce medium-wave instabilities ($\lambda \sim O(b_0)$ referred to as “Omega $\Omega$-loops”) that are very fast growing and lead to strong interaction between vortices and generation of small scales and turbulence. As a result the vortex will be very much diffused. Consequently, the 2nd strategy is based on the notion that fast growing instabilities can amplify downstream and lead to the efficient destruction of the wake system.
Thus, the two strategies represent different concepts that might change the local or the global characteristics of the vortex system. Local modifications are obtained by adding specific devices to the wing whereas span load changes can be obtained from Differential Flap Setting (“D.F.S.”) or Differential Spoiler Settings (“D.S.S.”). These concepts will be discussed more in the following sections.

But before that discussion, the question can be asked if a basic wing design can be optimised for minimal vortex hazard. The expressions as provided in the "Background" section above can give some guidance in this respect. Both $\Gamma_0$ and $t_0$ have to be minimised. For a given weight $W$ and (landing) speed $U$ the only remaining parameter is the vortex spacing $b_0$=$b_s$. Increasing $b_0$ leads to a weaker vortex but a much slower decay and the other way around. Since the vortex strength in the far field will be influenced mainly by the decay properties, a small value of $b$ or $s$ is to be preferred. The wake of the Concord is less harmful as the wake of the DC-9 when one is flying sufficiently far behind it. For a given span a low value of the wing load distribution $s$ ("inboard loading") seems to be advantageous, although it can only be varied within rather small limits. ‘Inboard loading’ has the additional advantage, as can be proven from energy considerations, that the vortex core radius $r_c$ is larger as compared with outboard loading (cf. [23]).

11.4 Wake vortex alleviation: what has been achieved so far

Devices, concepts or mechanisms for wake vortex alleviation have been studied in the past years from extensive sub-scale tests (using the combination of wind tunnels, towing tank and catapult facilities), from a few full-scale tests and from either CFD simulations or theoretical approaches. When available, all these different aspects will be evoked in the following discussions when dealing with:

- Wing add-on devices,
- Modification of spanwise wing loading,
- Active wake control (through either active surface or blowing)

Wing add-on devices

In the framework of the C-Wake project wind tunnel tests were first conducted with devices to achieve near-field control like: wing tip and flap tip modifications, flaplet, turbulence generator, wish-bone and spoilers (Fig. 5) [12].

Results pointed out that in the near wake region for $x^*<5$, reduction of peak vorticity and maximum cross-flow velocity could be achieved, in combination with an enlargement of the vortex core $[3,4,9,45]$. Generally speaking, spread of the vorticity could be obtained, while the circulation of the controlled vortex remained unchanged. Some tests revealed that a rather strong re-distribution of the vorticity with wing tip and flap tip modifications at $x^*=1$ did not have any effect at $x^*=5$ [32]. A rather thick spoiler could weakly promote or delay the merging of the two vortices emanating from the flap and wing tips at $x^*=10$, but the residual effect at $x^*=30$ remained within the experimental uncertainty [15].
Detailed investigations have been carried out later in the framework of the AWIATOR project in two wind tunnels, the HSVA towing tank and the B20 catapult, for three specific devices suggested by Airbus Deutschland, Airbus France and DLR partners.

One device consisted of a cylinder-type device, installed under the pylon extension fairing of the outboard nacelle (Fig. 5), aiming at injecting periodic perturbations into the flap vortex to enhance the instability of the four-vortex system generated from the outer edges of the flap and wing tips. Hot-wire measurements, made by TUM-AER in their wind tunnel using this device, verified that the expected frequency emitted in the wake of the cylinder (for Strouhal number ~0.2) could be recorded very close to the device. However, from a power spectra analysis, this frequency could not be seen anymore at 4.5 spans behind the model, indicating that this device could not alter significantly the wake.

Another device, referred to as the "half wish-bone" device (Fig 5), was installed in between the inboard nacelle and the fuselage, on the pressure side of the wing. The generated counter-rotating vortex (w.r.t. wing tip vortex) could be identified close to the flap gap vortex, with comparable strength; however, measurements at the DNW-NWB wind tunnel with a 5-hole probe at $x^*=1$ [44]) or at the catapult facility with PIV at $x^*=1.3$, 4.5 [29]) could only detect the large momentum deficit it caused. Although the vortex of this device can possibly be combined with the horizontal tail-plane vortex, the half wish-bone as a stand-alone vortex generator was rather ineffective.

Finally, a device will be discussed that looked like an inclined delta-type wing, installed at a spanwise location corresponding to that of the outboard nacelle, in the upper side of the wing trailing edge (Fig. 5). Former tests, performed at HSVA and INSEAN towing tanks, provided encouraging results [12]. More recent investigations at the HSVA towing tank pointed out larger vortex cores, $r_c$, compared to the baseline configuration with a substantial reduction in the vortex spacing and in the peak vortex
velocities, $V_t/V_\infty$ (Fig. 6a, [35]). Complementary tests, at the ONERA B20 catapult, with the same device mounted on the free-flight model at almost similar high-lift configuration, confirmed the above-cited observations (Fig. 6b, [6]). The change in vortex spacing does suggest that this device also acted to shift the wing load more inboard.

Some specific winglet-type devices, either standard or larger ones, were also investigated; to see how the wing tip device (size) might affect the wake turbulence. The effect of a standard winglet on the wake flow is rather important, of course, in the vicinity of the wing tip. However, several wind tunnel tests confirmed that at about one span behind the model, the effect on the iso-contours of the axial component of vorticity as well as on turbulent kinetic energy was within the experimental uncertainty [8]. At last, tests performed at HSVA towing tank with “large-sized” winglets (~3 times the dimensions of a “standard” one), applied to a large-transport aircraft type model, showed negligible effect on vortex sink speed, vortex separation distance, maximum tangential velocity or vortex core size.

There are unfortunately no CFD results for wing add-on devices for wake vortex control, partly due to the complexity of the calculations though some applications were reported for flap tip vortex manipulation with passive flaplets [12], partly related to noise assessments and concentrating only on the immediate near-wake flow field.

Finally, a few computations and experiments were devoted to the interaction between engine jets and vortex development [12]. Tests demonstrated that the wake structure could be modified significantly in a region where wake and jets are present. Using several millions grid-points, Euler computations, performed behind a very large transport aircraft-type model, revealed a strong interaction of the outer flap vortex with the outer engine jet. At a few spans behind the wing, the jet could be wrapped around the flap vortex and then trapped in the vortex region. It should be pointed out that one of the main goals of the E.C. Far-Wake project, launched in 2005, will be to provide a systematic insight into the interactions of a wake vortex with either a cold or a hot jet flow.
Modification of spanwise wing load distribution: theoretical considerations

This concept has got much attention in Europe for the last years, though it was investigated in the US in the 1970s. It was first evaluated experimentally by ONERA and DLR in the framework of the European C-Wake project [12], as part of their collaborative research programme [9], but also by ONERA under national research activities [8]. The European AWIATOR project provided the means to go in more detail using both theoretical and numerical approaches prior to and/or parallel to testing campaigns.

The basic idea is to enhance instabilities by creating multiple-vortex system. For a specific span load distribution $\Gamma(y)$, Betz theory states that i) vortices are created at the maximum of the absolute value of the derivative of $\Gamma(y)$, ii) the vortex strength is proportional to the area between two local extremes to the 2nd derivative of $\Gamma(y)$. Hence, by changing the load distribution, e.g. by flap deflection, multiple vortex systems can be generated in principle. Normally, for a high lift wing configuration (the baseline configuration), two main (co-rotating) vortices originate from the outer flap tip and wing tip (Fig. 7, left) that merge very quickly, within a couple of spans behind the model. ONERA did calculate the baseline load distribution and its variation for specific flap arrangements using 2D viscous computations on high-lift wing sections, combined with a 3D lifting surface [37]. The aim was to promote a strong inboard vortex, either co-rotating or counter-rotating relative to the combined outer flap / wing tip vortex (Fig. 7, middle and right, respectively). Illustrations of recorded wing span loading modifications as well as their effects in the wake flow field will be detailed later on, for large aircraft-type models (cf. Fig. 11).

Subsequently, UCL performed roll-up computations using a vortex method (AWIATOR project, [21]) starting from initial conditions taken from available data either from wind tunnel tests (using a rather fine grid resolution as in Fig. 11d) or from predicted lift distribution provided by ONERA (such as Fig. 11a). These calculations showed the evolution of the vortices and their final, double vortex pair, topology (Fig. 11e).

Stability theory could be applied subsequently, starting from such a multiple vortex system. It was shown that a configuration with two vortex pairs of opposite sign (counter-rotating vortices) leads to much higher amplification rates than the "usual" Crow instability for a single vortex pair [24,25,33]. Figure 8a provides some result of the linear theory for $\Gamma_i/\Gamma_o=-0.3$ (ratio of the circulations of the inner vortex to the...
outer one) and $b_i/b_o=0.30$ (ratio of the vortex spacings). The most amplified perturbation (over all wave numbers) was plotted after one revolution of the inner vortices around the outer ones; it was amplified by a factor three orders of magnitude greater than that of Crow instability [33]. These calculations confirmed available towing tank results on very generic configurations [1,22,38,40] for comparable values of $\Gamma_i/\Gamma_o=-0.37$ and $b_i/b_o=0.5$ (Fig. 8b). Since stability theory is restricted to linear perturbations, the observed highly non-linear character of the interaction could not be calculated. But 3D vortex filament simulations by UCL [21] were able to capture the non-linear dynamics up to and beyond the time of strong interaction between vortices as well (Fig. 8c).

UCL made also many 3D LES simulations to further investigate instabilities and decay of counter-rotating four-vortex systems, taking into account the influence of different initial perturbations and the effect of spatial resolution [21,46]. Their parametric investigation pointed out that a counter-rotating four-vortex system could significantly enhance vortex decay for appropriate ratios of circulation and spacing between vortices. The simulations visualised strong interactions between the counter rotating and the main vortices [21], with partial reconnection leading to fast generation of small scales, vortex bursting waves and turbulence. The so called “Ω-loops”, which develop on the secondary vortices, interact strongly with the primary vortices, resulting in increased dissipation (up to 80 % of the initial kinetic energy) due the generated small scale turbulence and eventually vorticity exchange through the mid-plane. Depending upon the configuration, one could observe that the remaining weak vortices were embedded in a relatively strong turbulence field.

A strategy for the optimization of 4-vortex systems to alleviate the wake vortex hazard was also described by DLR [43] based on the coupling of Euler and LES codes (Fig. 9). Once the parameters of the 4-vortex configuration, optimised for reducing rolling moment, are determined, the configuration of the considered aircraft is modified. This could be verified with a steady Euler-simulation for the modified aircraft configuration. The outcome of temporal LES simulation was displayed as iso-contours of the vorticity up to $\tau^*=1.76$ (Fig. 9). A significant decrease of rolling moment was calculated up to ~50% of the maximum rolling moment of a “standard” 2-vortex system. For this candidate 4-vortex system, the horizontal tail plane deflection was set such that it produced strong counter-rotating vortices.
Examples of wing load modifications on models.

Figure 10 illustrates some of the aircraft models that were used in the C-Wake and AWIATOR programs. For realistic aircraft configurations spanwise wing loading modifications could be obtained by specific flap arrangements. This is usually referred to as “D.F.S.” or Differential Flap Setting. Thus, inboard wing loading is obtained with larger deflection angles of the inboard flap than of the outboard flap, and vice-versa for the outboard wing loading. This concept has been applied successfully to two high-lift wing configurations with either two or three flaps. From numerical and theoretical investigations as discussed above, inboard and outboard wing loading configurations were defined and subsequently tested both in the B20 catapult and HSV large towing tank facilities (AWIATOR project) [35]. A synthesis of towing tank tests results will be discussed below in relation with the Figures 12 & 13 [5,35].
DLR employed more generic-type models [1], similar to investigations made in the US [22,40]. Several horizontal tail planes (different chord lengths and spans) were tested in the DLR WSG towing tank to generate a vortex that interacts with the tip vortex of a rectangular wing (Fig. 10, middle-top). This study showed that the interaction of counter-rotating tail vortices with tip vortices resulted in a promising self-destructive mechanism within the wake system similar to what was found in the calculation discussed above [1].

**Some results for inboard loaded wings**

For inboard loading cases, tomoscopy applied at the ONERA B10 catapult facility clearly identified two co-rotating vortices per each half-plane at $x^*=5$ (Fig. 11c). This four-vortex system subsisted till ~25 spans, where it merged into a single vortex pair, more closely spaced, provoking then a steeper vortex descent [8] and (theoretically) a faster decay.

Figure 11: Spanwise wing loading modifications for “Large transport aircraft-type model: a) computed load distribution [31]; b) measured load distribution [29]; c) tomoscopy of the wake flow field [6]; d) measured wake flow field at $x^*=1$ [4,31]; e) computed wake flow field at $x^*{=}14$ [40].

For the inboard loading case, HSVA towing tank measurements confirmed a significant reduction of the vortex spacing and a faster sink speed. In addition, a reduction of the maximal circumferential velocity, $V_{l,\text{max}}$, and an increase of the core radius (“fatter” vortex) were observed (Fig. 12). This latter point was also confirmed from catapult tests when plotting the tangential velocity profiles (Fig. 13, bottom-right). The evaluated circulation strength, $\Gamma_{5-15}$, was lower than the baseline case, the decrease being greater than that recorded from the catapult tests.

These results seem to suggest that the 4-vortex system does not exist for a sufficiently long time to enable the instabilities to develop and amplify to enhance the dissipation. Instead, the co-rotating vortices merge to establish a “conventional” vortex system,
more closely spaced with a theoretically faster decay. It is also to be noted that instabilities, notably short wave instabilities, play a role in the merger of co-rotating vortices but this apparently doesn’t lead to significantly increased dissipation. It remains to be seen if for other vortex topologies (e.g. a larger spacing for the two co-rotating vortices) the situation would have been different, or that merging would occur anyhow, though at larger distances. Nevertheless, the inboard loaded cases indicated some modest improvements relative to the base line.

\[ \Gamma = \frac{\text{circulation}}{\text{cross-sectional area}} \]

\[ x^* = \frac{x}{b} \]

\[ V_t \]

\[ V_\infty \]

\[ y/(b/2) \]

\[ \alpha = 10.9^\circ, C_L = 1.39 \]

\[ \alpha = 8.84^\circ, C_L = 1.43 \]

**Fig. 12 – Towing tank PIV results for inboard loading case on vortex spacing, peak velocity and circulation (from [29]).**

**Some results for outboard loaded wings**

Measurements, performed in the wind tunnel for the outboard loaded case at \( x^* = 1.0 \) in a half-plane normal to the free-stream direction, revealed two intense counter-rotating vortices at a distance of about 1/4th of the half wing span (cf. Fig 11d, [8,9]). It appeared that the two visible vortices from the wing tip and outer flap tip (cf. same Fig. 11d), had merged rapidly at \( x^* = 2.25 \). However, when tested in the mid-wake field in the B10 catapult facility, this multiple vortex system only lasted up till about 5 spans behind the wing (cf. Fig. 11c), leading to a "conventional" vortex pair which went slower towards the ground, in agreement with the recorded increase in vortex spacing [8,9,12].

For similar outboard loaded configurations, the circulation strength \( \Gamma_{5.15} \) as well as the maximum tangential velocity, \( V_{t,\text{max}} \), or the vortex core size, \( r_c \), were almost the same as for the baseline configuration (Fig. 13). No significant advantage seemed to be offered. The catapult Lidar measurements confirmed that the effect on velocity profiles was smaller than that for the inboard loading case. Thus, apparently the generated inboard counter-rotating vortex is too weak, compared to the main vortex from the outer part of the wing (flap and wing tip) or is destroyed too rapidly, or has escaped, so that the generated multiple-vortex system could not sustain for too long and thus did not allow instabilities appearance.
Flight tests with differential spoiler settings

In the AWIATOR program very modest span load variations were realized by deflecting spoilers (“D.S.S.”) as a "quick" substitute to differential flap settings for aircraft applications. Spoiler deflections are interesting because they do not require hardware modifications in contrast to "D.F.S" concept.

Flight tests were conducted during the 1st AWIATOR flight test campaign in 2003 by testing both inboard and outboard loaded configurations using two “D.S.S.” configurations. Unfortunately, because of weather effects (variations in turbulence levels and stratification) the Lidar data were not able to differentiate in vortex strength ($\Gamma_{5,15}$) between the various cases. However, the downward displacement of the vortices seemed to indicate the expected tendency, with the inboard loaded case moving faster downward (Fig. 14).
Further F/T campaigns scheduled to investigate both concepts (“D.F.S.” as well as “D.S.S.”) are in preparation. This will include CFD calculations as well as validation and verification in the wind tunnel and the water tank, as it was the case, for the “D.F.S.” concept. Indeed, some recent towing tank tests on an outboard deflected spoiler showed possibilities to alter the wake characteristics (lower peak velocity and larger vortex radius) similarly to the inboard loading case.

**Active wake control (through either blowing or active surface)**

The idea is here to act “actively” in order to trigger the most powerful instabilities. Crouch et al. [10] successfully demonstrated in a towing tank an active control system to break up a four-vortex system, the wake of which comprised two co-rotating vortex pairs. The instability was forced by a symmetric excitation scheme of the control surfaces, preserving both total lift and aircraft symmetry.

DLR took the opportunity of dedicated flight tests, in the framework of the AWIATOR project, to test some active control concept, using the ATTAS aircraft. The basic mechanism to introduce periodic disturbances into the flow field is a periodic alternation of the span-wise lift distribution, i.e. of the ratios of both the circulation and spacing of the distinct vortex pairs. In the flight tests Direct Lift Control (DLC) flaps were used oscillating at a frequency corresponding to either long-wave length instability (Crow-type ~0.5Hz) or medium-wave length one (~2.1 Hz), the adjustment of the respective lift variation being made by the pilot. Weather issues (clouds) did not allow getting a full documentation of the tests. However, for the counter-rotating configuration it appeared to be possible to trigger the Crow instability, while perturbations made at both frequencies gave similar results [20].

![Fig. 15 – Iso-vorticity surfaces from 3D LES simulations of the baseline configuration](image)

Temporal 3D LES simulations (over a large computational domain of about one oscillation cycle) were made recently by UCL to investigate the forcing of instabilities via periodic anti-phase inboard and outboard moving ailerons. They used the Vortex-In-Cell method combined with the parallel Fast Multi-Pole methods (“VIC-PFM”) [46]. Results plotted as iso-vorticity plots clearly demonstrated the growth of the Crow instability mode (Fig. 15b), the main vortices being substantially deformed,
while the same plots for the reference configuration, at a comparable vortex life-time time, did not reveal such perturbation (Fig. 15a) [20]. Spectral analysis confirmed a large increase of the temporal evolution of the Crow instability mode.

Another possibility of active control could be to blow in the vicinity of the outer part of a wing (outer flap, wing tip and aileron) to trigger instabilities to obtain a premature collapse of the wake vortex system. ONERA first worked with a simple counter-rotating topology, obtained from two half wings facing each other [7,39]. Continuous blowing at each wing-tip, in the free-stream direction at flow rate coefficients of about $1 \times 10^{-3}$, decreased noticeably the maximum level of vorticity and led to the disorganisation of the vorticity field [39] (Note that the flow rate coefficient is defined as $C_m = \frac{r_b U_b^2 S_b}{r_0 U_0^2 S_0}$, where indices $b$ and $0$ refer to blowing and free-stream conditions, respectively). Pulsed blowing at a frequency close to the Crow frequency (5.5Hz), but at a slightly higher flow rate ($2.5 \times 10^{-3}$), decreased significantly the maximum vorticity [7,39].

ONERA investigated subsequently for a more complex initial wake topology (behind generic large transport a/c type model) the effect of continuous and pulsed blowing on the extended near-wake field. For the baseline configuration, several types of blowing were tested at the wing tip: axial, discrete holes or slots, and also at the external flap tip or in the aileron vicinity, at maximum flow rate coefficients of about $1 \times 10^{-3}$ [8]. There was a minor effect on the maximum value of the axial vorticity component, while turbulent kinetic energy was increased in the vortex cores. At last, some pulsed blowing, using discrete holes, was applied. The pulsed frequency corresponded to the long-wave Crow instability that would be generated behind this model at such flow conditions (5Hz). At the furthest available downstream station ($x^* = 2.25$), hot-wire measurements, in the vortex core and also outside, indicated that the unsteadiness was still present in the flow (Fig. 16c). This is rather encouraging since no unsteadiness was recorded at such vortex age for tests performed for instance with the wing add-on (cylinder-type) device as discussed before.

Fig. 16 – a) Generic large transport a/c type model used for investigating blowing in the wing tip vicinity; b) axial-type; c) discrete holes (lateral); d) discrete holes (to the bottom); e) effect of pulsed blowing through discrete holes in the extended near-wake field from spectral analysis [7,8].
Further investigations will be devoted to the effect of blowing in the mid-wake field (at the ONERA catapult facility). Such study will raise challenging technological issues: pressurised tank as well as appropriate flow rates for the free-flight model.

11.5 **Wake vortex alleviation: recommendations**

The main features for Wake vortex alleviation concepts have been discussed in the preceding sections. Some important results (some understood, but others far from being understood), have been shown. In what follows, the findings will be summarized and recommendations for future work will be suggested, the list being of course not exhaustive.

**Wake physics and wake characterisation:**

Thanks to the research in Europe (as part of European and national programs) theoretical understanding, numerical simulation and measuring techniques have improved considerably over the last 10 years. The aircraft wake can be characterised in model experiments and in flight case to sufficient detail. However, in the far field (at distances behind the aircraft roughly similar to the present day separation standards) the flow is very sensitive to weather effects (turbulence, stratification). Hence, a large data set is needed for wake characterisation in flight. Similarly, a large data set will be needed to validate ground based measurements (towing tank) with flight data. **It is recommended to study the statistical aspects of wake development and characterisation (for ground facilities and in flight) in more detail.** **Such a study is also required to assess the benefit of (weather dependent) wake vortex warning systems (to support the safety case).**

**In more detail:**

- The basic physics of a single vortex pair wake is reasonably well understood. Scaling rules are (believed to be) known, although it has to be noted that there is in fact no ‘full size’ (Lidar) proof of the $t^4$ scaling (data sets not large enough to discriminate between aircraft of different sizes, too much scatter due to variation in weather conditions).
- Wake vortex formation, roll-up and evolution are rather well understood. A clear experimental “methodology” has been defined including its limitations (boundary-or end- or installation-effects) for towing tank and catapult, the only facilities that will provide answers about wake vortex characterisation and control in the mid-wake field. Although installation effects were identified, all the mechanisms as well as their modelling is not completely understood and more theoretical/numerical work should be helpful.
- Tools validation and cross-checks between complementary facilities completed this methodology. Thus, confidence has been gained to allow systematic detailed measurements of aircraft configurations before being flight tested.
- Reynolds number effects on vortex core (laminar/turbulent transition) are still only partially known. Moreover, the translation of the current understanding to a real aircraft is not fully developed, yet. More work is required to complete the methodology for wake vortex characterisation from ground tests.
- Specific instrumentation was developed to track wake vortices in sub-scale facilities. PIV measurement techniques can still be improved for the catapult and towing tank: increased number of cameras / resolution, the use of three-components and time resolving PIV… Lidar is the only instrumentation that enables a link between sub- and flight-scaled test campaigns using the same measuring technique.

- Ground-based measuring Lidar techniques have advanced significantly for full scale tests. Triangulation method using two CW-Lidars and pulsed Lidars showed great potential for tracking wake vortices. However, the tests are hampered by a significant spread in the results due to weather (stratification and turbulence). First attempts to use in-board Lidar measurements were made; further validation should be made.

- Numerical simulations (Euler, RANS and LES) have advanced significantly, allowing to look into the details of the flow. The evaluation of the sensitivity of vortex roll-up, merging and evolution to mesh resolution, longitudinal domain extent, numerical scheme or initial perturbations still needs further investigations.

- A full 3-D simulation of the representative wake of a real aircraft, with all details of flow development is still a too large problem. Several LES computations have started from test results or estimates provided by simplified methods; first attempts to couple LES to RANS methods developed around a complex high-lift wing configuration are reasonably foreseen in the near future.

- Vortex filament methods in combination with stability theory could be applied systematically for a quick selection of interesting configurations for wake minimisation. Long-wave cooperative instability is rather well understood; further investigations should be aimed at dealing with non-parallel aspects, non-linear and secondary instabilities: this can be done by using large-scale LES at high Reynolds number.

- Finally, a chain of various tools was defined for wake vortex characterisation including experimental, numerical and theoretical tools. Its validation has been conducted in the framework of the AWIATOR European project. But, is this chain complete and are important links missing?

**Wake vortex alleviation:**

Research so far has not been very successful in reducing the wake vortex strength behind an aircraft. Vortex formation is essentially related to lift generation and a weaker vortex can only result from design features that affect the decay characteristics far downstream. The problem, stated in this way, is far from obvious and only minor changes (estimated to be of the order of 10 - 25%, although larger values should not be excluded) can be expected. **The most promising results have been obtained for the following devices or concepts (though some should be further investigated also with respect to the implications for a real aircraft):**

- **inboard loading:** closer vortex spacing gives more diffused, faster decaying vortex,

- **outboard loaded configurations with multiple counter-rotating vortex pairs:** enhanced dissipation due to violent non-linear vortex interactions, the so called omega-loops; requires large configuration changes (realistic?)
o outboard spoilers: significantly more diffused vortex observed but the underlying causes not clear: favours inboard loading?, turbulence?, specific multiple vortex interactions?

o active control: moving flaps or ailerons, pulsed blowing to enhance instability modes like the Crow instability giving faster linking of the left and right vortex.

_in more detail (for add-on wing devices):

- The effect of add-on wing devices seemed to be size-dependent and seemed to scale with the size of the device.
- Most of the considered devices acted in the extended near-wake field, but had no measurable effect in the mid-wake field. Most of the proposed add-on devices did not modify the global lift. So, there might be no significant modification of the span load and thus the same vortex system resulted.
- A few devices do modify the vortex core structure (increase of core size and reduction of peak velocity) such as the inclined delta plate. Deflection of spoilers also seemed to have an effect, although it is not clear if this was caused by a change in spanwise wing loading or by the effect of (generated) turbulence on the wake development.
- Unfortunately almost no CFD investigations were made, which could help further understanding the effect of the devices.
- Further sub-scale tests are necessary before undergoing flight tests.
- There is no real indication how add-on wing devices can be made efficient and practical.

_in more detail (modification of spanwise wing loading distribution):

- A real potential of spanwise wing loading modification for wake vortex alleviation was deduced from theoretical, experimental and numerical studies.
- Inboard and outboard wing loaded configurations were computed and experimentally tested, some of them being also flight tested.
- Inboard loading (co-rotating four-vortex system): theory already indicates that this produces vortices with a larger core that are closer to each other and hence decay faster. That was checked from towing tank and catapult tests. Moreover, the multiple-vortex system subsists over a longer life-time than those for the outboard loading case. Therefore, can the instability mechanisms between these vortices be further exploited?
- Outboard loading: the “optimised” differential flap settings did not provide (from towing tank and catapult tests) the wanted effect of increased dissipation of energy due to interactions of the unstable multiple-vortex system.
- For a double pair of counter-rotating vortices and depending on their relative size and position, it has been shown through simulations and in tests on generic models that so called Ω-loops can be generated. They significantly enhance the dissipation of the vortex.
- However, these instabilities have not been observed in the multiple vortex systems as intended behind some realistic aircraft configurations. For such systems to be effective, the W-loops (or other instabilities) need a certain time to develop (effectively $t^* \sim O(1)$).
- Multiple vortex systems have only been observed in the first 5 to 10 wing spans behind the model. Hence, the realisation of a particular vortex topology for a
sufficiently long distance behind the aircraft is not an easy task. Manipulation of representative aircraft wing plan forms to produce well controlled multiple vortex systems appears to be far from trivial. This might limit some of the concepts described above in a practical sense.

- Also, one has to pay a price: to generate the same lift with a positive and a negative vortex has a large effect on the configuration and the low speed design. A careful trade-off is required and it is not clear if this really pays off.
- For practical applications, substitution of differential flap settings by differential spoiler settings looked encouraging from sub-scale tests. Flight tests have to confirm this, since first attempts did not allow drawing any conclusion (only small modifications of the wing loading, some experimental uncertainty due to weather).
- Limitations towards practical implementations on an aircraft should be clearly assessed, as well as applicability and viability of such concepts in the future.

In more detail (with active wake control):
- Active wake control could be achieved by active control of moving surfaces or by blowing in some specific regions of the flows.
- Sub-scale tests, notably for blowing concepts, are very difficult and “almost impossible” to handle correctly.
- Numerical simulations pointed out the potential of moving surfaces to enhance vortex decay. First flight tests performed by varying load control surfaces on a small aircraft should be re-visited with appropriate measurement tools.
- Continuous and pulsed blowing at Crow’s frequency showed their potential. The forced unsteadiness could still be captured in the extended near-wake field. Its efficiency on the wake far-wake field has to be checked as yet.
- Combination of blowing with modified span loading configurations could be considered.
- Applicability of active wake control to a real aircraft has to be envisaged.

11.6 Bibliography


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APPENDIX:  
List of WakeNet2-Europe Workshops  

The workshops listed below have been organised by the Thematic Network WakeNet2-Europe in co-operation with WakeNet-USA. The program, presentations and technical evaluation can be found (in most cases) at the WakeNet2-Europe internet site:  [http://wwwe.onecert.fr/projets/WakeNet2-Europe/](http://wwwe.onecert.fr/projets/WakeNet2-Europe/)

1 The WakeNet2-Europe Annual Workshops

**WN2E Workshop (1): “Wake data and safety assessment methods”**  
November 11-12, 2003, London Heathrow, UK

NERL (NATS) was the host of this meeting. In total 65 persons participated from which 19 from the US, 2 from Russia, 1 from Canada and 1 from the Czech Republic. There were 23 presentations including 9 from the US and 1 from Russia. The sessions were devoted to:

a) Wake vortex transport and decay data,  
b) Wake encounter flight test and flight simulation test data,  
c) Wake vortex incident reporting and detection  
d) Safety assessment methods.

There were also 3 presentations dealing with the joint effort by FAA, EUROCONTROL and AIRBUS to assess the safety aspects of the A380 wake. Peter Crick from EUROCONTROL made a technical evaluation of the workshop.

**WN2E Workshop (2): “Capacity Gains as Function of Weather and Weather Prediction Capabilities”**  
November 30 – December 1, 2004, Langen, Germany

This workshop was organized by and held at DFS in Langen. This workshop was well attended by about 60 participants in total including 16 participants from the US. From the meeting it became clear that weather is the most critical issue to determine if there is an actual benefit in weather dependent reduction of separation distances. There are different issues here: the actual time during which favourable conditions exist (based on local weather statistics), the fraction of this time that can effectively be used to reduce separation in an operational system (e.g. due to limitations to forecast the weather, lead times for operational changes, changes only acceptable for longer periods) and the requirements to prove that the system is actually safe. Further
studies for specific airport situations and operational scenario’s (CONOPS) are required to establish if there is a benefit in particular cases.

Andrew Harvey from EUROCONTROL provided the Technical Evaluation at the end of the meeting

**WN2E Workshop (3): How can Wake Vortex Separation Standards be revised?**
29 – 30 November 2005, Bretigny, France

The third annual workshop was organised by the Eurocontrol Experimental Centre, Brétigny in France. This workshop was very well attended with 84 participants, including 16 from the US and 9 from other countries. The workshop ended with an interesting ‘stakeholders forum’. The technical evaluation was done by Claire Pugh from NATS. She pointed out some of the main issues. Should risk assessment be done in an absolute or relative way? A relative assessment will be limited to cases where the risk is less than for the current operational practice. An absolute assessment is much more challenging (if possible at all) but might be able to answer the question if the present rules are too conservative. In the future a clear path is needed to move forward. And most of all, it is essential to continue the communication and collaboration. The wake vortex problem is far too complex to solve individually.

### 2 WakeNet2-Europe Working Group Workshops

**WG-2 Workshop: “On the Relevance and Treatment of EDR for Aircraft Wake Vortex Problems”**
17-18 February 2004 at DLR in Oberpfaffenhofen.

**WG-5 Workshop: “Wake Vortex Encounters in Flight & Flight Simulation”,**

**WG-7 Workshop: “Principles of Wake Vortex Alleviation Devices”**
February 9-10, 2005, ONERA/CERT in Toulouse, France

### 3 Other Workshops

WakeNet2-Europe contributed actively (e.g. by setting-up benchmark computations) to a workshop organised by WakeNet-USA on “The Prediction of Wake Vortices In-Ground Effect in an Operational Context”, New Orleans, LA, USA, April 27 – 29, 2004
# GLOSSARY

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<tr>
<th>Abbreviation</th>
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<tr>
<td>ACARS</td>
<td>Aircraft Communications And Reporting System</td>
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<td>ADREP</td>
<td>Accident/Incident Reporting</td>
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<td>AIM</td>
<td>aerodynamic interaction model</td>
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<td>AMAM</td>
<td>Arrival Manager</td>
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<td>AMDAR</td>
<td>Aircraft Meteorological DAta Relay</td>
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<td>ASAT</td>
<td>Airspace Simulation and Analysis for TERPS (developed by FAA / ATSI)</td>
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<td>ASRS</td>
<td>Aviation Safety Reporting System</td>
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<td>CONOPS</td>
<td>Concepts of Operation</td>
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<td>CREDOS</td>
<td>Crosswind Reduced Separations for Departure Operations (recently approved European Research program)</td>
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<td>CSPR</td>
<td>Closely spaced parallel runway’s</td>
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<td>DRVSM</td>
<td>Domestic Reduced Vertical Separation Minimum</td>
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<td>DWA</td>
<td>Detection, Warning and Avoidance</td>
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<td>ECCAIRS</td>
<td>European Co-ordination Centre for Aviation Incident Reporting Systems</td>
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<td>EDR</td>
<td>Eddy Dissipation Rate (to characterize turbulence)</td>
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<td>ESARR</td>
<td>Eurocontrol Safety Assessment Regulatory Requirement</td>
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<td>ETWIRL</td>
<td>European Turbulent Wake Incident Reporting Log</td>
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<td>FDR</td>
<td>Flight Data Recorder</td>
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<td>HALS/DTOP</td>
<td>High Altitude Landing System/ Dual Threshold Operations</td>
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<td>HMI</td>
<td>Human Machine Interface</td>
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<td>Instrument Flight Rule</td>
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<tr>
<td>LIDAR</td>
<td>Light Detection And Ranging</td>
</tr>
<tr>
<td>NOWVIV</td>
<td>Nowcasting Wake Vortex Impact Variables (developed by DLR)</td>
</tr>
<tr>
<td>OGE</td>
<td>Out of Ground Effect</td>
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<tr>
<td>P2P</td>
<td>Probabilistic Two-Phase wake vortex decay and transport model (developed by DLR)</td>
</tr>
<tr>
<td>PDF</td>
<td>probability density function (or distribution)</td>
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<tr>
<td>P-VFS</td>
<td>Probabilistic Vortex Forecast System (developed by an international team for ‘Transport Canada, further developed by UCL)</td>
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<tr>
<td>QAR</td>
<td>Quick Access Recorder</td>
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<tr>
<td>RVSM</td>
<td>Reduced Vertical Separation Minimum</td>
</tr>
<tr>
<td>RWY</td>
<td>Runway</td>
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<tr>
<td>SHAPE</td>
<td>Simplified Hazard Area Prediction model (developed by DLR)</td>
</tr>
<tr>
<td>SMP</td>
<td>Separation Mode Planner</td>
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<tr>
<td>SODAR</td>
<td>Sonic detection and ranging</td>
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<tr>
<td>Acronym</td>
<td>Description</td>
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<td>SOIA</td>
<td>Simultaneous Offset Instrument Approach</td>
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<tr>
<td>TBS</td>
<td>Time Based Separations</td>
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<tr>
<td>TLS</td>
<td>Target level of safety</td>
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<td>VESA</td>
<td>Vortex Encounter Severity Assessment (developed by Airbus)</td>
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<tr>
<td>VMC</td>
<td>Visual Meteorological Conditions</td>
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<td>WakeScene</td>
<td>Wake Vortex Scenarios Simulation (developed by Airbus / DLR)</td>
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<td>WAVIR</td>
<td>Wake Vortex Induced Risk assessment (developed by NLR)</td>
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<td>WSVBS</td>
<td>Wirbelschlepvenhorersage- und beobachtungssystem (Wake Vortex Prediction and Monitoring System)</td>
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<td>WSWS</td>
<td>Wirbelschleppen-Warnsystem (Wake Vortex Warning System)</td>
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<td>WTR</td>
<td>Wind Temperature Radar</td>
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<tr>
<td>WV</td>
<td>Wake vortex</td>
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<td>WVAS</td>
<td>Wake vortex advisory system</td>
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<tr>
<td>RASS</td>
<td>Radio Acoustic Sound System</td>
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<tr>
<td>$\Gamma_{5,15}$</td>
<td>Averaged circulation between 5 and 15 meter from the vortex centre</td>
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THE END of PART II