

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

Part I

Summary & Recommendations



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 a 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.

Bram Elsenaar
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.

The co-ordinator is Bram Elsenaar, NLR, Anthony Fokkerweg 2, 1059 CM AMSTERDAM, The NETHERLANDS

WN2E has an active site, maintained by ONERA: <http://www.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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Executive summary

Wake turbulence separations, which are in many cases in excess of the radar separation, are a major factor limiting the capacity at many European airports. Several additional movements per hour and per airport seem possible, if the behaviour of the trailing vortices could be predicted accurately enough. Separation distances and flight paths tailored according to the ambient meteorological conditions can be employed to safely avoid potential wake encounters and therefore maintaining the current level of operational safety of the air transport system.

The expected capacity benefits seem achievable at comparably low cost; however no-one so far has succeeded to develop, implement and operate such a system or procedure on a routine basis. Several concepts of operation, CONOPS, are currently investigated. Some successful attempts corroborate the overall feasibility of novel wake turbulence avoidance procedures, but they also reveal that there are still remaining issues that need to be solved prior to a much broader and more frequent application.

Among other aspects, the successful proof that the safety requirements can be met constitutes a major challenge for future activities. There are no specific requirements set by the authorities with respect to novel wake vortex related procedures and it is left to the proposer of such methods to demonstrate that the safety requirements are met. The methods that describe the behaviour of wake vortices and the severity of a wake turbulence encounter need additional validation in order to change a plausible argument into a stringent proof.

Certainly many of the necessary models, methods and tools have been improved vastly during the past decade, but further improvements are needed for a successful completion of the mission to reduce the wake turbulence separation minima under certain conditions and to support the corresponding rule-making process. Areas where additional research is required most are:

- Various operational scenarios (CONOPS) are proposed to increase airport capacity without loss of safety. High level studies have generally indicated substantial capacity gains. It is important to extend these studies into a more detailed analysis taking into account specific (site-dependent) details to quantify potential benefits.
- A continuing effort to collect data for model validation is still required; this is needed to strengthen the arguments for safety assessments.
- Inter-comparisons between probability-based safety assessment methods to build confidence in these methods.
- Efforts to improve the capabilities for all-weather wake vortex measurement.
- To support operational changes, the collection of incident and encounter statistics is needed; hence particular attention has to be given to more objective, partly automated methods using Flight Data Recordings.
- An evaluation of the prospects of on-board wake vortex detection, as integrated within wake avoidance procedures.

A 'proof of concept' as the main goal of an 'integrated project' is strongly recommended to find out where the weak points are and how large the achievable benefits really are.

This document may be used as an initial guideline for coming wake vortex related research activities. It is divided into two parts.



Part I provides a general overview and lists more specifically than in this Executive summary the recommendations made. It also emphasizes the necessary links between the various themes.

Part II describes for the respective specialists the state of the art in more detail as well as the research needed to better understand various aspects of the problem of wake vortices and means to mitigate its effects.



Section 1 Introduction and Overview

The document 'Wake Vortex Research Needs' has emerged from the activities of Wakenet2-Europe, a European sponsored Thematic Network [1] that has been active between 2003 and 2006. Over a much longer period (see Fig 1 and Fig 2), 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 as the adequacy of separation standards for new and larger aircraft has to be demonstrated.

Wake vortex research is presently at interesting cross-roads. EUROCONTROL is of the opinion that we are at the transition phase to introduce changes to the present system within the next 5 years e.g. by introducing time based arrivals and weather based departures [2]. This is partly based on (high level) studies that indicate substantial capacity benefits for e.g. time based separations [3]. Similar cost / benefit studies in the US [4] also show large benefits. Yet at Frankfurt Airport the original expectations that the proposed procedural changes with a weather dependent Wake Vortex Advisory System (WSWS) will increase capacity while still maintaining safety, have not been realised so far in spite of a considerable effort [5], [6]. It might be the right time to step back a bit to see if our knowledge is sufficient to implement real changes.

The Thematic Network WakeNet2-Europe (WN2E) has brought together many parties that are interested in wake vortices, both from the operational and from the research side. At the mid-term review meeting (November 2004), the two reviewers and the scientific officer of the European Commission urged to document the research needs. This has been picked-up by the various Working Groups of WN2E and resulted finally in this document that should also be regarded as the final deliverable of this network.

This report (Part I in general terms for the interested reader and Part II for the specialist) provides an analysis and assessment of the present situation as viewed by the various WN2E partners. The interesting question is how to proceed from here as far as the research efforts are concerned. The 7th European Framework Program might provide new opportunities to continue the activities. WN2E has also helped to open the door to more international co-operation, like the contacts with WakeNet-USA (that has been started in the US, inspired to some extent by WakeNet-Europe). This has resulted in a very profitable exchange of information for all parties and WakeNet-USA has to be acknowledged for that. Moreover, NASA/FAA are also partners in the new recently approved EU project CREDOS. Very recently the initiative has been taken within the Russian Federation to start WakeNet-Russia.

When overlooking the research over the last 10 years, it becomes apparent how much progress has been made, notably in the areas of wake vortex modelling, wake vortex sensing technology and safety assessment tools. The recommendations in this report indicate where the WakeNet2-Europe partners believe that more research is still needed. For more detail the reader is referred to the Specialists Reports presented in Part II. All recommendations need careful considerations but for this introduction a few recommendations will be highlighted below:

- Various operational scenarios (CONOPS) are proposed to increase airport capacity without loss of safety. High level studies have generally indicated substantial capacity gains. It is important to extend these studies into a more detailed analysis taking into account specific (site-dependent) details to quantify potential benefits.



- Continuing efforts in model validation; the collection of data for model validation is still required; this is needed to strengthen the arguments for safety assessments
- Inter-comparisons between probability based safety assessment methods to build confidence in these methods
- Efforts to improve the capabilities for all-weather wake vortex measurement
- To support operational changes, the collection of incident and encounter statistics is needed; hence particular attention has to be given to more objective, partly automated methods using Flight Data Recordings
- An evaluation of the prospects of on-board wake vortex detection, as integrated within wake avoidance procedures.

Some of this research might have approached its limits. The physics of wake vortices is very complicated and the interaction with a large variation in weather conditions that have a direct effect on the vortex life time, introduces an essentially stochastic element. The question can be put forward if more refinements of the models still 'pay off' or that one has to concentrate on the implementation now. One of the key issues is to quantify the potential capacity increase, when all boundary conditions (uncertainties in weather and wake prediction, system complexity, operational aspects, proof of safety) are properly dealt with.

To make further steps forward it might very well be essential to consider research predominantly in relation with questions that evolve from the process to implement new wake vortex separation procedures. So far, the European research programs on wake vortices have set their own goals that resulted to a large extent from the combined interest of the individual partners. To improve the co-ordination between the various projects the European Commission introduced the mechanism of the 'Thematic Networks' like WakeNet2-Europe. But such a (still rather loose) co-ordination might not be enough to make real progress. A 'proof of concept' as the main theme of an 'integrated project' will be required to find out where the weak points are and how large the real benefits really are. The implementation of new systems requires the approval of the authorities and this very well might prove to be the hardest part, necessitating additional validation efforts. But this can only be assessed for a fully defined concept.

The introduction of new wake vortex separation procedures can be viewed as a multidisciplinary activity. The disciplines should not work for themselves and a 'smart integrator' is needed to bring the implementation closer. The role of the 'smart integrator' is to define the particular project goals (clearly aimed at a specific implementation and not in generic terms), to interface with the 'end users' and to orchestrate the required specific research actions. This requires a high level of technical competence of the integrator, one or more interested stakeholders and the funds for the research and the implementation of new systems and measures.

This of course is not new at all. In the US the 'Wake Turbulence Research Management Plan' (RMP) acts as a 'smart integrator'. It has been set up in 2003 under joint management of FAA / NASA for wake turbulence related programs with a total budget for six years of the order of 120 million \$. The goals of this program are:

- near term: procedural changes like SOIA and 2500 ft CSPR rule
- mid-term: enhance capacity by providing weather sensitive procedural alternatives
- long term: enhance capacity by providing a range of technology based solutions for wake turbulence avoidance.



In Europe, DFS is a 'smart integrator' for a long time already aiming for a capacity increase at the parallel runways of Frankfurt Airport. And more recently, EUROCONTROL Experimental Centre is taking that role as well. As far as encounter avoidance and wake vortex alleviation is concerned, AIRBUS is of course likely to have the role of an integrator.

The partners of WakeNet2-Europe hope that reading this document will help you to understand where to go next.

Bram Elsenaar
Co-ordinator WakeNet2-Europe



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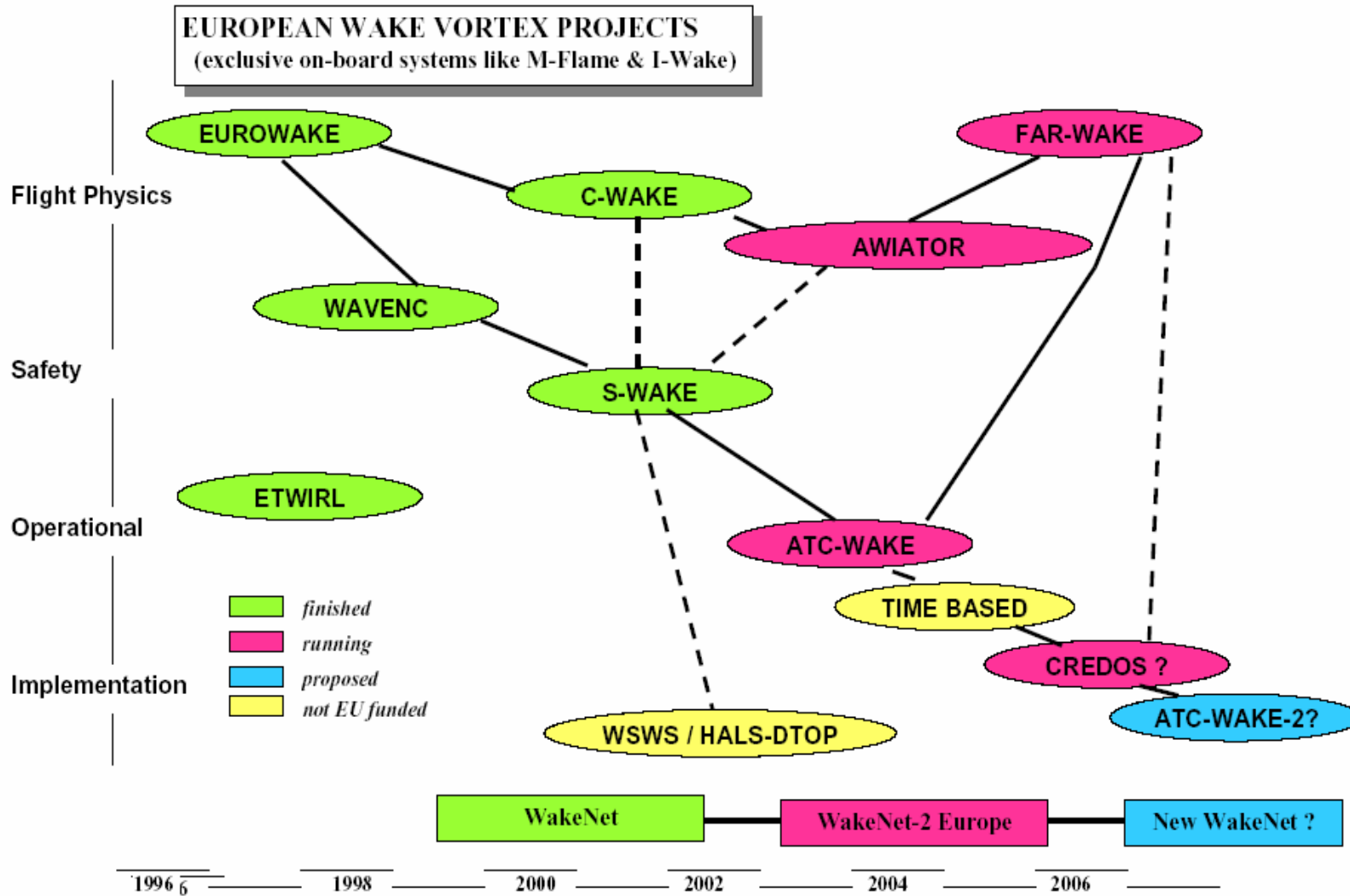


Figure 1 Overview of all European wake projects vortex (physics and ATC related)

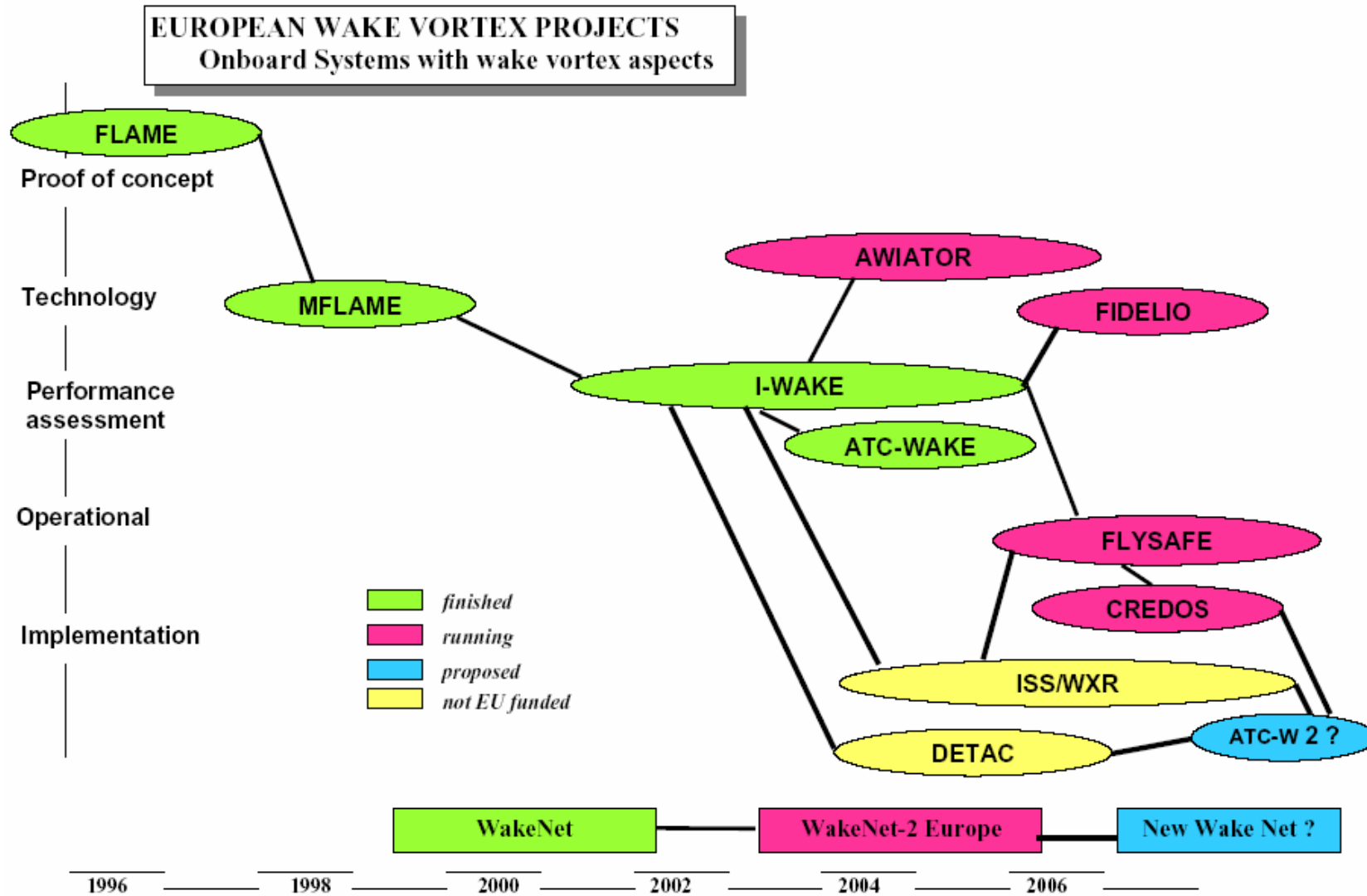


Figure 2 Overview of all European projects related to wake vortex awareness in the cockpit



Acronym	Topic	Coordinator	Status	Remarks
ETWIRL	European Turbulent Wake Incident Reporting Log	Red-Scientific (UK)	completed	Successful program resulting in (the definition of) a common database; unfortunately no follow-up
EUROWAKE	near field wake characterization	Airbus Germany	completed	first program in Europe to characterize the (near field) wake from windtunnel tests and numerical computations
WAVENC	characterization of wake vortex encounter	NLR	completed	first wake vortex program in Europe looking into the effects of wake vortex encounters
MFLAME	on board atmospheric hazard detection	THALES Avionics	completed	first European program for on-board hazard detection (wind shear, clear air turbulence, vortex wakes)
C-WAKE	far field wake vortex characterization and reduction through control and design	Airbus Germany	completed (Jan00 - Mid03)	program that looked into possibilities to reduce vortex wakes by design
S-WAKE	assessment of the safety aspects of wake vortices	NLR	completed (Jan00 - Mid03)	Program to develop and synthesize the tools to assess their safety aspects of wake vortices
ISAWARE	Increasing safety through collision avoidance warning integration	THALES Avionics	completed	program to increase the operational awareness using cockpit displayed information (either locally generated or relayed)
AWIATOR	demonstration of new wing technologies; part of the program devoted to wake turbulence reduction devices	Airbus-Deutschland	running (Jul02-Jul06 + extension)	only part of the program related to wake vortices, aimed to synthesize some of the (alleviation) ideas from C-wake; mainly concerned with wake physics and test techniques including full-scale flight tests
I-WAKE	continuation of MFLAME for system integration and flight tests	THALES Avionics	completed (May02-Dec06)	demonstration that an onboard Lidar system could detect a wake vortex
ATC-WAKE	integration of wake vortex advisory systems in ATM environment	NLR	completed (Jul02-Dec05)	development of an integrated platform (+ demonstration) to combine the necessary tools (wake vortex prediction, weather forecasting, ATC displays, safety assesment) for the implementation of weather dependent separation distances
FAR-Wake	fundamental aspects of wake vortices	IRPHE (Univ of Marseille)	running (Feb05-Feb08)	to better understand the basic physics behind instabilities, external turbulence and wakes in ground effect
FLYSAFE	Safety Improvement, Flight Hazard Protection and All Weather Operations from on-board warnings	THALES	running (Feb05-Feb09)	Integrated Project for the design of a Next Generation Integrated Surveillance System (NG ISS)
CREDOS	Crosswind Reduced Separations for Departure Operations	EUROCONTROL	recently approved (end 2005 - end 2008 (?))	Development of Operational Concept to reduce separations for departures (based on actual weather conditions)

Table of European Programs (EC sponsored) for wake vortices



Section 2 Operational Concepts

Based on contributions from Antoine Vidal (Eurocontrol Experimental Centre) and Wayne Bryant (NASA)

2.1 ICAO separations: and safety aspects

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 imposed separation distance during landing and take-off phases. Wake vortex separations have been implemented to ensure that an aircraft does not enter into an unsafe situation due to the wake turbulence of a preceding aircraft. To day they are based on an ICAO recommendation made in the 70-ies that prescribes specific separations (4, 5 or 6 miles) at landing depending on the size of the leader and the follower aircraft.

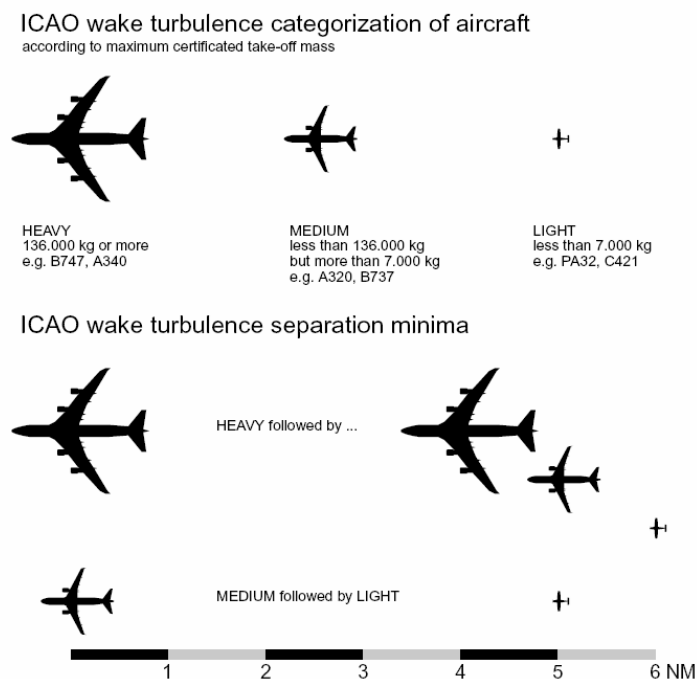


Figure 2-1: ICAO recommendation for wake induced separation distances (landing)

Other recommendations have been provided for take-off and cruise or for closely spaced parallel runways. Although there have been occasionally wake encounters for larger separation distances, no serious accidents have been reported.

It is well known that in a quiet atmosphere the wake vortices can live very long. The fact that the recommended distances are still apparently safe can be understood from the fact that in general a



pair of wake vortices descends due to the mutual interaction of the vortices and hence moves away from the glide path. When the atmosphere is turbulent,

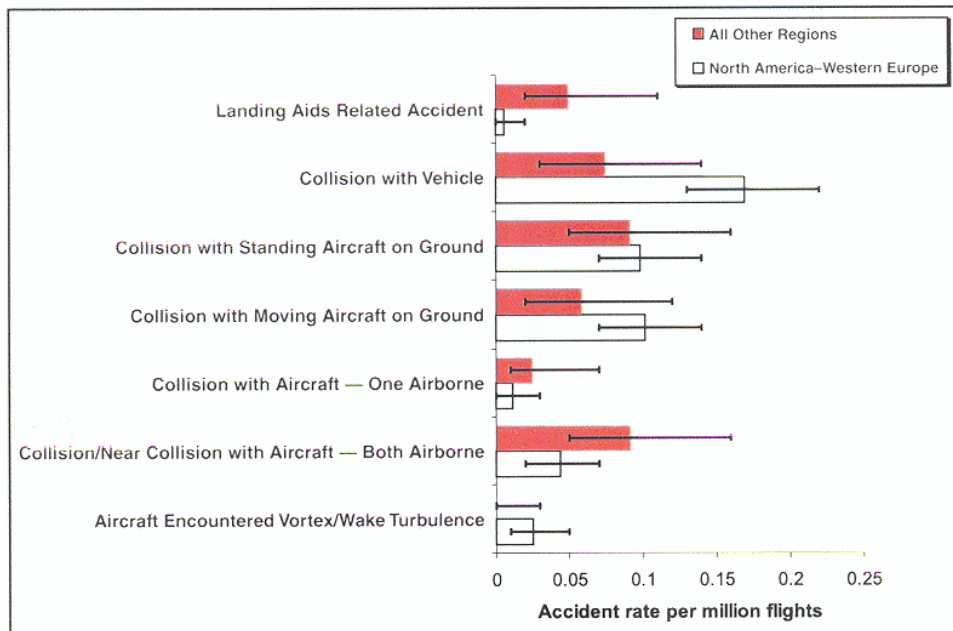


Figure 2-2: ATM related accident rate by event type and regions (from NLR Aviation Safety Data Base)

wakes will decay faster whereas strong cross winds tend to blow the vortices away from the glide path. For these conditions the separation distances are over-conservative and can be reduced without loss of safety and to the benefit of airport capacity. More general the question can be asked for what specific operational concepts the separation procedures can be relaxed depending on weather conditions or the runway layout. This section describes some of these concepts to illustrate what is contemplated today.

One can roughly distinguish, with an increasing level of complexity, between simple rule changes, changes in operational procedures and vortex warning systems that enable the use of dynamic, weather dependent separation distances. A useful distinction can additionally be made with respect to the effect of a change: ‘tactical’ and/or ‘strategic’ improvements. Only in the latter case the number of slots per hours (the declared capacity) can be increased. Tactical improvements are of interest to reduce delays when they are building up for whatever reason in the system.

Different concepts of operations are presently studied and some of them will be discussed below in more detail.



2.2 Schemes currently in study

SOIA: Simultaneous Offset Instrument Approach (San Francisco):

Parallel Runways are only treated to be independent when they are more than 2500 ft apart. In the US the ICAO separation rules are only applied for IFR conditions since the pilot has a much greater situational awareness when the leading aircraft is in sight. In the SOIA procedure such conditions are favored by allowing simultaneous approaches 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. This procedure is actually applied at San Francisco Airport. It is of interest to note here that this procedure does not involve a modification of the existing separation rules: they are still obeyed.

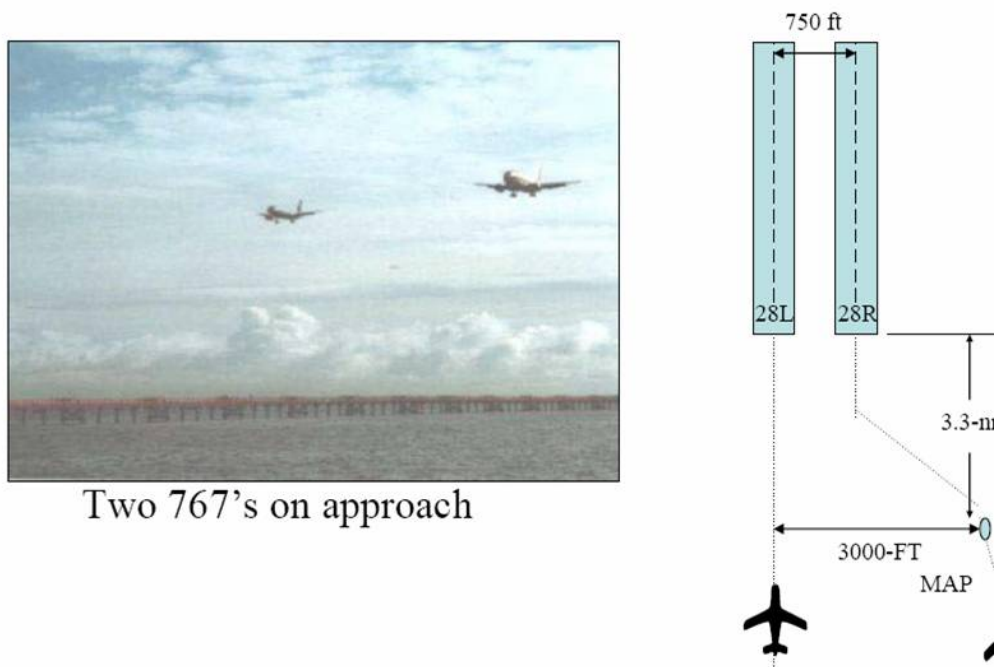


Figure 2-3: Illustration of SOIA procedure

Reduced diagonal separations (St Louis Airport)

Another example for closely spaced parallel runway's (CSPR) concerns a study made at St Louis Airport (STL) in the US. 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 behavior 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. 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.

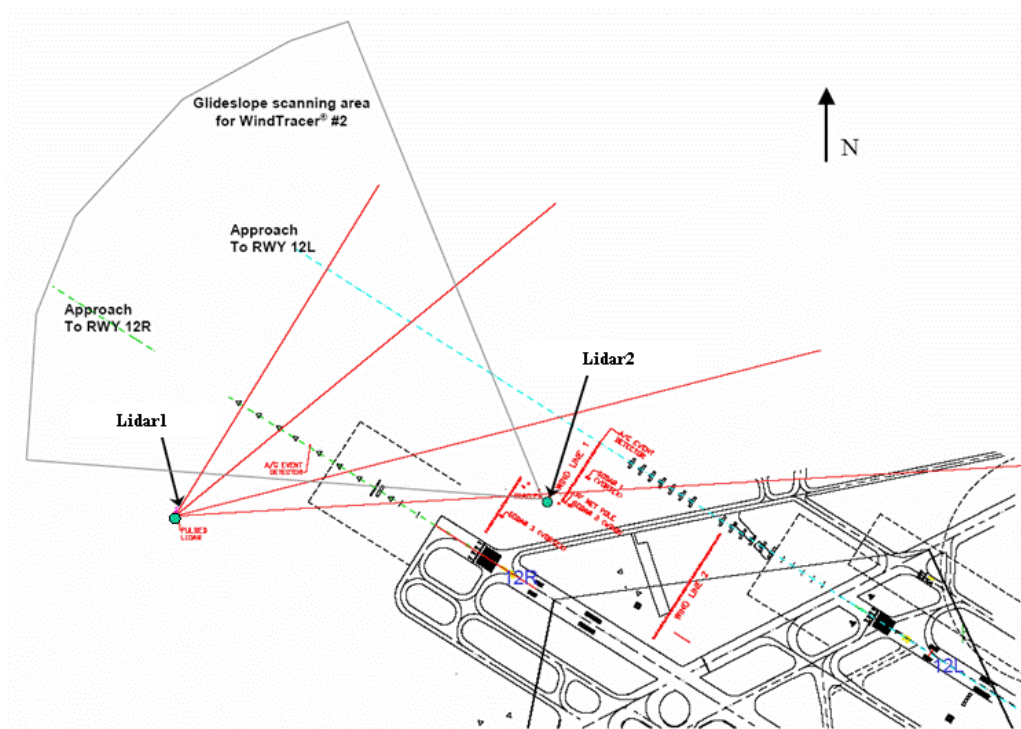


Figure 2-4: Sensor layout at the terminal area of St Louis to collect data in support of a waiver for reduced diagonal separation; two Lidar positions measure the wakes in the direction of the indicated lines (from presentation by VOLPE at WakeNet-USA meeting, Boca Raton, March 2005).

WSWS: Wirbelschleppen-Warnsystem (Wake Vortex Warning System)

Work on 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.

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

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.

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 vertical extension to cover the whole glide path is now under development before starting operations using WSWS. This system uses a Wind Temperature Radar to measure wind conditions up till 1500 m. A re-introduction didn't materialize so far since the safety case (in an absolute sense!) could as yet not be proven.



Figure 2-5: The Wind Temperature Radar (WTR) as installed at Frankfurt Airport intended to be used for the WSWS. The system provides wind velocity and temperature up till 1500 m height by combining Doppler-Radar for clear air measurements and Radio Acoustic Sound System (RASS) for measurements in bad weather.

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.

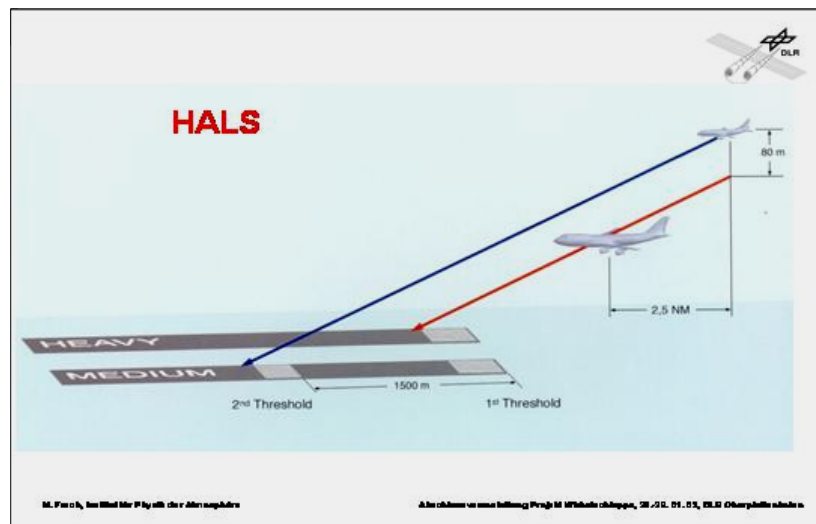


Figure 2-6: Schematic view of the HALS/DTOP operation at Frankfurt Airport

ATC-Wake:

This concept has been developed by the European sponsored ATC-Wake Consortium. 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 defines 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 ATCO's 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.

The objective of the program was to develop and build an integrated Air Traffic Control wake vortex safety and capacity platform. This platform is subsequently used to assess the interoperability of an integrated ATC system with existing ATC systems currently used at various European airports, to assess the safety & capacity improvements and to evaluate the operational usability & acceptability of such a system.

The project was successfully concluded in December 2005 with a real time simulation involving pilots and air traffic controllers demonstrating how ATCO's can actually schedule the landing aircraft with a 2.5 nm separation.



Operation	Runway throughput [ac/hr]			Delay [min]		
	ICAO	ATC-Wake	Change	ICAO	ATC-Wake	Change
SRD	37.8	38.6	+2.1%	N/A	N/A	N/A
SRA	35.2	37.0	+5.0%	3.0	2.15	-29%
CSPRA (non-segr.)	35.2	35.7	+1.5%	3.0	2.74	-8.6%
CSPRA (segregated)	35.2	37.6	+6.8%	3.0	1.84	-38.7%
CSPRA (semi-segr.)	35.2	35.8	+1.6%	3.0	2.73	-8.9%

Figure 2-7: Predicted capacity benefits for the ATC-type of operation (from ATC-Wake Final Review Meeting, December 2005).

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 “Wirbelschlepe”, 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.

Time Based Separations (TBS):

The operational concept is presently studied by the Eurocontrol Experimental Centre. In head wind situations, the ground speed of the landing aircraft is reduced. Hence, for the prescribed separation distances, the wake of the preceding aircraft has more time to decay. By prescribing a separation time instead of a separation distance, some of this loss of runway capacity can be recovered. Specific tools are needed to assist the ATCO’s like the Intelligent Time Vector (ITV; see Fig 2-8) or the •Target Trailing Position (TTP). These are presently evaluated. NATS has shown an interest to study such a system for application at London Heathrow.

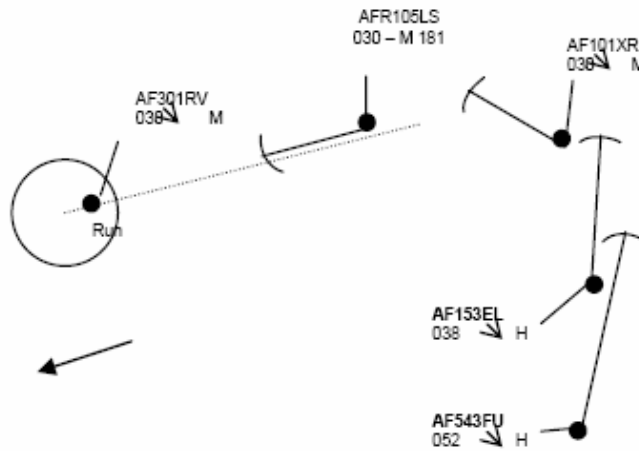


Figure 2-8: Example of the 'Intelligent TimeVector' as a tool to assist the Air Traffic Controller in guiding the approach aircraft.

CREDOS: Crosswind Reduced Separations for Departure Operations

CREDOS is a recently approved program sponsored by the European Commission to develop a concept for departures. To day specific delays between departures are described (usually 2 minutes) but, depending on the atmospheric conditions, these times can be safely reduced. 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 define the procedures, working methods and tools needed to apply reduced separations between departures in crosswind conditions. The CREDOS program has been approved end of 2005.

2.3 Capacity aspects

What are the expected capacity benefits? Figure 2-7 indicates the estimated capacity gain (in a tactical sense, hence depending on the weather conditions) for the ATC-Wake scenario. Recently, a study (the so called Euroben study) has been made by Eurocontrol, NATS and the UKMetOffice to estimate the benefits for some of these systems. The study is based on actual weather conditions for various airports taking into account the actual capacity situation. Hence, the largest improvements will be realized when the demand for the particular airport is high and when the weather conditions are favorable for a reduction in separation distances. The table below (Fig 2-9) summarizes the results of this high level study.



Airport	ATC-Wake		CREDOS		TBS
	3Nm	2.5Nm	90s	80s	
Heathrow	10,858	26,280	6,843	9,490	1,788
Frankfurt	3,923	11,315	0	91	2,801
Schiphol	1,277	5,565	547	638	431
Paris CdG	638	1,916	0	0	0
Madrid	547	4,653	273	456	169
Munich	0	0	0	0	0
Rome	0	0	0	0	26
Zurich	0	365	0	0	0
Barcelona	0	0	0	0	0
Gatwick	0	0	0	0	0
Manchester	0	0	0	0	0

Figure 2-9: Annual Totals of 'Extra Movements' (Maximum hourly benefit) as estimated from the Euroben study for some of the discussed CONOPS. Note that the extra movements may not be schedulable (from ATC-Wake Final Review Meeting, December 2005).

Other cost-benefit studies have been made in the US and they also indicate large benefits. Figure 2-10 shows how delays can be reduced when a wake vortex advisory system (WVAS; depending on weather conditions) is implemented

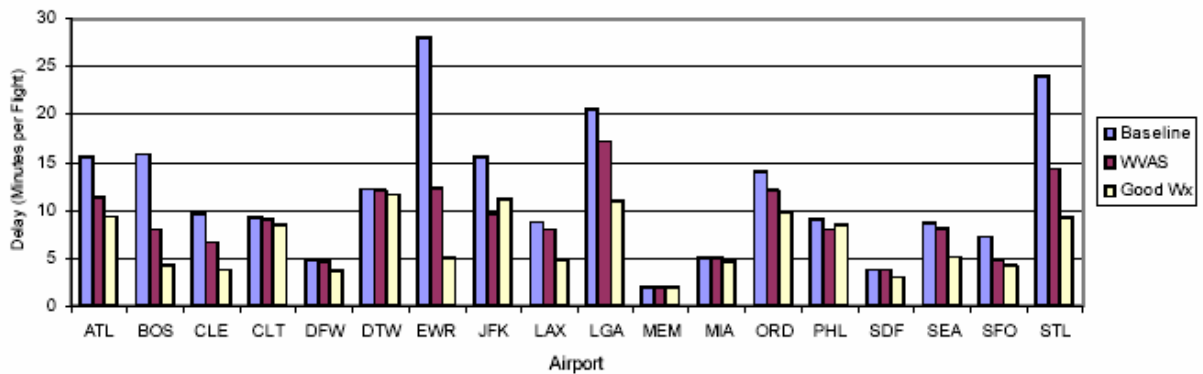
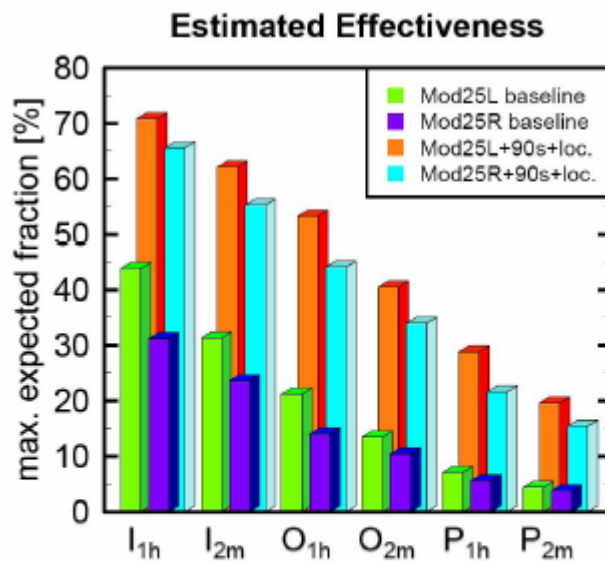


Figure 2-10: Example of reduction of delays (minutes per flight on the average) due to wake vortex advisory system Total airspace including 18 Airports, based on 2005 demand (taken from LMI Business case analysis report).



Both studies indicate the potential for significant capacity improvements. One should realize that these studies are still rather high level: although based on the actual traffic situation, a number of assumptions had to be made with regard to the details of the system and the local weather conditions. Further restrictions in the use of a particular CONOPS scheme might result from a detailed safety assessment. In illustrative example in this respect is the WSWS as contemplated for Frankfurt Airport as mentioned above. In a study presented at the 2nd WakeNet2-Europe Workshop in Langen, Germany, it was shown that the effectiveness of a wake vortex warning system drops very substantially when it is required to make a forecast 20 minutes ahead of time (see Figure 2-11).



Label	Wake Transport Based on
I _{1h}	actual measured 1 hour averaged wind
I _{2m}	actual measured 2 minute averaged wind
O _{1h}	an optimistic forecast of the 1 hour averaged wind
O _{2m}	an optimistic forecast of the 2 minute averaged wind
P _{1h}	a more pessimistic forecast of the 1 hour averaged wind
P _{2m}	a more pessimistic forecast of the 2 minute averaged wind

Figure 2-11: The estimated effectiveness of a wake vortex warning system as contemplated for Frankfurt Airport. The colors indicate the expected usage of the system in % of the time for the various runways. The effectiveness drops drastically if one has to forecast 20 minutes in advance that the glide path is free of vortices for a period of 2 minutes (from Konopka, DFS, 2nd WakeNet Workshop, Langen, 2004).

It is a good example that if more details are taken into account, like the forecast period or the wind variation during a 2 minutes period along the entire glide, the benefit of wake vortex warning systems might be reduced. Some further reduction might result from safety studies. In the simulations to support the safety case, simplifications may be needed that will reduce the apparent safety, what is equivalent to less benefit for the same (proven) safety.

This illustrates that although there is a large potential in the use of some of the wake vortex mitigation schemes, the actual outcome might be appreciable less when all restrictions due to the



actual (weather and ATM) situation and all safety aspects are taken into account. Our knowledge of weather prediction and wake vortex behavior also enters into the equation to balance capacity and (the proof of) safety. Improving our knowledge here will definitely have an effect on the final outcome. The following sections are dealing with that question: what do we know today and where should our knowledge be improved?



Section 3 Regulatory framework and means of compliance

Based on contributions from Peter van der Geest (NLR Safety and Flight Testing, Amsterdam), Frank Holzäpfel (DLR Institut für Physik der Atmosphäre, Oberpfaffenhofen) and Gordon Höhne (AIRBUS, Hamburg)

ICAO, with 185 contracting States, is the dominant rulemaking organisation in civil aviation. ICAO is functioning primarily at the rulemaking level and is not responsible for either certification/approval or for supervision/enforcements. These functions are strictly the competence of national aviation authorities. Guide lines for wake turbulence separation minima ('recommendations') are laid down in ICAO Annex 14. Most states follow the requirements scrupulously but there are various states (e.g. US, UK) that use deviant separation minima, based on national experience and reported incidents.

Within Europe EUROCONTROL (comprising today 35 states) has assumed responsibility with respect to safety related rulemaking. The harmonised framework for ATM safety regulation is currently embodied in the EUROCONTROL Safety Regulatory Requirements (ESARR). The EC is preparing a new directive that will transfer in the near future (around 2010) the regulatory competences to EASA.

For wake vortex related procedural changes e.g. as defined in CONOPS, there are no specific safety requirements. The authority will leave the design and the associated design requirements largely to the applicant (manufacturer or service provider) and would approve the system if it can be proven that the system or procedure would meet a certain pre-defined and agreed target level of safety. The basic requirements for such an analytic approach are laid down in ESARR4. A safety case has to be build to show that these requirements are actually met.

ESARR4 specifies a 'target level of safety' (TLS) for the ATM related activities. Per flight hour the chance of a catastrophic accident (involving loss of life) should be less then 1.55×10^{-8} . This number has been derived from the requirement that the safety should remain on the present level for the years ahead when the air traffic has doubled.

The application of ESARR4 is not without difficulty. First of all one has to specify what part of the total 'risk budget' is devoted specifically to wake vortex induced accidents. To proof that such an absolute target level of safety is reached for wake vortex applications is most likely extremely difficult, mainly due to the complexity of the problem (a very large number of variables like aircraft types, complex wake physics, variations in weather conditions, wake intercept geometries, human factors . . .). The methods used to calculate the safety level should ideally simulate all aspects of the system in great detail. The following sections illustrate to what detail models are developed for use in simulations. In practice simplifications will still be required, simplifications that will have to be made 'on the safe side'. With each 'short cut' it will be more difficult to proof, of course depending on the particular case, that a capacity benefit can actually be realized. A possible outcome might be that an absolute estimation of the actual risk can not be performed with sufficient accuracy.

In the past the ICAO matrix has been derived in a heuristic way using a combination of flight tests, wind line measurements, simple models and common sense. It is of interest to note here that, as yet, it has not been attempted to derive the ICAO safety matrix from a rigorous safety analysis involving complete simulations of the involved aircraft-types and wake characteristics. Therefore, alternative methods should be investigated. It is known that relative estimates have smaller ranges of uncertainty, and thus are less susceptible to model simplifications. If it can be proven that a new



system or procedure is at least equally safe as the one it replaces, 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.

When a safety case is made and accepted for a specific CONOPS, it would be wise to make a gradual and controlled transition from the standard operation to the full operational application of the system. In the context of wake vortex advisory systems it is therefore prudent to conduct further research to specify a suitable introduction phase for such systems. The safety enhancement methods as discussed in the sections 8, 9 and 10 are concerned with this.

At present there are three methods, based on a probabilistic risk assessment (see the flow chart, figure 3.1 for a short description) that can be used for a probabilistic safety assessment that quantify the (relative) safety. They are:

- WAVIR (the oldest one of the three and developed by NLR),
- WakeScene/VESA (developed by DLR/AIRBUS; see e.g./ fig. 3.2) and
- ASAT (used in the US, a more generic simulation package that can also be used for wake vortex safety assessment).

All these methods model with different degrees of sophistication, the wake evolution and the encounter probability and severity for realistic operational conditions. All methods allow for Monte Carlo simulations, with varying meteorological conditions, aircraft types, etc. to estimate frequencies of certain risk events within a certain scenario. It is presently unknown how the various model assumptions and model simplifications in the mentioned models affect the final risk assessment results. This is undesirable and as part of a future research program it is recommended to direct efforts into a comparison of the available models and validation of the employed sub-models. An assessment of the ICAO separation matrix would make a good case for such a comparison.

For each proposed CONOPS (rule and/or procedural change) a safety case will have to be made to convince all users and the authorities that the proposed change is safe. This can only be successful when the methods used are traceable, transparent, validated and accepted by independent experts.

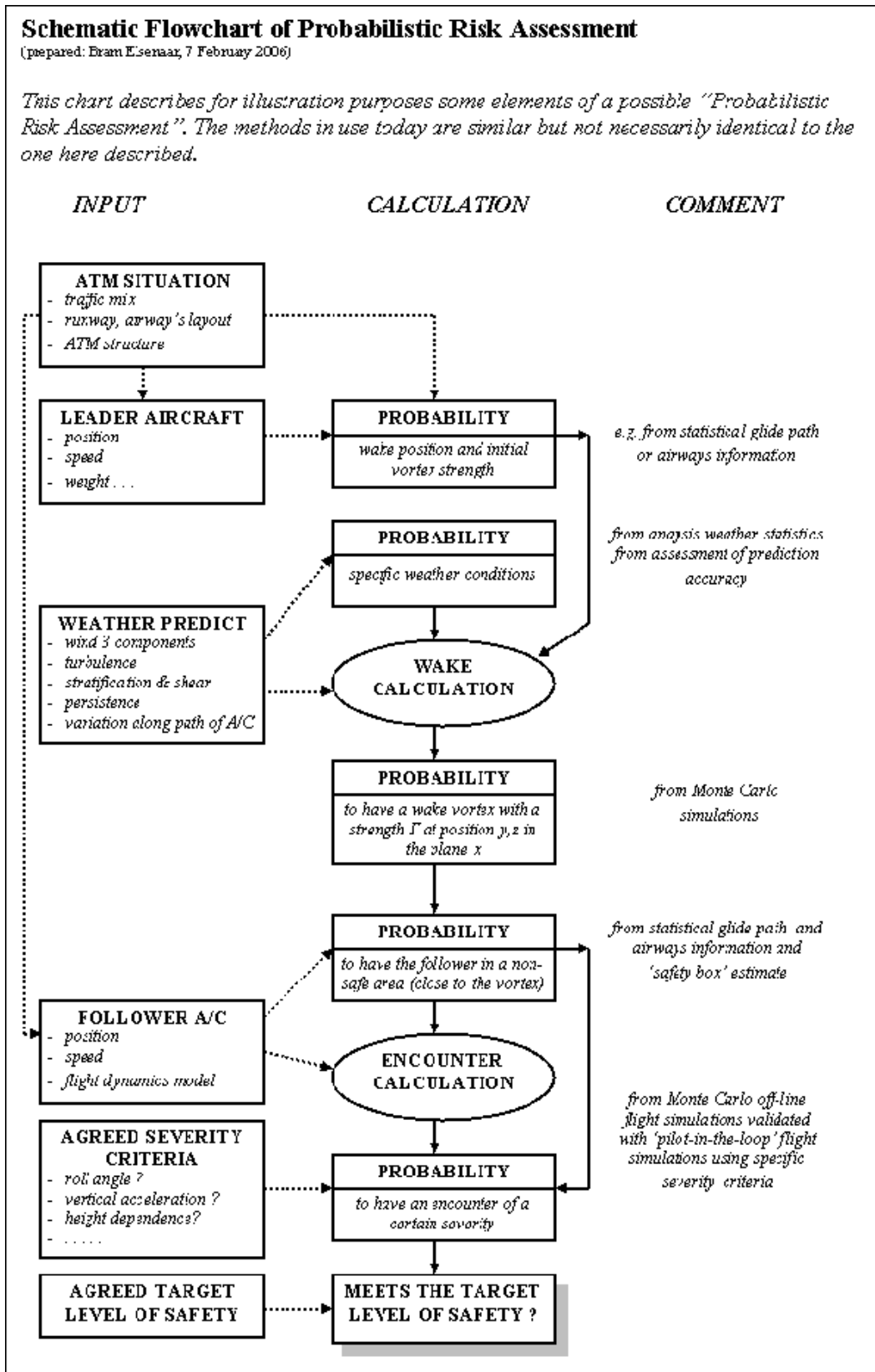


Figure 3-1: Schematic Flow Chart for Risk Assessment

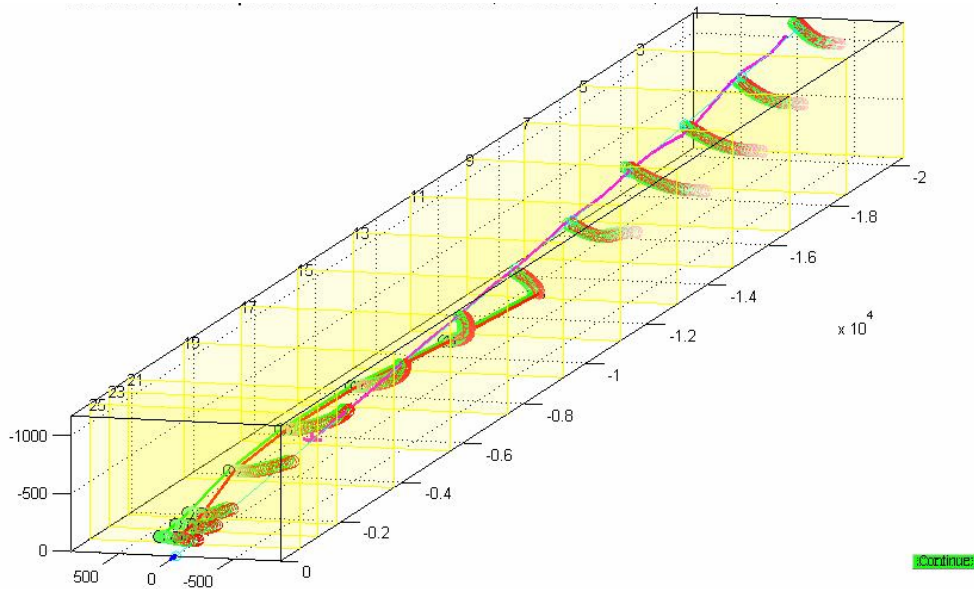


Figure 3-2: Development of wake vortices visualized by circles in 13 gates from final approach fix (gate 1) to threshold (gate 25). Wake-generating aircraft has already landed, path of follower aircraft indicated in magenta; location of port and starboard vortex indicated by green and red line respectively at the time/ position where the follower is indicated (near gate 17) . Note the change in crosswind direction and the final 'rebounding' of the vortex close to the ground. All dimensions in meters (example from WakeScene.).



Section 4 Probabilistic prediction of wake strength and position

Based on contributions from Grégoire Winckelmans and Olivier Desenfans, Université Catholique de Louvain (UCL), Mechanical Engineering Dept., Louvain-la-Neuve, Belgium and Frank Holzäpfel, DLR Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany

The strength of a pair of vortices in the wake of a particular aircraft depends, when it is formed, on the aircraft characteristics (weight, span, speed, wing loading). It will decay subsequently due to turbulence, wind shear and stratification. For very quiet conditions, the vortex pair can last very long, requiring even larger distances than the present separations. This is in general not a problem since a pair of vortices will descend (due to the mutual interaction between the vortices) and will be carried away by the wind.

Exceptionally, the vortex pair will rise due to vertical winds (convection), wind shear, and temperature stratification. Vortices will also rise very close to the ground: they bounce back from the surface.

The initial wake vortex strength can be derived from the aircraft characteristics but the subsequent vortex movement and decay is more difficult to predict. Simple analytical models have been replaced in recent times by detailed CFD methods ('vortex models') and so called 'Large Eddy Simulations' (LES) that simulate in time and space the vortex development for a given atmospheric condition (defined by a mean velocity field, turbulence intensity and length scales). At the end of a vortex life, its strength is rather sensitive to small variations and together with the variations in the actual weather conditions, the results of these calculations can only be judged in a stochastic or probabilistic way.

In Europe two successful models have emerged over the last years, which both consider all relevant environmental parameters (wind, wind shear, turbulence, temperature stratification, and ground proximity):

- P2P: the 'Probabilistic Two-Phase wake vortex and decay model' (developed by DLR). The method has been 'calibrated' against LES and actual measurement data whereas the probabilistic element is introduced by adding an observed statistical variation to the final calculated result, notably for wakes in ground effects.
- P-VFS: the Probabilistic 'Vortex Forecast System' developed by an international team for 'Transport Canada' and further developed by UCL. This is based on a vortex method that can include wind shear and ground effects; it is also 'calibrated' with LES calculations; the stochastic element is introduced by adding an uncertainty at the input part of the calculations.

Both methods have some interesting differences and can be considered as supplementary to some extent. But in spite of the impressive detail of these methods, some phenomena are still approximated e.g. both methods assume straight vortices, whereas in reality the vortices are bent and curved. Another uncertain aspect, the effect of engine exhaust jets on vortex formation (most relevant for Take-Off conditions) will be studied in the European FAR-Wake program.

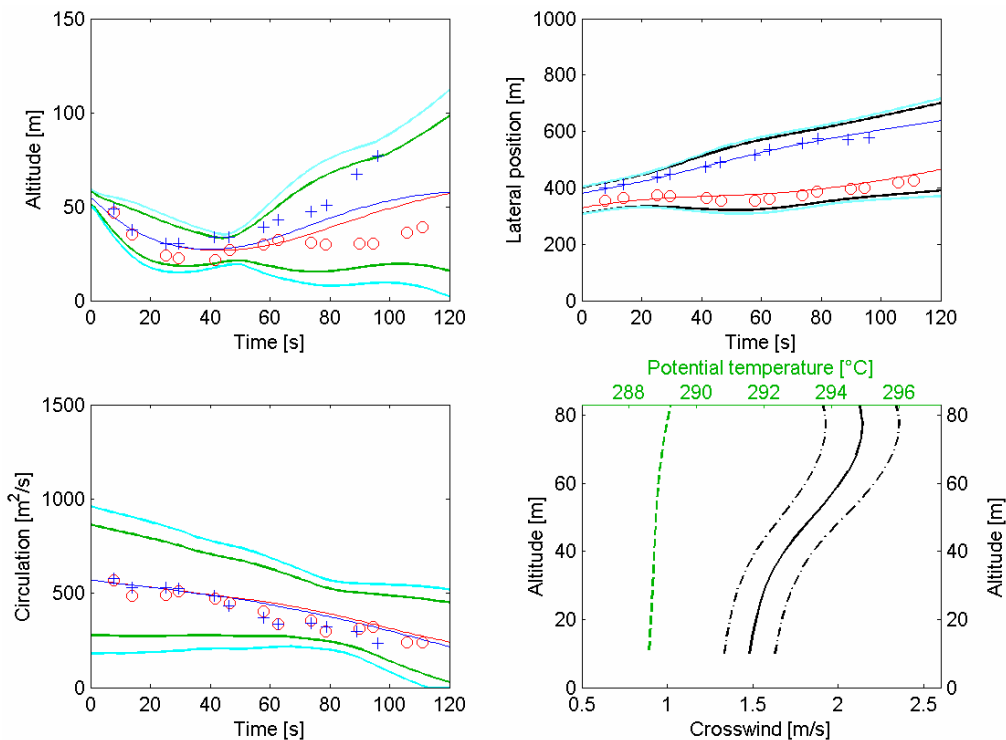


Figure 4-1: Wake vortex behaviour as observed at the Dallas Fort-Worth test campaign (case DFW 2021) and compared with calculations using P-VFS by UCL. The symbols denote the actually measured values (+ for starboard vortex and o for port vortex). The lines represent the predictions: red and blue lines 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-dotted black) and temperature (green).

A considerable work has been spent to validate these models by comparing with actual measured data (e.g. from Lidar measurements; see section 9). Due to the stochastic nature of the problem and due to the fact that the atmospheric conditions are only partially measured (e.g. at a few locations, limited vertical positions, 20 minutes averaged values etc.) such a validation has its limitations. Fortunately, in more recent test campaigns (e.g. at St Louis in the US and at Frankfurt Airport) new detailed information has been collected over longer periods. This information has not been made available yet. When available, it will allow a more systematic assessment of the two models as is already ongoing in the European FAR-Wake program.

As can be seen in figure 4-1, the prediction of the wake vortex strength and position is done in a probabilistic way. The probabilities are expressed as probability density distribution (PDF) that allows further risk calculations and the quantification of confidence levels. They reflect the uncertainties, e.g. due to the uncertainty in the weather prediction and the stochastic nature of the wake development itself. If this uncertainty is large, the potential capacity gain will decrease accordingly. The question if in a particular CONOPS application, the capacity can be increased while still maintaining safety (as derived from a probabilistic risk assessment), can only be answered when a full detailed analysis is made: the 'loop' has to be closed!
It is recommended:



- to make available well defined and agreed data set's from more recent test campaigns,
- to document the available calculation methods in sufficient detail, including all (external) information used to 'calibrate' the method to provide optimal transparency for the user and to allow an independent assessment by experts,
- to (further) compare the available methods with some agreed data sets and to analyse the possible differences in results with respect to deficiencies and possible improvements in the modelling,
- to extend the models and their validation to take-off conditions,
- to assess the limitations of using straight vortex lines.



Section 5 Wake Vortex Encounter Assessment

Based on contributions from Klaus-Uwe Hahn (DLR Institute of Flight Systems), Gordon Höhne (Airbus) and Carsten Schwarz (DLR Institute of Flight Systems)

From the wake vortex models of section 4 the velocity field induced by the vortices can be quantified. The effect on a following aircraft that flies into this field ('encounters the wake vortex') can then be derived from flight mechanical calculations in an offline simulation or from flight simulator studies with a 'pilot in the loop'. Extensive studies have been made in the European S-wake program and during the development of the VESA program of Airbus. The wake vortex velocity field models and the aerodynamic interaction models (AIM) used in these studies have been validated against wind tunnel and flight tests.

Even with the present separation rules, wake vortex encounters may occur during normal operation (see section 8). But since they are usually weak, they do not present a serious problem. For a quantitative risk assessment it is essential to have severity criteria that relate objective aircraft parameters to the subjective pilot's assessment of a wake vortex encounter (based on extensive pilot-in-the-loop wake vortex encounter severity investigations). Although relevant parameters have been proposed (e.g. a maximum roll angle or sink rate) a set of agreed criteria has not been established yet. Also, automatic detection of wake encounters (see section 8) will be very valuable to assess the present situation and to validate the severity criteria for weak encounters.

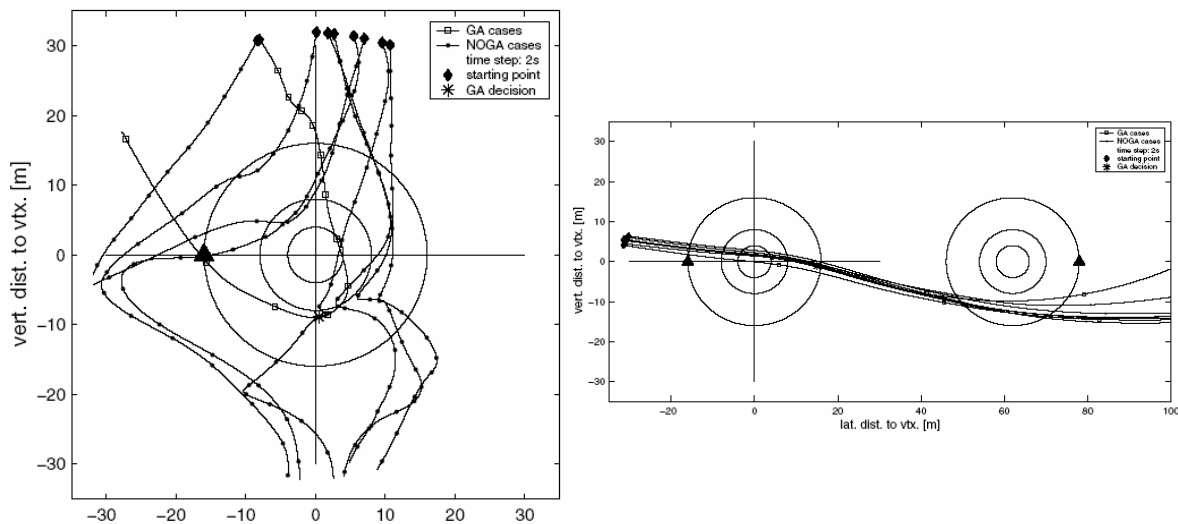


Figure 5-1: Aircraft motion in wake encounter from flight simulation studies. Left: shallow intercept from above (vertical intercept angle is 2 deg.); right: quick intercept from aside (horizontal intercept angle is 20 deg.) (from S-Wake study by AIRBUS).



The following recommendations are made:

- **To define and agree upon relevant criteria to assess the effects of an encounter, on the basis of extensive flight simulator tests,**
- **to improve wake vortex encounter pilot models for offline simulations,**
- **to extend the encounter studies to all ICAO wake categories and to all phases of flight,**
- **a further validation of aerodynamic interaction models is still required, notably for transport aircraft with swept wings,**
- **to further develop the aircraft capabilities to detect/predict and evade wake vortices and to cope with wake vortices in case of an unwanted and unintended encounter,**
- **to assess automatic recording of encounters by Flight Data Recorders (see section 8), to support the choice of severity criteria for weak encounters.**



Section 6 Weather prediction, monitoring and statistics

Based on contributions from Michael Frech and Thomas Gerz (DLR Institut für Physik der Atmosphäre, Oberpfaffenhofen) and Debi Turp (UK MetOffice, Exeter)

What are the meteorological parameters that have to be measured and/or forecasted for wake vortex warning systems? Mean wind (all three wind components) and wind variability, turbulence, virtual potential temperature and vertical wind shear are all known to influence the wake development. 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, for aircraft departures a cross-wind nowcasting system for the horizontal wind components (and its associated temporal and spatial variability) is only required for a short time horizon on the order of 10 minutes at most. 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 a growing uncertainty as time increases. 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 and that only forecasts on a probabilistic basis may succeed.

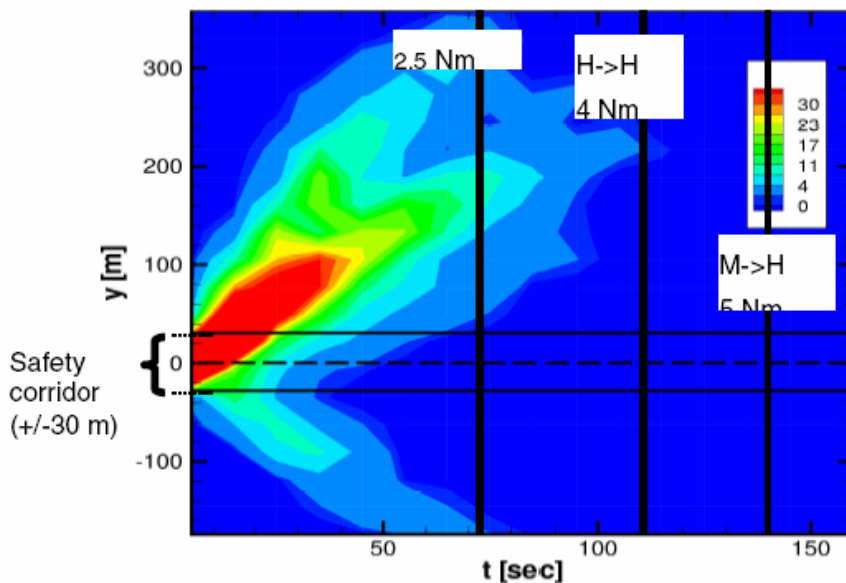


Figure 6-1: Lateral transport of vortices out of the flight corridor due to crosswind, frequency, distributions (in %). These results are based on an analysis of the Memphis data for vortices out of ground effect and cross winds (either sign) > 2 m/s (252 cases). From S-Wake study by DLR.

Is the accuracy of these predictions good enough? Most predictions concentrate on the cross winds. In the ATC-Wake study it was concluded that a mode separation of 2.5 NM for Single Runway Applications can be applied safely provided:

- a sufficiently accurate prediction of the crosswind during the approach is available. This implies that the wind forecast error may not have a bias and the standard deviation of the wind forecast error must be less than about 1.0 m/s.
- improved navigation performance (compared to ICAO-CRM) is available.



Otherwise, the number of alerts provided by system will exceed the maximum acceptable level of 0.2%. This is quite a stringent requirement and this might very well prove to be the bottle neck for such systems that have to make use of a forecast about one hour in advance.

Although vortex transport is the dominant mechanism to reduce the effect of a vortex, decay due to atmospheric turbulence is also important. Decay models are based on turbulence intensity and/or so called eddy dissipation rate (EDR), quantities that are not easy to measure and predict, especially EDR.

To further improve the weather prediction skills it is recommended:

- **to develop test algorithms for an optimum fusion of observation and forecast data ,**
- **to assess the potential to integrate AMDAR/ACARS (on-board) data within a wake vortex monitoring and prediction system and**
- **to develop and improve algorithms that can deduce eddy dissipation rates from various measurement sources and forecast models to improve the prediction of the vortex decay.**

It is finally concluded that the combination and integration of the tools in a prototype system and its implementation at the airport is necessary now.



Section 7 Collection and Analysis of Empirical Data

Based on the contribution from Jens Konopka, DFS Deutsche Flugsicherung GmbH

Wake turbulence separation minima have been established by ICAO in the 1970'ies. Since then only very few changes have been made compared to these standards. Already from this finding it can be concluded 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 and notably incident reporting. Therefore their potential application is likely site-dependent and limited to specific conditions.

Wake vortex transport and decay models as discussed in the previous sections are either based on numerous input variables, some of which are difficult to measure (turbulence, temperature, wind-profile ...) or they contain statistical elements that 'lump' some of these effects together. Although considerable validation work has been done for these models, the quality of the data sets that are used for these validations is not always optimal, either because spatial and temporal variations of meteorological conditions were not considered adequately or measurement sites for meteorological quantities and wake vortices were too far apart. The most recent European campaigns already tried to avoid some of these shortcomings. Further it is not clear how many measurements are needed to proof a certain level of confidence (e.g. to define the relevant (not necessarily Gaussian) probability density functions (PDF)). Obviously, unusual meteorological conditions that lead to the tails of PDFs of wake vortex behaviour are measured rarely and it remains to be seen how to handle this in a safety assessment. Moreover, wake vortex behaviour data is not available or very rare for some particular conditions, e.g. during fog, when turbulence is small or during aircraft manoeuvres (e.g. missed approaches, sharp turns in take-off's).



Stratification statistics

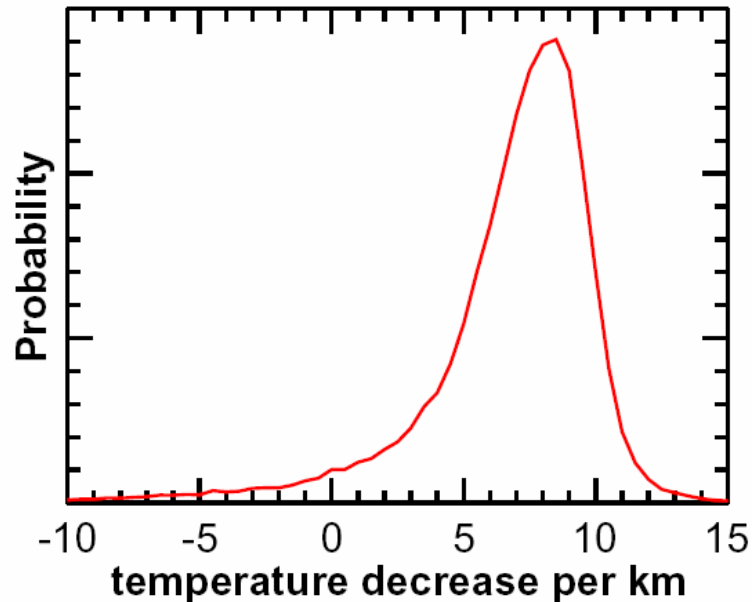


Figure 7-1: Distribution of temperature gradients in the boundary layer at Frankfurt airport. Inversions are roughly found (depending on humidity) on the left of the peak. Strong inversions might give rise to situations where the vortex pair bounces up. These conditions are rare, as the 'long tail' on the left in the figure illustrates, but they might be of critical importance for the safety.

The following recommendations are made:

- **Continue to work on the correlation between meteorological quantities on the one hand and the vortex transport and decay properties on the other; ideally these variables are to be collected during long-term observations with dedicated measurement equipment.**
- **Standardize meteorological measurements in wake vortex related measurement campaigns.**
- **Perform long-term campaigns, in which the meteorological parameters, wake trajectories and wake decay are measured in parallel.**
- **Establish (site dependent) statistics to estimate the fraction of time where wake turbulence separation can be reduced in a (capacity) beneficial way.**
- **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 as well as its spatial variation along the glide path.**



Section 8 Incident Reporting and the Analysis of FDR Recordings

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

Wake vortex encounters are currently not systematically recorded, although the more serious encounters are captured by various (International/European/National) reporting schemes like ADREP (ICAO) and ECCAIRS (EU). From this information it can be concluded that there have only been a few occurrences where wake vortex has led to a serious incident or accident. This conclusion seems to justify that the present wake separations are adequate from a safety point of view.

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. The most noticeable examples are the NATS voluntary reporting scheme and the RVSM schemes by Eurocontrol and (recently) in the US.

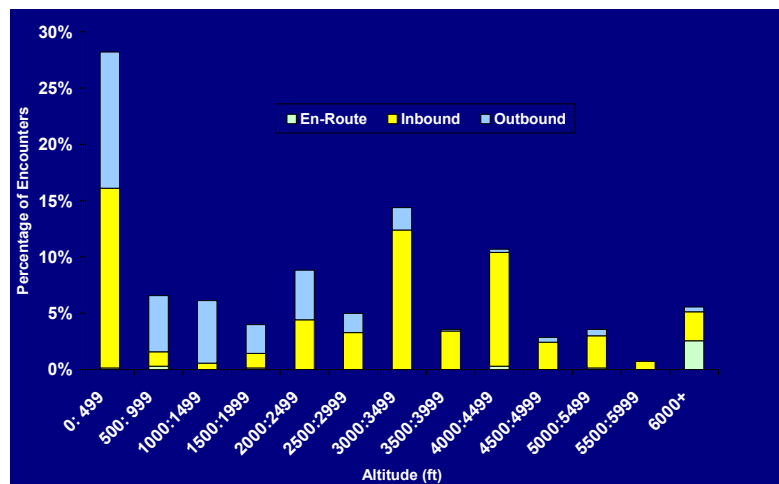


Figure 8-1: Reported wake vortex incidents in UK airspace depending on the height of the aircraft according to the NATS voluntary reporting scheme.

Note that there is a peak in reported incidents very close to the ground (due to vortices that bounce up) and around 3000 and 4000 ft, the location of the glide path intercept. This kind of information is very essential to monitor the safety situation.

The NATS reporting scheme 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.

Collecting statistics on wake vortex encounters serves two purposes:

- Provide data to assess new/changed procedures (e.g. RVSM).
- Provide data to validate safety arguments.



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. No information is obtained from the less severe events, information that might be very useful for an evaluation of safety aspects. 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.

Automatic registration of wake encounters would provide in principle an objective alternative. During the European S-wake project, all flights of a given carrier had their FDR traces analysed to see if they had suffered a wake encounter. The NLR-VORTEX algorithm developed by NLR (now renamed WAVENDA) was used to identify from these FDR traces whether the aircraft had encountered a wake vortex. The present system is not perfect (partly due to poor data recordings) and work is underway (e.g. as proposed in the CREDOS program) to try to improve and validate the algorithm for future FDR work.

Both a more general reporting scheme for wake vortex encounters and the automatic registration and analysis of wake encounters would entail more resource and is probably only feasible for dedicated campaigns in support of specific measures that are likely to affect the safety with respect to wake vortices or for a continuous observation at a specific site.

In conclusion:

- **Ideally the best way to capture wake vortex encounters would be to have an empirical scheme (for example the automated analysis of Flight Data Recordings) in conjunction with a pilot reporting scheme. This would allow the subjective (pilot report) data to be aligned with the objective (FDR) data.**
- **To enable this, further work and research would be needed to better extract the relevant information from FDR recordings.**
- **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 criteria of a wake encounter.**



Section 9 Safety enhancement tools: real time monitoring of wakes

Based on the contribution from Chris Hills (QinetiQ), Frederic Barbaresco (Thales), Friedrich Köpp (DLR) and Agnes Dolfi (ONERA)

For the remote detection of wakes the main methods are Lidar, passive acoustic, active acoustic, and Radar. This is needed to assess the performance of wake vortex prediction schemes (like the ones discussed in section 4) and to monitor the wake position during operation with reduced wake separations as a safety precaution.

Wind profiling is essential for weather forecasting and to characterize the weather as input for wake vortex prediction schemes. For wind profiling the main methods are Lidar, Sodar and Radar.

Lidar, with its fine precision of both spatial and velocity (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.

The following figure gives an overview of the ideal instrumentation package as available today (taken from a study by Sauvage et al of Leosphere; study for EUROCONTROL, 2005).









	ILS		Approach and Climb		Critical			
	 Vortex	 Wind	 Wind	 Turbulence	 Turbulence	 Vortex	 Wind	 Temperature
No rain	Lidar PC2 μ							RASS SODAR
Fog			RASS SODAR		Lidar PC2 μ		RASS SODAR	
Heavy rain		TDWR			Windlines and met tower (up to 45m)			

Figure 9-1: Ideal instrumentation package (using 'on the market' systems) for weather and vortex measurements to support wake vortex warning systems (from Sauvage et al, Leosphere, 2005).

But technology is changing fast and new systems might become available in the future as indicated below. A crucial question here is that operation is required for all weather conditions.

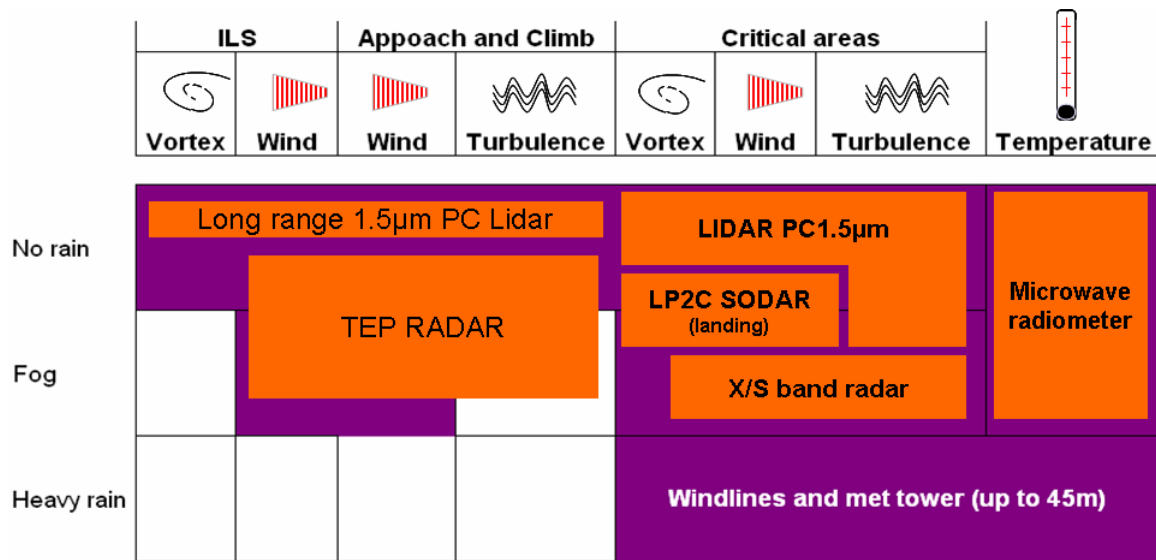


Figure 9-2: Possible future instrumentation package (using latest European and American R&D) for weather and vortex measurements to support wake vortex warning systems (from Sauvage et al, Leosphere, 2005).

It is recommended:

- **The look into the complementarity of Radar, Sodar and Lidar: e.g. extending the use of ATC radars in wet conditions, when lidars are handicapped.**
- **To assess by independent parties the performance claims by the manufacturers of LP2C Sodar and SOCRATES Lidar.**
- **To review frequently the technical state of the art; published comparisons are 'snapshots' that become quickly outdated.**



Section 10 Safety Enhancement Tools: On Board Wake Detection

Based on the contribution from Laurence Mutue (THALES, Aerospace Division)

The pilots' community has always been very supportive to the development of onboard systems to visualize the wakes in the cockpit. Industry is interested to develop such systems, not only to detect wakes but also for wind shear and clear air turbulence. A number of European projects are concerned with these issues (e.g. MFLAME, I-Wake, FLYSAFE and FIDELIO).

The onboard Atmospheric Hazard DWA (Detection, Warning and Avoidance) 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 research projects on instrumentation for onboard wake vortex detection focused on Lidar in combination with model capability for the approach and landing phases.

On the instrumentation side, ground and air borne tests have indicated that the IR 2 μ m Lidar gives satisfactory results for the operational requirement of 5 to 10 km range. 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: 2 μ m technology requires free space optics. A further development could be a 1.5 μ m Lidar system. Its technology is less mature than the 2 μ m but carries the promise of easier aircraft installation since the Lidar will be fibered. On the other hand, the energy that an optical fiber can transport 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 1.5 μ m technology. Research needed in this area is twofold:

- **pursue the use of 2 μ m Lidar improving weight and compactness**
- **investigate 1.5 μ m Lidar for the potential of optical fibers**

To enhance the overall reliability of an airborne system a fusion with an independent system that can predict the wake vortex on the basis of weather and ATM information is pursued. This is needed since Lidar can only detect vortices in clear dry air conditions. The wake vortex model used for the onboard system as tried in I-Wake is the Vortex Forecast System (VFS – See Section 4). In this respect it is equally of interest to study the feasibility of wake detection using onboard weather radar to mitigate the effect that Lidar requires clear dry air conditions.

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. It is recommended to have an Integrated Project where wake related issues both on the ground and onboard could be resolved through technology assessment and operational use.



If and to what extent on-board wake vortex detection can improve the overall safety level of particular operational procedures to reduce wake separation distances (e.g. for one of the CONOPS as discussed in section 2) needs to be further assessed in a complete 'safety case'.

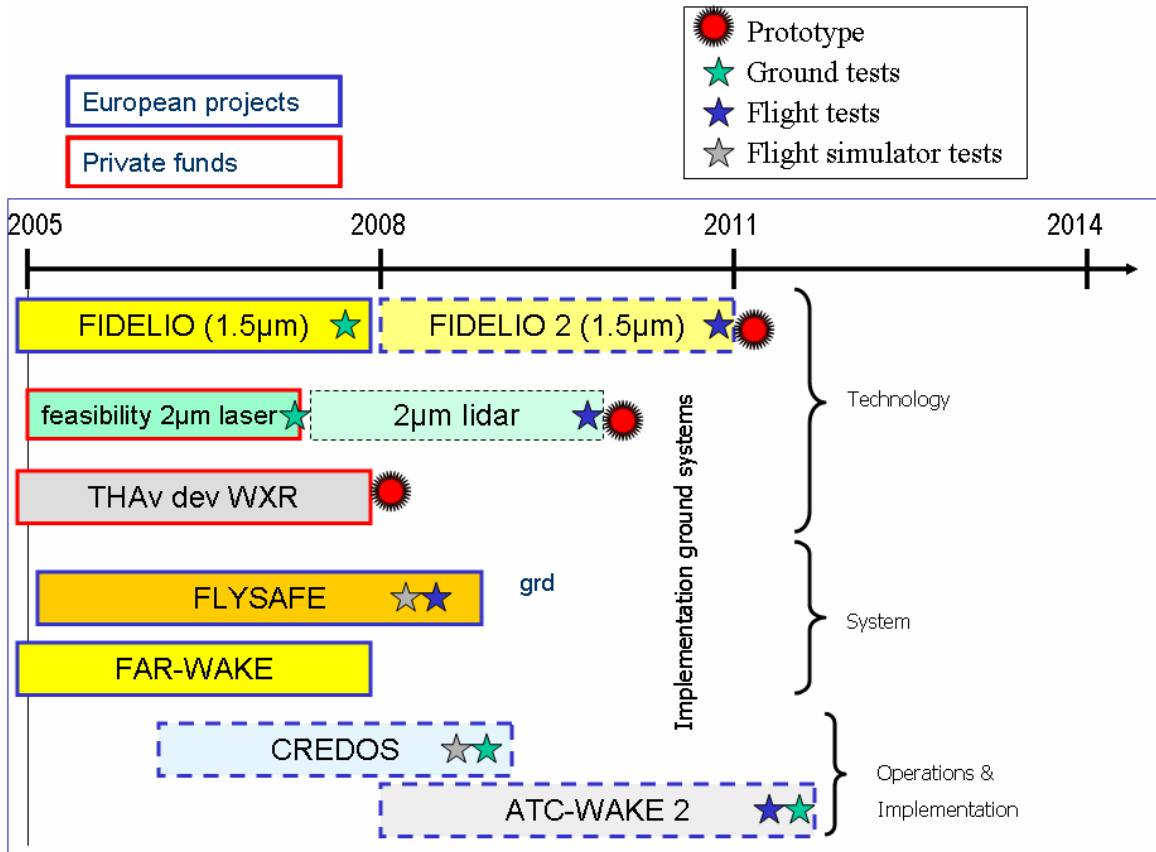


Figure 10-1: Roadmap for onboard wake detection systems as seen by THALES (presented by Laurence Mutuel, WakeNet2-Europe Final Review Meeting, November 2005).



Section 11 Wake vortex alleviation studies and prospects

Based on contributions from Eric Coustols (ONERA), Bram Elsenaar (NLR), Anton de Bruin, Greg Winckelmans (UCL), Laurent Jacquin(ONERA), Florent Laporte (AIRBUS and Geza Schrauf (AIRBUS)

Is it possible to design aircraft such that the vortex wakes are less harmful? That of course would cure the problem at the source.

A number of European projects have addressed this question like Eurowake, C-Wake, AWIATOR and FARWAKE.

Vortex formation is inherently related to the lift generated by the aircraft wing to support the aircraft weight: the air trapped between the vortex pair is pushed downward to generate the momentum to keep the aircraft aloft. The basic physics of a vortex pair behind an aircraft are reasonably well understood. Also the scaling rules are believed to be known: larger aircraft will have in general more severe wakes that last longer.

There is no real evidence that (when properly scaled) there are differences between different aircraft: all aircraft behave roughly the same, roughly but not exactly. Theoretically, there will be differences between the strength and decay of wakes for different aircraft types, even for the same weight and span. They are due to variations in e.g. wing loading, aspect ratio and landing speed. But it is difficult to proof this since the data sets (e.g. from measurement campaigns with Lidar) are not large enough to discriminate between these kind of differences mainly due to scatter resulting from variations in weather conditions. The fact that no large variations have been observed between flying aircraft might also indicate that a 'low vortex design' is not obvious.

Measuring techniques have advanced significantly as a result of the programs mentioned above, notably full scale wake characterization with Lidar, and sub-scale tests in the towing tank and the catapult facility. Unfortunately, full scale tests generally show a significant spread in the results due to variations in weather conditions although some corrections are possible to compensate this.

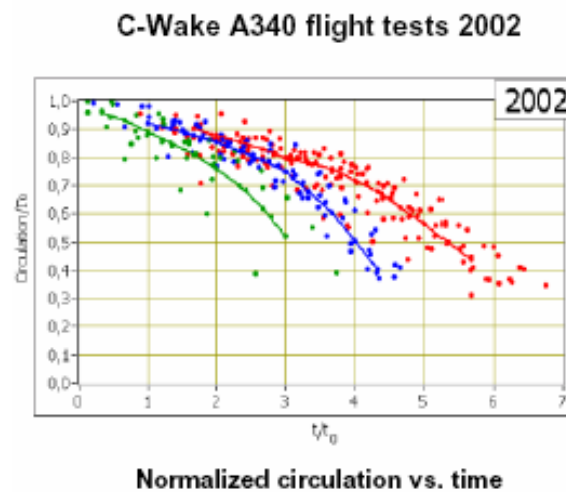


Figure 11-1: Lidar measurements of the decay of vortex strength behind an A340. The vortex strength is expressed here as the averaged circulation in a ‘ring’ around the vortex core divided by the initial circulation. The time is made dimensionless with a characteristic time t_0 , the time needed for the vortex pair to move downwards over a distance equal to the spacing of the two vortices – around half a minute in this case). The different colours indicate different weather (turbulence) conditions, indicating a large effect of the atmospheric turbulence (results obtained by DLR during the C-Wake campaign in 2002 at Tarbes, France).

Over the last years the computer simulations of the development and decay of vortices, even including the weather conditions, have advanced significantly (e.g. see section 4) and allow a detailed evaluation of the details of the vortex development.

Hence in principle the tools are available to see if and how wake vortices can be reduced by design. There are some alleviation concepts that are pursued:

- The distribution of the load along the wing span can be varied to effect the distances between the vortices (when they are closer together they will decay faster) or to create multiple vortices that can more easily be de-stabilized (see below).
- Theory and experiments show that a double pair of counter-rotating vortices lead to a situation where one vortex wraps itself around the other one. This turns out to be a very efficient mechanism to dissipate (take the energy out of) the vortex. But one has to pay a price to generate such a multiple vortex system: special wing shapes are required that affect the performance and the low speed design. A careful trade-off is required and it is not clear if this really pays off.



Figure 11-2: Crow instability as observed behind a Boeing 747 at cruise altitude (FL350) estimated to be at about 9 nm behind the aircraft. This instability manifests itself as an oscillation in the vortices leading finally to a 'connection' and the formation of vortex rings. (Courtesy of Arun Karwal, test pilot NLR).

- Instabilities in the vortex precede its final destruction. The most well known example is the Crow instability that can easily be observed in clear skies. Can the wing be designed such that these stabilities are favoured? This is not to be excluded e.g. by the generation of external turbulence, the deployment of spoilers or changes in the tail section that effect the vortex shed by the tail. This may be called 'vortex management' and studies in this direction are continuing.
- One step further is an active triggering of the instabilities. This is an 'old' concept that seems to work but with an aircraft integration problem. It works for a single vortex pair but it is not very effective in this case. To be more effective one needs multiple vortex systems.

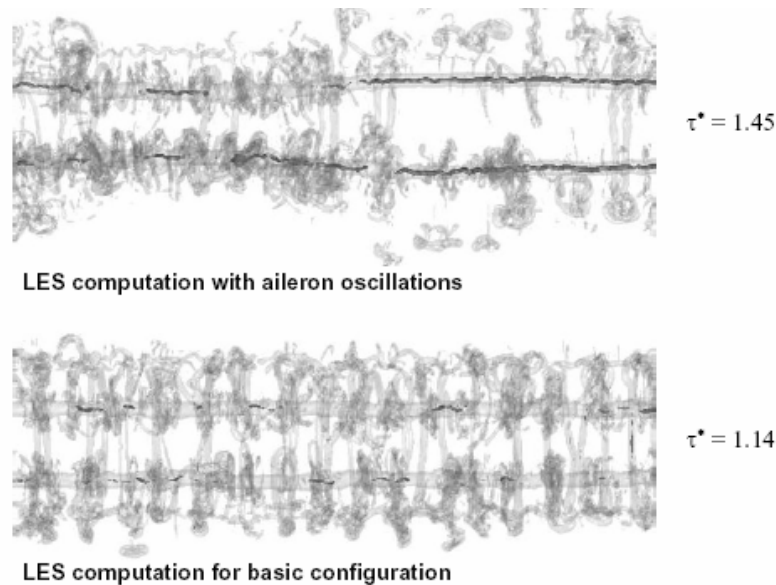


Figure 11-3: Large Eddy Simulations (LES) of the effect of aileron oscillations on the wake stability. With an oscillating aileron (upper part of the figure) the so called Crow instability has been enhanced, leading to a faster decay. The 'rings' around the vortices are indicative of the interaction between atmospheric turbulence and the vortex as part of the decay process (calculations by Greg Winckelmans, UCL).

Although research so far has not been very successful in designing 'low vortex' wings, research in this area should continue. Some specific recommendations can be made:

- **future research should consider both 'proof of concept' and applicability,**
- **the study of multiple vortex systems (its generation and stability characteristics) should be further pursued,**
- **fundamental studies on stability, temperature effects, external turbulence, axial flow in the core of the vortex should continue since new alleviation concepts might result from a better understanding of the physics (such studies are ongoing in the FAR-Wake project).**



Glossary

ACARS	Aircraft Communications And Reporting System
ADREP	Accident/Incident Reporting
AIM	Aerodynamic Interaction Model
AMAM	Arrival Manager
AMDAR	Aircraft Meteorological DATA Relay
ASAT	Airspace Simulation and Analysis for TERPS (developed by FAA / ATSI)
ASRS	Aviation Safety Reporting System
ATCO	Air Traffic Controller
ATM	Air Traffic Management
CFD	Computational Fluid Dynamics
CONOPS	Concepts of Operation
CREDOS	Crosswind Reduced Separations for Departure Operations (recently approved European Research program)
CSPR	Closely spaced parallel runways
DRVSM	Domestic Reduced Vertical Separation Minimum
DWA	Detection, Warning and Avoidance
ECCAIRS	European Co-ordination Centre for Aviation Incident Reporting Systems
EDR	Eddy Dissipation Rate (to characterize turbulence)
ESARR	Eurocontrol Safety Assessment Regulatory Requirement
ETWIRL	European Turbulent Wake Incident Reporting Log
FDR	Flight Data Recorder
HALS/DTOP	High Altitude Landing System/ Dual Threshold Operations
HMI	Human Machine Interface
IFR	Instrument Flight Rule
ILS	Instrument Landing System
IGE	In Ground Effect
IMC	Instrument Meteorological Conditions
LES	Large Eddy Simulations
LIDAR	Light Detection And Ranging
NOWVIV	Nowcasting Wake Vortex Impact Variables (developed by DLR)
OGE	Out of Ground Effect
P2P	Probabilistic Two-Phase wake vortex decay and transport model (developed by DLR)
PDF	probability density function (or distribution)
P-VFS	Probabilistic Vortex Forecast System (developed by an international team for 'Transport Canada, further developed by UCL)
QAR	Quick Access Recorder
RVSM	Reduced Vertical Separation Minimum
RYW	Runway
SHAPE	Simplified Hazard Area Prediction model (developed by DLR)
SMP	Separation Mode Planner
SODAR	Sonic detection and ranging
SOIA	Simultaneous Offset Instrument Approach
TBS	Time Based Separations
TLS	Target Level of Safety
VESA	Vortex Encounter Severity Assessment (developed by Airbus)
VMC	Visual Meteorological Conditions



WakeScene	Wake Vortex Scenarios Simulation (developed by Airbus / DLR)
WAVIR	Wake Vortex Induced Risk assessment (developed by NLR)
WSVBS	Wirbelschleppenvorhersage- und beobachtungssystem (Wake Vortex Prediction and Monitoring System)
WSWS	Wirbelschleppen-Warnsystem (Wake Vortex Warning System)
WTR	Wind Temperature Radar
WV	Wake Vortex
WVAS	Wake Vortex Advisory System
RASS	Radio Acoustic Sound System
Γ_{5-15}	Averaged circulation between 5 and 15 meter from the vortex centre

END of PART I