WakeNet3-Europe

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Aircraft Wake Vortex
State-of-the-Art & Research Needs

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Aircraft Wake Vortex

State-of-the-Art

&

Research Needs

A document prepared by the partners

of the

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for

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This report has been prepared by the partners of the WakeNet3-Europe Coordination Action project in 2012, which was the last year of activity within this project.

Believing that the information contained in this report – although reflecting a technical status of 2012 whereas relevant advances in the topic of aircraft wake turbulence have since been achieved – is still of relevance, the WakeNet3-Europe partners agreed in 2015 to issue this public version. Compared to the version from 2012, some remaining open points in the summary have been addressed and a few additional editorial tasks have been completed. This public 2015 issue has been approved for public dissemination by the WakeNet3-Europe Coordination Board consisting of AIRBUS, DLR, NATS, NLR, THALES and Eurocontrol.

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Foreword

This document has been created as part of the Coordination Action project WakeNet3-Europe, funded by the European Commission within the 7th Framework Program (FP7).

Networks are carried by people and a consolidated view of European wake vortex research accomplishments and needs could only be established based on the commitment of a large number of experts in their respective fields and numerous discussions. Many of these discussions took place during the various workshops organized as part of WakeNet3-Europe and have directly influenced the preparation of this report.

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In addition, the support of the European Commission and the active participation, interest, and expertise of the EC scientific officer to the WakeNet3-Europe project, Dietrich KNÖRZER, is highly appreciated.

Frank Holzäpfel, Andreas Reinke (Editors)

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1. Introduction

As an unavoidable consequence of lift, aircraft trail a pair of counter-rotating vortices that pose a potential hazard to following aircraft. Wake turbulence separation minima are prescribed to avoid this hazard but they are limiting airport capacity growth. Increasing airport congestion, the increasing diversity of aircraft types (e.g. the advent of Very Light Jets), the introduction of new aircraft, and the availability of new technologies have promoted extensive wake vortex investigations in recent years.

Comprehensive flight testing, numerical simulation, improved wake vortex detection, and characterization by remote sensing have helped to better understand wake vortex physics, including the impact of meteorological conditions on wake vortex behaviour and lifetime. As a consequence of these achievements, the activities of the last decade have progressed from improved physical understanding of the wake vortex phenomenon itself towards the development of new operational concepts, supporting systems and rulemaking making best use of this knowledge.

Today, wake vortex studies primarily relate to the following two key improvements:

- The replacement of the current rigid and often overly conservative methods of wake turbulence separation minima by new, more precise and potentially dynamic separation systems.
- The safe reduction of separation minima with associated capacity increases through application of new procedures as well as new ground-based and airborne advisory and detection systems, enabled by dedicated sensors, reliable modelling and real-time data exchanges.

The wake vortex topic involves a large number of disciplines ranging from wing aerodynamics to regulatory safety oversight. The involved parties comprise researchers, operational users (airports, pilots, and airlines), air navigation service providers, regulators as well as aircraft and equipment manufacturers.

This large spectrum of disciplines and organisations necessitates a dedicated effort for information exchange and discussion which has been the principle aim of the European Coordination Action project WakeNet3-Europe (2008 – 2012), funded by the European Commission within the 7th Framework Program (FP7). This third European network on aircraft wake turbulence was launched amid – and partly against – many believing that research had reached a level of maturity that would allow putting the knowledge gained previously into operational practice quickly. The WakeNet3-Europe project itself reflected this trend with strengthened links into operations and increased focus on operational wake vortex concepts and systems. And in fact several operational changes related to wake turbulence separations could be implemented in Europe and in the USA during the runtime of WakeNet3-Europe.

But still, several ambitious projects encountered difficulties as witnessed by delays or outright cancelation. While the reasons for these difficulties are manifold and certainly not only of technical nature, they still point towards additional research needs and consolidation of models and methods, especially in support of safety assessments where it appears mandatory to fully understand even quite specific aspects of wake vortices in order to avoid undesirable surprises. In addition, the recently started development of operational systems that are intended to deliver and support several of the envisioned new wake turbulence separation concepts uncovers additional research needs, e.g. with regard to the required level of modelling detail or simplification and the associated validation requirements. Then, a number of emerging fundamental technologies and applications, for example in the fields of vortex sensing and aircraft control, promise even higher benefits if further explored. Last but not least, changes in air traffic management as endeavoured as part of SESAR in Europe and NextGen in the USA have an impact on wake separation concepts or are themselves impacted by the necessity to manage the wake turbulence encounter risk.

The continued interest in the wake vortex topic and related research is also attested by the steady high levels of attendance to the yearly workshops of WakeNet3-Europe as well as the regular meetings of WakeNet USA. It has also been highlighted during two invited sessions called “Managing Wake Vortex Encounter I and II” of the AIAA Atmospheric Flight Mechanics and the Atmospheric and Space Environments Conferences, 2-5 August 2010, Toronto, Canada.

This specific interest in the wake vortex topic should remain high since a number of wake vortex related concepts promise to directly answer to the continuing European societal need to safely and efficiently accommodate the growing demand for air travel as it is expressed in ACARE's Flightpath 2050.

Given this background, the partners of WakeNet3-Europe have prepared this public report with the following objectives:

- Provide an overview of the state-of-the-art in the field of aircraft wake vortices
- Review the needs expressed in Flightpath 2050 and the wake vortex related concepts that can answer to these needs
- Identify those research activities that need to be supported in order to put these new wake vortex related concepts into practise
- Highlight major axes of research activities together with priorities and timelines in order to allow key stakeholders to make informed decisions that are optimally addressing societal needs

This report follows a top-down approach by starting from the top-level societal needs and connecting these with the individual research needs at different supporting levels, like those required to progress new operational concepts, establish supporting systems, to advance specific underlying technologies and methods as well as to advance on related safety assessment aspects, Figure 1.

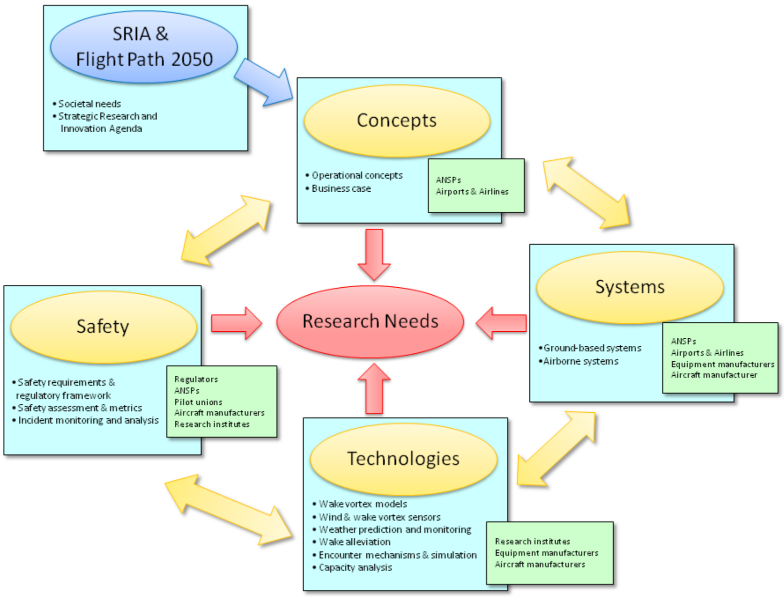

Figure 1: From top-level needs to research needs

This structure largely reflects the internal organisation of the WakeNet3-Europe project, although with the addition of a "Systems" section:

- "Concepts" applied at airports or en-route directly respond to top-level needs and are intended to reduce wake turbulence risks and to safely increase capacity at constrained airports.
- "Systems" support the operational implementation of new concepts unless they purely affect procedures.
- "Safety" frames and supports the implementation of new concepts including the evaluation and substantiation of the associated safety levels.
- "Technologies" enable the development, validation, and implementation of concepts, systems and safety assessments.

Key elements of this report are the recommendations for future research activities and concept implementations that are listed at the end of each section. A consolidated and comprehensive summary of the research needs is given at the end of the report.

The WakeNet3-Europe “State-of-the-Art & Research Needs Report 2012” stands in the tradition of a series of predecessor reports.

A report called “Position Paper” (Gerz et al. 2001) was compiled in the framework of the first European Thematic Network on Wake Vortex (“WakeNet”, 1998 – 2001). This Position Paper presented a consolidated European view on the status of knowledge of the nature and characteristics of aircraft wakes and of technical and operational procedures of minimizing and predicting the vortex strength and avoiding wake encounters as available at that time. The Position Paper was also published in the international review journal Progress in Aerospace Sciences (Gerz et al. 2002). In the Position Paper research needs were phrased as lists of questions and forthcoming actions. A revisit of these lists indicates that a substantial number of these questions could be answered but some issues like “A valid and agreed definition of a hazardous vortex encounter is still lacking” still persist. Another highlighted issue of crucial importance at that time was: “A proved and robust method to characterize and control wake vortices from the near field to the far field is not available.”. This, too, is an issue which has not been resolved until today. In contrast, considerable progress has been demonstrated in recent years with regard to an issue described in 2002 as follows: “Operational wake-vortex forecast and monitoring in the terminal area are not yet feasible at reasonable costs.”. Finally, the topic “An elaborated sequence of detection, warning and avoidance (DWA) for the wake-vortex problem is necessary for the daily air traffic management.” corresponds to one of the research themes that receives much attention today.

The “Wake Vortex Research Needs” document (Elsenaar et al. 2006) emerged from the activities of WakeNet2-Europe, a follow-on EC-sponsored Thematic Network that has been active between 2003 and 2006. This report was divided into two parts. Part I provided a general overview emphasizing the necessary links between the various themes. Part II was devoted to the respective specialists and described the state-of-the-art in more details as well as the research needed to better understand various aspects of the problem of wake vortices and means to mitigate its effects. The most pressing research needs identified in the Wake Vortex Research Needs document (2006) have been:

- 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 report has been compiled by the partners of the WakeNet3-Europe consortium with the support of several external experts. It describes the present international state-of-the-art in wake vortex research and application – focusing on recent developments in the various involved disciplines – and specifically evaluates research activities needed in order to provide operational benefits in line with ongoing SESAR developments, in response to ACARE goals and following Europe's vision for aviation, Flightpath 2050. The authors acknowledge that due to the complexity of the subject, the large number of actors, and disciplines involved, this report is not and cannot reflect all related activities worldwide. The broad spectrum of the involved research disciplines and the large number of authors with different backgrounds and with different views on what is defined as research unavoidably also leads to a certain manifold in structure, style and contents of this report which the editors have tried to minimize.

This report has been prepared for the European Commission and is made publicly available via the WakeNet3-Europe website (www.wakenet.eu).

2. The link with Flightpath 2050

The High Level Group on Aviation Research of the Advisory Council for Aviation Research and Innovation in Europe (ACARE) prepared a report entitled "Flightpath 2050, Europe's Vision for Aviation, Maintaining Global Leadership & Serving Society's Needs" on invitation by the European Commission, Directorate-General for Research and Innovation and Directorate-General for Mobility and Transport, in 2011.

Flightpath 2050 defines five top level goals as follows:

- Meeting societal & market needs
- Maintaining and extending industrial leadership
- Protecting the environment and the energy supply
- Ensuring safety and security
- Prioritising research, testing capabilities & education

Within the detailed descriptions of these goals the *capacity* and *safety* of the European air traffic system – which are both directly affected by aircraft wake turbulence aspects – are specifically addressed:

- An air traffic management system is in place that provides a range of services to handle at least 25 million flights a year of all types of vehicle [...] with 24-hour efficient operation of airports. European air space is used flexibly to facilitate reduced environmental impact from aircraft operations.
- Flights arrive within 1 minute of the planned arrival time, regardless of weather conditions.
- Overall, the European air transport system has less than one accident per ten million commercial aircraft flights.

Aircraft encounters with wake turbulence created by preceding aircraft remain a potential *safety* hazard to the air transport system. Relevant occurrences of the past, dedicated tests as well as analyses of pilot and air traffic controller reports of wake turbulence encounter events (see section 6.3 of this report) show that encounters with wake turbulence do occur regularly and can occur during all phases of flight. In its most recent annual safety review (2011) EASA does not include wake turbulence as an accident category on its own but wake turbulence is listed as a first event type for in-flight loss of control occurrences in the European Central Repository (ECR) of occurrence reports in civil aviation. In consequence, the number and probability of wake turbulence encounters – and with it the probability of accidents in which a wake encounter plays a contributing role – is expected to increase with air traffic density, hence future traffic growth, unless it is specifically controlled and mitigated. Reducing the risk of wake encounters thus directly contributes to the Flightpath 2050 goal of the European air transport system having less than one accident per ten million commercial aircraft flights despite the envisioned growth in traffic.

Mandatory wake turbulence separation requirements between departing as well as between arriving aircraft are – next to the separations required for collision avoidance in the air and on the ground – limiting the effective runway throughput *capacity*, especially at large airports. For example, the wake turbulence separation requirement according to ICAO for an Airbus A320 approaching directly behind a Boeing B747 is 5 nautical miles today, under all operational conditions. Without wake turbulence separation constraints, the same pair of aircraft could arrive at the same airport with a separation of 3 nautical miles or less. This exemplary decrease in separation distance by 40% is directly linked to the runway and hence airport capacity. Any such reduction could be used to accommodate a part of the expected increase in flights per year as well as to increase airport capacity resilience to challenging weather conditions without the need to build additional runways. New operational concepts effectively reducing wake turbulence separation requirements thus directly contribute to the Flightpath 2050 goals of accommodating 25 million flights a year of all types of vehicle, arriving within 1 minute of the planned arrival time, regardless of weather conditions.

All operational concepts presented in section 3 of this report and from which further research needs are derived address wake turbulence related safety and capacity aspects and hence directly correspond with the goals of Flightpath 2050.

3. Operational Concepts

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In recent years there has been extensive research and development on wake vortex concepts at an international level. This has been spurred by increasing airport congestion, the increasing diversity of aircraft types (e.g. the introduction of Very Light Jets and the A380 into service) and the availability of new technologies.

The concepts have been driven by researchers, operational stakeholders (airports, pilots and airlines), air navigation service providers, regulators and aircraft equipment manufacturers. The activities of the last decade have progressed from a physical understanding of the wake vortex phenomenon itself to the development of new operational concepts and rulemaking.

Many of today's active wake vortex concepts focus on changing current ATC operating procedures in order to address the capacity limitations imposed by wake turbulence separations. There are several projects that have helped to improve wake vortex detection and characterisation by remote sensing (see §5.2), as well as to better understand wake vortex physics (§5.1). In particular work has focused on the meteorological influences on wake vortex behaviour and lifetime (sections 5.1 and 5.3). This section aims to summarise a number of key active wake vortex operational concepts and projects in Europe and the USA. It will also investigate any further wake turbulence research outside the scope of these projects, according to the needs and requirements of the operational stakeholders, which should be undertaken to enable the successful implementation of these projects into the operational environment.

3.1 Crosswind Operations

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3.1.1 Overview

Crosswind operations rely on the simple effect that sufficiently strong crosswinds may transport wake vortices out of the flight corridor which may support temporary suspension of the need to apply wake turbulence separations between successive aircraft.

CROPS (CRosswind OPerationS) is a EUROCONTROL funded project focused on runway use optimisation by the conditional reduction of wake turbulence distance-based separation minima between arrivals on final approach by taking advantage of the effect of crosswind on the wake turbulence decay and transport, while maintaining an acceptable level of safety regarding possible wake vortex encounter (WVE). It is a natural follow-on of the completed R&D project CREDOS (Crosswind REduced separations for Departure OperationS). The main driver of CROPS is congestion at major airports and fixed ICAO separations (not weather dependent).

The scope of the CROPS project is currently limited to determination of crosswind conditions for a safe 0.5NM reduction of WT separations applied on final approach segment. This is done mainly by analysis of collected wake vortex and MET data. The results of this analysis form part of the key evidence in the safety assessment report.

Although the CROPS concept of operations for a specimen operational environment relies on current ATM procedures, without a priori need of developing specific new ATC tool, the necessary changes to ANS/ATM system to allow operational application of CROPS will need to be assessed at local implementation level. It depends on the local ATM system in place and its performance, in particular regarding wind nowcast and forecast information.

NATS incorporated the concept of operations for CROPs for arrivals within the scope for ‘Reduced Final Approach Separation’ (RFAS). RFAS considers both minimum headwind and crosswind component requirements for a 0.5NM separation reduction to selected wake constrained arrival pairs at Heathrow.

3.1.2 CROPS benefits

CROPS benefits arise from a temporary increase in runway throughput and/or reduction of airborne delays.

Emphasis is to be put on the fact that CROPS is not expected to add strategic capacity in terms of scheduled slots. The major benefits are to be achieved when a single segregated runway is used for arriving traffic and during peak periods or when queuing creates delays. The actual benefits are dependent mainly on local wind conditions, traffic mix (number of wake turbulence separated pairs), of the usage, orientation and layout of the runway(s) and standard arrival route structure. For example, a detailed benefit study (using HERMES model) with local traffic mix and wind conditions at London Heathrow (LHR) shows a maximum possible reduction of average arrival delay per aircraft from 5.9 min to 3.4 min (assuming a perfect forecast, and sustained wind conditions over periods studied). If 30 minutes stability of the wind was required, the procedure could have been applied in 17% of total operating hours at LHR airport (assuming required wind thresholds are based upon average wind conditions at the runway surface level only.

3.1.3 CROPS implementation

The CROPS implementation will consist of procedural changes to the ATM system. It is envisaged that, during temporary trial phase, wind threshold higher than the minimum required value will be applied, in order to gain confidence in CROPS application. Local implementers will determine the appropriate deployment strategy. Guidance for implementers shall be developed in 2012.

The CROPS project shall provide a transitional step towards SESAR IP2 related operational improvements to be addressed by the SJU project P6.8.1 in Phase 2 - Weather Dependent Separations (WDS).

To date the following stakeholders have expressed an interest (feedback received at EUROCONTROL's Airport Operations Team stakeholder meeting) to explore the possibilities of implementation: BAA, NATS and UK CAA (for London Heathrow), DSNA (for Paris Charles de Gaulle) and Schiphol airport, Amsterdam.

3.1.4 Current Status

The initial CROPS generic concept of operations was completed and presented at the EUROCONTROL Wake Vortex Task Force (WVTF) in June 2010. The benefit assessment results were presented to the WVTF in November 2010 and initial safety assessment results were presented to the WVTF in April 2011.

Under the NATS/EUROCONTROL TBS activities and now under the SESAR P6.8.1 TBS activities an intensive LIDAR data collection campaign has been carried out at London Heathrow airport since October 2008. The WV trajectories, circulation as well as wind intensities have been collected for NGE/IGE behaviour (October 2008 to December 2010) and is being collected for OGE behaviour (from January 2011 ongoing). The possibility of 0.5 NM WT separation reduction was assessed by comparing the probability of wake vortex persistence in calm wind conditions (0-5 kt – baseline) to the probabilities observed in crosswind conditions using the Heathrow NGE/IGE measurements. The computation of frequency & severity curves for different wind bands and comparison against baseline resulted in definition of required wind threshold criterion of 7-8 knots (runway surface wind conditions). The potential local application of this generic criterion was also evaluated at two European hubs, London Heathrow and Paris Charles de Gaulle. The resulting local thresholds were very similar to the generic threshold (min. 6 knots at EGLL and 7 knots at LFPG). The local application of the separation reduction is made possible by integrating the local wind distributions into the generic results. The identified wind criterion is consistent with the outcome of the CREDOS project and will provide the key technical evidence into the final CROPS safety assessment report. It shall not be applied without development of the local safety case.

Due to lack of resources, the safety work on CROPS has not progressed in the second half of 2011, but it is planned to resume in 2012 leading to delivery of:

- a preliminary safety assessment report to present the safety argument and supporting evidence, from wake and weather data collection and analysis, that the reduction of WT separation minima is acceptably safe when the weather-dependent conditions are satisfied and to provide a guidance to support development of safety assessment on local implementation by ANSPs; and
- an updated concept of operations for CROPS, according to the safety assessment results.

The NATS RFAS project has completed the 'Feasibility and Options' phase to assess concept viability and cost benefit. This phase lasted 12 months and has concluded that the concept is feasible from both a safety and operational concept perspective. However, the project will not be further pursued for implementation at Heathrow given the short duration of expected benefits when taking account of planned implementation of Time Based Separation (TBS) at Heathrow. Progress and achievements from the RFAS project are outlined below:

- A concept of operations was developed and refined based upon real-time simulation validations and controller workshops. This has provided a mature set of operational requirements (including procedures and HMI).
- A safety methodology has been proposed and internally agreed (at a high level) among NATS safety stakeholders. This provided a high level view of the safety performance requirements and evaluation criteria. Safety workshops and hazard identification workshops have taken place to refine the safety plans and identify, scope, and direct, the required activities.
- LIDAR analysis from the joint NATS and EUROCONTROL data collection campaign at Heathrow has been developed and undertaken (for near ground effect data) by both EUROCONTROL and NATS with complimentary results. This has provided early indications of the wind conditions required near-ground

to satisfy the safety requirements (from a wake encounter perspective). Data gathering from the measurement campaign out of ground effect continues.

- Wake modelling was scoped, and innovative methods designed to further aid wake encounter assessment at higher altitudes at Heathrow, and at glide-path intercept.
- Requirements for met monitoring and forecast were developed (based upon the above initial safety assessments). Collaborative work with the UK Met Office has established a feasible short-term solution to (potentially) meet the required objectives, and a plan developed to research, build, and test, the proposed system.
- A benefits model was developed and results provided estimates of the concept benefit (in terms of movement recovery and delay), under a range of weather conditions, and forecast success rates.

3.1.5 Lessons learned from CREDOS

The EU project CREDOS (Crosswind-Reduced Separations for Departure Operations) intended to demonstrate the operational feasibility of a concept of departure operations that uses measures of the prevailing crosswind component to allow temporary suspension of the need to apply wake turbulence separations between successive departing aircraft.

Monte Carlo simulations of the Frankfurt traffic mix with WakeScene (see §6.2.2.4, Holzäpfel & Kladetzke 2011) indicate that for current operations 66% of the potential encounters are restricted to heights below 300 ft above ground. Within this altitude range clearance of the flight corridor by descent and advection of the vortices is restricted: stalling or rebounding vortices may not clear the flight path vertically and weak crosswinds may be compensated by vortex-induced lateral transport. Further, minor peaks at altitudes of 1300 ft and at 1800 ft occur which can be attributed to flight path diversions (change of climb rate and heading) in combination with adverse wind conditions (headwind and crosswind) which increase the encounter risk compared to approximately parallel flight of the leader and follower aircraft.

Statistics of encounter frequencies and encounter conditions have been established for 60 s and 90 s departure separations and minimum crosswinds from 0 to 10 knots in 2 knot increments, respectively. The reduction of aircraft separations from 120 s to 60 s approximately triples the number of encounters, whereas the fraction of strong encounters increases due to the reduced time for vortex decay.

An investigation of wind direction effects on the encounter frequencies reveals an intriguing phenomenon: Headwind situations lead to the highest encounter probabilities because headwind transport of the wake vortices may compensate wake vortex descent or even lead to rising wake vortices with respect to the generator aircraft trajectory. This effect increases encounter frequencies because the medium weight class followers usually take off earlier and climb steeper than the leading aircraft and therefore usually fly above the wake vortices. In contrast, the encounter frequencies for tailwind situations are much lower because tailwinds support wake vortex descent.

Initially surprising, the beneficial effects of crosswinds are not symmetric. The smallest encounter frequencies are observed for crosswinds from the starboard side. Here the crosswinds close to the ground reduce encounter frequencies. With increasing height the wind direction turns on average to the right. Consequentially, a tailwind component is added to the crosswind which supports relative vortex descent and thus reduces encounter frequencies aloft. This turning of the wind direction with height is related to the concept of the Ekman spiral which describes the resulting wind direction in the atmospheric boundary layer by equilibrium of the driving pressure gradient force, the Coriolis force, and the friction force. Due to the same mechanism crosswinds from port side receive a headwind component with increasing height. As a consequence, the port crosswind situation leads to significantly more encounters than the starboard side crosswinds.

From a WakeScene-D perspective it can be concluded that for 60 s departure separations along the northern departure routes as used routinely at Frankfurt airport acceptable encounter frequencies are found for crosswinds below -6 knots (wind from starboard side) and for crosswind magnitudes above 8 knots. The respective assessment of the related encounter risks with VESA (Kauertz et al. 2012) leads to the same conclusions also for straight departure routes. Crosswind departure procedures could be refined by using only departure route combinations where the leading aircraft is flying on the downwind route.

Crosswind transport certainly is the most effective mechanism to clear a flight corridor from wake vortices. However, the applicability of purely crosswind based wake vortex advisory systems covering vertically extended domains is impeded by the veering wind with altitude. As a consequence, either the flight tracks of subsequent aircraft must be separated already at quite low altitudes such that the crosswind does not change significantly within the considered height ranges or the advisory system must also consider vortex descent and/or vortex decay either explicitly or implicitly as in the presented concept.

3.1.6 Research Needs

As the CROPS project provides only an interim step towards a Weather Dependent Separation (WDS) concept, the following key validation areas should be further researched under the SESAR WP6.8.1 Phase 2:

- Definition of the weather criteria (not only crosswind) allowing the reduction of wake turbulence separations (by 0.5 or 1.0 NM)
- Definition of the weather dependent reduced wake turbulence separations under different weather conditions
- Assessment of the wake vortex encounter risk associated to the reduction of wake turbulence separations under pre-identified weather conditions
- Assessment of the spatial and temporal stability of the weather conditions allowing the reduction of wake turbulence separations
- Assessment of the potential benefits for various airports considering the distribution of their wind conditions throughout the year
- Definition and assessment of the HMI and ATM component requirements and operational procedures allowing the air traffic controller to apply weather dependent wake turbulence separations
- Definition of the requirements and operational procedures allowing the flight crew to safely apply the controller proposed weather dependent wake turbulence separations
- Definition of the high level system, functional and algorithm requirements of the WDS tool support
- Assessment of the high level system, functional and algorithm requirements of the WDS tool support

3.2 Time-Based Separations

Main contributing authors:
Charles Morris, Jennifer Sykes – NATS

3.2.1 Overview

The TBS operational concept applies on final approach, from when both the lead and follower aircraft establish on the final approach localiser, until the lead aircraft crosses the runway landing threshold to touchdown.

The TBS concept proposal is to apply time based wake turbulence radar separation rules on final approach, so as to aid towards recovering the reduction in landing rate experienced when applying Distance-Based Separations (DBS) in headwind conditions on final approach. With a reference landing rate based on applying a steady 160kt IAS (165kt TAS) over the spacing to 4DME in a 5kt mean headwind:

- 15kt Mean Headwind = 6.7% time spacing impact on the landing rate
- 25kt Mean Headwind = 14.3% time spacing impact on the landing rate
- 35kt Mean Headwind = 23.1% time spacing impact on the landing rate

TBS will partially recover the reduction in achieved arrival capacity currently experienced when applying distance based wake turbulence radar separation rules in the headwind conditions experienced on final approach. The amount of recovery is dependent the impact of the surveillance and other runway operations separation and spacing constraints, and in particular the minimum radar separation of 2.5NM for spacing minimum pairs. The amount of recovery is impacted by the Heavy/Medium/Light traffic mix and the resulting percentage split of wake and spacing minimum pairs.

The final approach controller and the tower runway controller are to be provided with the necessary TBS Tool support to enable consistent and accurate delivery and monitoring to time based wake turbulence radar separation rules on final approach. An indicator is to be displayed on the extended runway centre-line of final approach of the separation or spacing required behind the lead aircraft of each arrival pair as a separation or spacing reference for the follower aircraft, Figure 2.

Figure 2: Illustration of Indicator Visualisation of the TBS behind each Lead Aircraft

The TBS rules have been derived from applying the DBS rules when flying a standard reference indicated airspeed profile over the DBS to threshold in 5kt headwind conditions.

The TBS is the distance separation equivalence of the TBS rules in the prevailing wind conditions on final approach to threshold when flying the standard reference indicated airspeed profile to threshold.

The mean headwind effect on the ground speed profile of aircraft over the spacing to threshold for the prevailing wind conditions on final approach is required to calculate the TBS distance.

The final approach controller and the tower runway controller remain responsible for applying spacing practice, for monitoring for separation infringement, and for timely intervention action.

Integral to the validation of the TBS concept is an assessment of the potential impact to the wake turbulence encounter risk. Under TBS procedures aircraft will be more closely spaced in headwind conditions greater than 5kt compared to DBS. As wake turbulence decays over time there is the potential that aircraft may encounter younger and hence stronger wake turbulence (in comparison to the distance based separation standard in equivalent conditions). This may increase the likelihood of a wake turbulence encounter occurring in these conditions. Conversely in headwind conditions less than 5kt, still wind and tailwind TBS will result in more distance spacing compared to DBS which may reduce the likelihood of a wake turbulence encounter in these conditions.

As there are currently no guidelines for what wake turbulence strength is ‘acceptable’ to encounter, it is not envisaged that an absolute risk assessment for TBS will be possible. It is proposed that a comparative assessment will be carried out based on the assumption that the current risk associated with DBS operations in light wind, still wind and tailwind conditions is acceptably safe.

In order to investigate and quantify wake turbulence behaviour on short final, a *WindTracer* LiDAR was installed at London Heathrow in September 2008 to measure the wake vortices generated by aircraft arriving on Runways 27L and 27R. Measurements were taken at a location that intersects the approach path at approximately 280ft aloft until December 2010, and since measurements have been targeted at a location intersecting the approach path at approximately 1,200ft aloft.

3.2.2 Current Status

There are two project streams in TBS, a procedural TBS project, and the full TBS project.

The procedural TBS project is a transitional step involving a specific reduction of the ICAO Distance Based Separation when the headwind exceeds a specific threshold has been identified. This could result in a 0.5 NM reduction of the required wake turbulence separation minima between aircraft pairs on final approach. This step could be applied without the need for development of any controller support tools and hopes to have an implementation of this transitional step within an 18 month timeframe.

The full TBS project is currently in the SESAR stages of development and validation as a release 2 concept with a target date of V3 maturity in Q1 2013.

3.2.2.1 Procedural TBS Project

The concept of operations for Procedural TBS has been developed by EUROCONTROL.

The concept of operations for local deployment at Heathrow has been developed by NATS. This is under the Reduced Final Approach Separation (RFAS) project for Heathrow.

A safety assessment is under development for the intermediate step and the safety case will follow. NATS and EUROCONTROL have been investigating the concept feasibility and requirements (including safety requirements and arguments).

3.2.2.2 SESAR P6.8.1 Flexible and Dynamic Use of Wake Vortex Separations

The project partners are EUROCONTROL (lead), NATS, Thales, Airbus and ONERA (for DSNA).

TBS is the first phase of SESAR P6.8.1 from 2010 to 2012.

An OCD & OSED for TBS has been developed taking into account the concept development and validation results from the EUROCONTROL, NATS and RESET projects from 2003 to 2010 and through further Heathrow User Group Workshops in 2010 and 2011. References to the earlier projects are listed in the OCD & OSED.

A Validation Strategy and Plan has been developed taking into account the validation strategy and plans from the EUROCONTROL and NATS projects.

An initial draft SPR has been developed and issued.

The planned validation activities for 2012 for contributing to V3 maturity are:

- Heathrow Approach Simulation – February/March 2012
- Heathrow 360° Tower Simulation – July 2012
- Heathrow OGE LIDAR Wake Measurement Campaign – to December 2012

- Wake Turbulence Safety Analysis
  - Final NGE/IGE – 2012
  - Final OGE – 2012/2013
- Transversal Assessments – 2012
  - Safety
  - Human Performance
  - Business benefit
  - Environment
  - Security

3.2.2.3 Capacity Analysis

Methodology of capacity analysis and results

Real-time simulations have been carried out at the EUROCONTROL Experimental Centre that evaluated the impact of headwind strength and heavy aircraft type. The results of this study demonstrated benefits for the TBS concept but further studies including a comparison to the current DBS and realistic wind scenarios that include 4D-changes of the wind characteristics along the glide path were recommended.

In the scope of the RESET project (http://reset.aena.es) the TBS concept was also investigated and tested in a real-time simulation with human-in-the-loop (HIL) at the LFV NARSIM site in Malmö. The controllers used a spacing tool that supported TBS operations. The results indicated an improved throughput when using TBS compared to DBS, but it could not be clearly distinguished between contribution of the TBS procedure and the spacing tool.

An efficiency study was also conducted that used the HIL simulation results for calculation of potential benefits (as they were considered more accurate than fast-time simulation results that were also conducted during the project). Among other criteria, the efficiency study assessed the amount of recuperated capacity and delay avoidance. It was found that TBS increased throughput 14% under medium and 40% under strong headwind conditions compared to DBS (this amount can vary with controller ability). TBS could be shown to recuperate between 88% and 95% of the delay attributed to medium to strong headwinds. Figure 3 illustrates the potential benefit.

Both the real-time simulation and the efficiency study recommended that the capacity assessment to be conducted e.g. in SESAR P6.8.1 should use a larger set of data from multiple simulations.

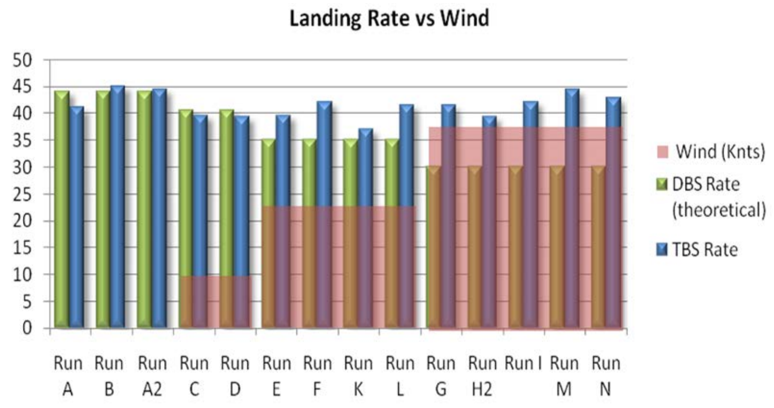

Figure 3: TBS runway throughput compared to DBS theoretical rate.

3.2.3 Research Needs

Emphasis is on establishing wake turbulence encounter safety arguments that will satisfy the concerns of all stakeholders; the concerns of the ANSP internal stakeholders including system safety, division of safety, approach operations, Tower runway operations, approach controllers and runway controllers; the concerns of pilots and pilot associations as they are in the ‘front line’ of wake turbulence encounters and their consequences; and the concerns of controller associations, airline operators, airport operators, and safety regulators.

3.2.3.1 Assessment methods for WVE Risk

Further research and verification is required to establish agreed methods for anticipating and/or measuring the acceptability of encounters. As there are currently no guidelines for what wake vortex strength is ‘acceptable’ to encounter, absolute risk assessments are not feasible. Current assessment methods focus upon relative comparisons of wake strength at the calculated separation time. Modern research methods are moving toward metrics that consider the encountering aircrafts roll inertia and wake induced roll acceleration. Updated global guidance is required to establish acceptable metrics and methods for the evaluation of WVE risk to enable the assessment of emerging concepts for operational deployment.

The role of WV behaviour models towards providing safety evidence in support of safety arguments remains an important issue. The challenges associated with the validation of models such that the analysis results can be considered reliable enough to be used as safety evidence remains a research needs challenge. WV behaviour models have the potential to considerably reduce the need for WV behaviour data collection campaigns.

3.2.3.2 Provision of the Glideslope Wind Conditions Aloft Profile

There is a need to establish cost effective approaches for the provision of the current and forecast glideslope wind conditions aloft profile to the TBS tool.

The utilization of the previous aircraft flying the approach path as meteorological sensors for the current wind conditions on final approach should be fully explored. This includes the utilization of the current enhanced Mode-S down-linked parameters. There is a need to establish whether these down-linked parameters are sufficiently dependable for utilization by the safety related function for calculating the TBS distance for the Indicators used as the wake turbulence separation reference by the approach controllers.

There is a need to establish a dependable source of a current and forecast wind conditions aloft profile to the TBS tool utilizing a combination of the wind conditions derived from down linked airborne parameters, the wind conditions measurements from ground based wind profilers, and the wind conditions from local weather nowcast and forecast services.

3.2.3.3 Meteorological Data Measurement and Understanding

The availability of meteorological information in support of WV concepts is very important. Meteorological data measurements are required for correlation with WV behaviour measurements. Meteorological climatology information is required to support business case analysis activities and to identify and establish the range of meteorological scenarios that each of the WV concepts needs to be subjected to in the validation activities.

Meteorological analysis studies are required to be conducted into wind profiles in support of TBS. There is a need to increase the concept development understanding of the impact of wind shear and other effects (such as low level topological effects such as buildings) that could undermine the continuity of the wind profile. There is a need to increase the concept development understanding of how quickly wind conditions can change in changeable wind conditions.

3.3 Closely-Spaced Parallel Runways Procedures

Main contributing authors:
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3.3.1 Overview

Closely-spaced parallel runways (CSPRs) pose a specific challenge in terms of wake vortex safety and therefore airports with a CSPR layout often suffer from significant capacity constraints when operated under instrument meteorological conditions (IMC). Airports with parallel runway centerlines spaced closer than 2500 ft are not capable of supporting simultaneous, parallel instrument approaches under IMC. Increased air traffic delays occur when weather conditions will not permit simultaneous visual approaches. In order to alleviate the capacity limitations while at the same time keeping or even improving the level of safety, several dedicated procedures have been designed for CSPRs. There are procedures for the arrival and landing as well as for the take-off and departure phases of flight.

Major enabling technologies for the CSPR procedures listed and described below are precision aircraft surveillance aids as well as airborne navigation aids (RNAV, GPS). For some of the procedures prospected for the mid- to long-term, also wind and wake vortex monitoring sensor technology and forecasting functions are of importance.

3.3.2 Current Status

Several projects and initiatives have been concentrating on the development of CSPR procedures during the last decades and there has been a progress towards operational implementation in the recent years. Current projects are working on the development of advanced procedures increasing capacity benefits and improving availability and applicability of CSPR procedures.

Several concepts have been developed in the scope of the projects listed below. There is a certain overlap between European dynamic separations concepts described in §3.4 that have also been developed for CSPRs and the concepts developed in the USA.

Current projects:

- Crosswind Operations (CROPS), see §3.1
- Flexible and Dynamic Use of Wake Vortex Separations, SESAR WP 6.8.1, see §3.4
- FAA order 8260.49A: Simultaneous Offset Instrument Approaches (SOIA)
- FAA order 7110.308: 1.5-Nautical Mile Dependent Approaches to Parallel Runways Spaced Less Than 2,500 Feet Apart
- Wake Turbulence Mitigation for Arrivals (WTMA) - Procedure (P) and –System (S)
- Wake Turbulence Mitigation for Departures (WTMD)
- Wake Vortex Prediction and Monitoring System (WSVBS), in the scope of DLR projects “Wirbelschleppe” and “Weather and Flying”, see §4.1.2.2.

Past projects:

- High Approach Landing System/ Dual Threshold Operation (HALS/DTOP)
- ATC-Wake
- Crosswind-Reduced Separations for Departure Operations (CREDOS)
- Wake Independent Departure Operations (WIDAO)
- Wake Vortex Warning System by DFS (Wirbelschleppen-Warnsystem, WSWS)

3.3.2.1 FAA order 8260.49A: Simultaneous Offset Instrument Approaches (SOIA)

The FAA has authorized special procedures to address the capacity problem occurring on closely-spaced parallel runways during instrument meteorological conditions (IMC). Two of them will be presented here as they are already being applied and have shown a significant capacity impact.

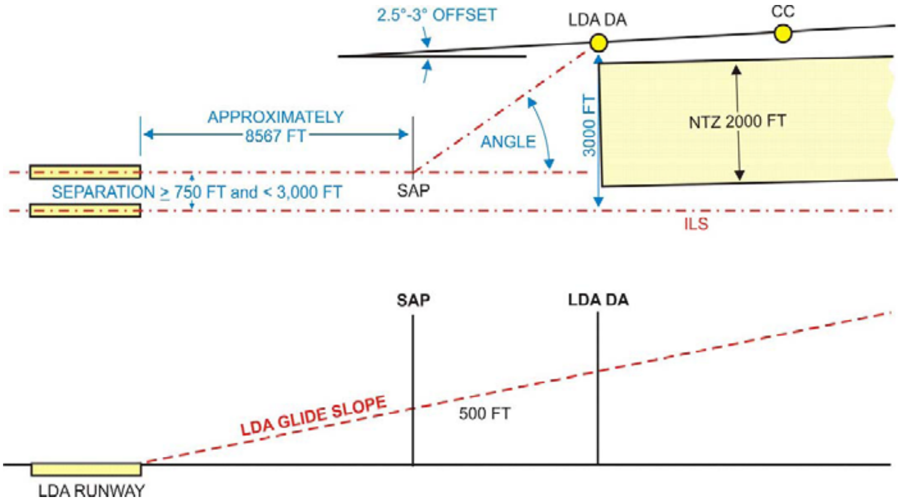


Figure 4: SOIA geometry [FAA order 8260.49A]

The SOIA procedure enables simultaneous approaches to parallel runways utilising a straight-in ILS approach to one runway, and a localizer-type directional aid (LDA) with a glide slope instrument approach to the other runway, as shown in Figure 4. This procedure has been operational at San Francisco International Airport (SFO) since 2005. An arrival rate of up to 38 aircraft per hour can be achieved when SOIA is in use, compared to otherwise 30 aircraft per hour in the same degraded visual conditions but without SOIA, see (RASP 2007). The resulting recovered capacity of *about 27%* is regarded as *tactical* and is used to reduce delays in unfavourable conditions.

3.3.2.2 FAA order 7110.308: 1.5-Nautical Mile Dependent Approaches to Parallel Runways Spaced Less Than 2,500 Feet Apart

A new wake turbulence procedure has been approved (end of 2008) for use at several airports that allow arrivals to reduce separation between aircraft on parallel approaches in weather below visual approach minima using a parallel dependent staggered arrival operation. This procedure, documented in JO 7110.308, allows aircraft to arrive in staggered pairs, with Large and Small wake category aircraft in the lead. The diagonal separation between the leading aircraft on the one runway and the trailing aircraft on the other can be reduced to 1.5 nautical miles. With this procedure, approximately half of the capacity normally lost due to deteriorating weather can be regained. Several airports have been authorised to use the procedure (e.g. in Boston, Cleveland, St Louis, Seattle etc.).

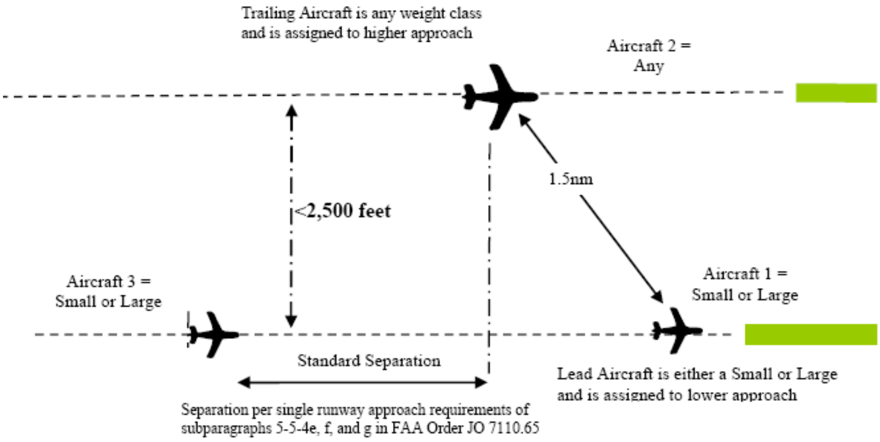


Figure 5: Dependent Staggered Approach Procedure [FAA order JO 7110.308]

3.3.2.3 Wake Turbulence Mitigation for Arrivals (WTMA)

Additional arrival procedures for CSPRs are being explored by the FAA, such as Wake Turbulence Mitigation for Arrivals (WTMA) that will allow additional gains in capacity. WTMA extends the concept of 1.5 NM dependent approaches described above by providing separation reduction for dependent staggered approaches when Heavy or B757 aircraft are in the lead and any aircraft type is trailing on the parallel approach. Currently, two categories of wake turbulence mitigation operations are investigated: those, in which procedural separation can be applied, referred to as WTMA-Procedure (WTMA-P), and operations which require an active crosswind forecast system, referred to as WTMA-System (WTMA-S), see [Audenaerd, L. et al., 2009].

The main objectives of the projected procedure changes are:

- to provide improved runway use in IMC and resulting from this increased arrival capacity
- to benefit from reduced separation minima based on current or forecast crosswind conditions
- to preserve or rather improve the current safety level with regard to wake vortex safety on arrival

The operational implementation of WTMA will also depend on the functionality of the currently deployed Automated Traffic Proximity Alert (ATPA) system that will monitor separation between aircraft on the final approach. This system is being developed in three phases; phase two will be able to monitor diagonal separations, whereas phase three will be able to switch diagonal separations subject to crosswind conditions.

Methodology of capacity analysis and results

The MITRE Corporation's Center for Advanced Aviation System Development (CAASD) has been supporting the Federal Aviation Administration (FAA) Wake Turbulence Office to evaluate the feasibility and capacity benefit of the wake turbulence mitigation operations described above.

The methodology used to determine the capacity increases for each procedure is a CAASD-developed modelling tool, *runwaySimulator*. Using this tool, the capacity of the Boston airport was modelled in depth to determine the effects of the various arrival concepts. This allowed comparing achievable capacities with current rules, with JO 7110.308, WTMA – P (Wind Independent) and WTMA – S (Wind Dependent). Table 1 summarises the results dependent on the expected fleet mix.

	7110.308 Rule	WTMA-P	WTMA-S
B757 Mix	62.1%	78.4%	79.3%
Heavy Mix	59.7%	80.5%	86.4%
Regular Mix	76.3%	84.3%	87.1%

Table 1: Simulated percentage increase of WTMA concepts over current rules (Audenaerd, L. et al., 2009)

3.3.2.4 Wake Turbulence Mitigation for Departures (WTMD)

The WTMD project, funded and conducted by the FAA, focuses on increasing departure rates at airports with CSPRs. The concept has parallels to the CROPS concept as well as to SESAR WP6.8.1 phase 2 operations (see sections 3.1 and 3.4 respectively). When wind conditions are favourable, WTMD allows independent departures on CSPRs after Heavy aircraft or B757 take-offs from the adjacent downwind runway. The project has two phases:

- Phase 1: three robust stand-alone prototype systems developed that will be used operationally at IAH (George Bush Intercontinental Airport, Houston), SFO (San Francisco) and MEM (Memphis). Collection of benefit and usability data.
- Phase 2: if evaluations of operational prototypes show benefit, system will be implemented at remaining airports requesting WTMD capability

It is envisioned that phase 1 of WTMD becomes operational in early 2012, starting at IAH. Supporting technologies for WTMD are surface wind sensors (LIDARs preferably) but also real-time downlinks of winds from the aircraft, which will probably become available in several years. It is also important for the safety of the procedure that aircraft dispersion is reduced which will be achieved by using RNAV(GPS) departures.

3.3.3 Research Needs

Due to the similarities and overlaps between the CSPR procedures and the crosswind concepts as well as dynamic separation operations discussed in the sections 3.1 and 3.4 also many of the research needs overlap. This concerns the needs for safety assessment and risk analysis issues as well as the needs for weather information. Needs more specific for CSPR procedures are listed below.

3.3.3.1 Information on enabling weather conditions

As many CSPR procedures focus on reducing wake vortex separation minima based on favourable wind conditions (so-called conditional reduction of separation minima) there is a strong need to have an appropriate knowledge of the present and even more of the future meteorological conditions within the planning horizon of the procedure. Further activities in this area should take into account the following research needs:

- A stable and reliable prediction of the weather and in particular of the wind conditions is important which should be adapted to the needs of the ATC system (concerning time horizons, stability, lead time for procedure change etc). It should also comprise all relevant parameters needed by the supporting systems (a requirement similar for the ground based wake vortex advisory systems addressed in §4.1)
- Weather data acquired by airborne measurements should complement the ground based meteorological measurements and model based prediction thus increasing the confidence level and covering the area along the glide path. For this purpose, investigation of which airborne measurements can be provided and how they can best be integrated into the existing weather network is needed.

3.3.3.2 Controller support tools

To enable successful implementation of adapted CSPR procedures it is important to provide the controller with a supporting function containing the elements of planning, procedure selecting and monitoring. The thorough definition of the ATC interface can be crucial for stakeholder acceptance and success of the procedure. Following issues are of high interest and should be addressed by future research:

- The level of automation of the procedure and procedure changing modes should be evaluated concerning to what is required and acceptable. Following questions should be addressed: How can controller workload be reduced while using CSPR procedures? What is the influence of an increased automation on the situational awareness?
- The monitoring function which is an important element of the safety system should be designed so as to be supportive to the controller. Investigations on what should be monitored (separations, wind, procedure mode forecast, etc) and how it should be best presented to the controller would add to the common understanding.

3.4 Dynamic Separations

Main contributing authors:
Charles Morris - NATS

3.4.1 Overview

Current departure and arrival wake turbulence separations are considered at times to be over-conservative since they are fixed regardless of the prevailing meteorological conditions and therefore irrespective of the transport and decay of the wake turbulence. The term “dynamic separations” refers to concepts that adapt aircraft separations depending on the actual lead and follower aircraft characteristics, and depending on the prevailing meteorological conditions and the resulting wake vortex behaviour.

The objectives are to develop solutions to:

- Permanently provide arrival capacity resilience to challenging wind conditions such as headwinds.
- Conditionally provide arrival and departure throughput increases in favourable prevailing meteorological conditions to more efficiently handle peaks and queues in arrival and departure demand.
- Permanently provide arrival and departure capacity increases across all conditions for both more contingency provision for non nominal conditions and more provision for capacity declaration across all conditions.

The proposed merged and final concept and system shall allow controllers to sequence arriving or departing aircraft using time based weather dependant pair wise separations consisting of the three following main concept elements:

- Time based separation will ensure a more consistent runway throughput independent of (in particular) headwind conditions on the day of operations.
- Weather dependent application of wake turbulence separation will increase runway throughput in favourable weather conditions and introduce dynamic separation concepts.
- A definition of wake turbulence separations per pair of aircraft type will increase runway capacity. This will be achieved by taking into account the potential wake vortex encounter (WVE) severity as a function of the leading aircraft’s wake generation and the following aircraft wake response characteristics and by employing more efficient separation resolutions than the current 1NM and 1 minute resolutions of today. Relevant aircraft characteristics to be taken into account will be static or dynamic.

These elements will progressively be developed and integrated in the concept and system along the three proposed phases.

These concepts will address the final approach phase for arrivals including the transition from standard intermediate approach radar separations to final approach separations and the transition from final approach separations to standard missed approach radar separations. These concepts will address the take-off and initial climb phase for departures up to the transition to standard departure radar separations. Various runway layouts (single runway, CSPR…) will be considered in order to contribute to medium-term solutions to runway capacity and resilience issues of the many major and medium-sized European airports.

In order to consider wake turbulence separation, it is necessary to have sufficient available data for safety analysis that support the concepts.

The spacing delivery aspects will be considered so as to enable these wake turbulence separation concepts to be deployed efficiently within the operationally observed diversity of aircraft speeds employed for both arrivals on final approach, and for departures on the take-off and initial climb phase of flight. The user and high level system requirements for controller tool provision will be considered across both wake pairs and spacing minimum pairs so as to address the consistency issues across all pairs from the human factors perspectives of the impacted controller roles.

3.4.2 Current Status

Procedural crosswind reduction of arrival and departure wake turbulence separation are currently being addressed by EUROCONTROL in the CROPS project.

The RECAT project is revising the wake turbulence categories and associated wake turbulence separation requirements, also see §3.5. This is being progressed by an ICAO working group. The RECAT project has plans to address the dynamic aspects of wake turbulence separation in subsequent phases.

Dynamic separation concepts are to be addressed in SESAR in 2013-14 for weather dependent separation and 2015-2016 for pair-wise separation.

For pair-wise separation a new method is being developed to assess the potential severity of a wake vortex encounter according to the leading and following aircraft characteristics respectively (the list is not exhaustive):

- Weight, wing span, wing loading, air speed for characterising the wake generated by a leader aircraft; and
- Weight, moment of inertia, wing geometry, air speed, wake encounter avoidance or alleviation systems, wake encounter geometry, and the flight control system characteristics for characterising the follower aircraft’s resistance to a wake encounter.

Using this method, a pair wise optimisation of the arriving and departure wake turbulence separations will be first defined and then validated as safe for each aircraft pair. In a first step this will only take into account static aircraft characteristics, like geometric data or typical speeds and weights, and can therefore also be termed "Static Pair Wise Separations". It is likely that certain aircraft groups will be defined.

Further improvement is possible by capturing dynamic information like actual weight, air speed etc., which requires corresponding in-flight data. This potentially allows greater benefits and could be termed "Dynamic Pair Wise Separations". One potential enabler for this solution will be the data link to support the leading and following aircraft broadcast to the ground of their respective relevant characteristics as described above.

Aircraft system support for the alleviation and avoidance of wake turbulence encounters are being addressed in SESAR and are to be taken into account by the dynamic pair-wise separation concepts.

3.4.2.1 SESAR project 6.8.1 Flexible and Dynamic Use of Wake Vortex Separations

The project partners are EUROCONTROL (lead), NATS, Thales, Airbus and ONERA (for DSNA).

Weather dependent separation is the second phase of SESAR P6.8.1 from 2013 to 2014.

Pair-wise separation is third phase of SESAR P6.8.1 from 2015 to 2016.

The planned activities for weather dependent separation (WDS) in 2013 to 2014 to contribute to V3 maturity are:

- OCD & OSED for WDS
- Validation Strategy and Plan for WDS
- Safety and Performance Requirements (SPR) for WDS
- Approach Simulation for Arrivals
- Tower Simulation for Departures
- LIDAR Measurement Campaign
- Wake Turbulence Safety Analysis
    - Arrivals crosswind transport analysis
    - Departures crosswind transport analysis

- Transversal Assessments
    - Safety
    - Human Performance
    - Business Benefit
    - Environment
    - Security

The planned activities for pair-wise separation (PWS) in 2015 to 2016 to contribute to V2 maturity are:

- OCD & OSED for PWS
- Validation Strategy and Plan for PWS
- Safety and Performance Requirements (SPR) for PWS
- Approach Simulation for Arrivals
- Tower Simulation for Departures
- Wake Turbulence Safety Analysis
    - Arrivals
    - Departures
- Transversal Assessments
    - Safety
    - Human Performance
    - Business Benefit
    - Environment
    - Security

3.4.3 Research Needs

Emphasis is now being placed on establishing wake vortex encounter safety arguments that will satisfy the concerns of all stakeholders, with particular emphasis on the concerns of pilots and pilot associations given that they are in the ‘front line’ of wake vortex encounters and their consequences, and also airline operators, controllers, controller associations, ANSPs, airport operators, and safety regulators.

3.4.3.1 Understanding of wake behaviour in different regions and conditions

There is still only a limited amount of wake turbulence behaviour measurement data being collected through measurement campaigns. This is a concern as this is holding back the WV behaviour analysis activities that need to be conducted to generate the understanding and the evidence to satisfy the WVE safety concerns and to support the WVE safety arguments. Consideration should be given to how to cost- effectively carry out continuous and simultaneous data collections over several key sample positions on aircraft paths to be protected such as on the final approach path from turning on to join the localiser until touchdown, and on the initial departure path from take-off rotation until the departure aircraft diverge on to standard lateral or vertical separations. Data collections are required in a variety of atmospheric conditions and aircraft configurations to better understand the combined impacts of wind strength and direction and atmospheric turbulence with other meteorological conditions e.g. stratification.

The WV behaviour analysis and WVE safety analysis activities are very involved and labour intensive and so it takes a long elapsed time before analysis results become available. There is a need for a more automated and systematic process founded on standard data formats for the wake turbulence measurement data, the correlated aircraft data, and the correlated meteorological data. Automated methods need to be developed for data cleaning which automatically generate an auditable file to support the safety arguments and safety evidence requirements. Automatic methods need to be developed to carry out the safety analysis and generate the safety analysis results. Safety metrics need to be developed against which to assess the safety analysis results. It will be of particular importance to the in-service monitoring that new WV separation procedures continue to be safe through quarterly and annual safety trend monitoring.

3.4.3.2 Assessment methods for WVE risk

Further research and verification is required to establish agreed methods for anticipating and/or measuring the acceptability of encounters. As there are currently no guidelines for what wake vortex strength is ‘acceptable’ to encounter, absolute risk assessments are not feasible. Current assessment methods focus upon relative comparisons of wake strength at the calculated separation time. Modern research methods are moving toward metrics that consider the encountering aircrafts roll inertia and wake induced roll acceleration. Updated global guidance is required to establish acceptable metrics and methods for the evaluation of WVE risk to enable the assessment of emerging concepts for operational deployment.

The role of WV behaviour models towards providing safety evidence in support of safety arguments remains an important issue. The challenges associated with the validation of models such that the analysis results can be considered reliable enough to be used as safety evidence remains a research needs challenge. WV behaviour models have the potential to considerably reduce the need for WV behaviour data collection campaigns.

3.4.3.3 Improved monitoring of WVE

In support of Wake Vortex Encounter safety monitoring there is a need to supplement the current subjective WVE reporting of pilots with more systematic approach for monitoring for WVEs. There is a need to develop on-board automatic recording WVE events in such a way that they can be systematically processed after every flight and collected into a global WVE database to support future global WVE safety monitoring and WVE safety analysis activities.

3.5 Re-Categorization

Main contributing authors:
Robert Luckner – TU Berlin

3.5.1 Overview

The objective of the international project Re-Categorization (RECAT) is to harmonize wake turbulence separation standards for existing and new aircraft and to safely increase capacity. ICAO tasked the FAA and EUROCONTROL to lead this effort. RECAT consists of three phases, Figure 6:

- Phase I: Optimised Categories (2011): The objective is to categorize the current aircraft fleet into 6 categories taking into account the existing traffic mix of both U.S. and European airports.
- Phase II: Static pair-wise separation (planned for delivery to ICAO in late 2014): The objective is an optimized airport-specific static pair-wise spacing that is valid for all atmospheric conditions. It will take into account airport-specific fleet mixes and provide further capacity increases by optimizing each airport for the aircraft that constitute the local arrival and departure demand.
- Phase III: Dynamic pair-wise separation (2020). This phase will provide dynamic pair-wise spacing supported by Trajectory Based Operations. Pair-wise spacing will vary with atmospheric conditions and aircraft performance.

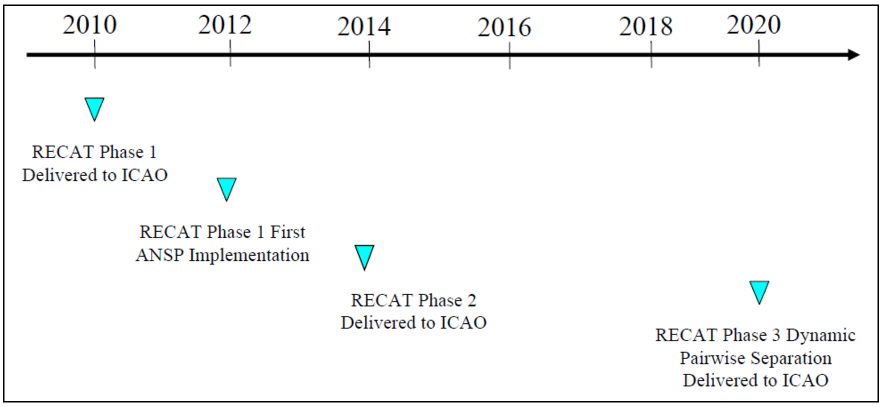


Figure 6: Time schedule for RECAT, from (Delisi and Lang 2011)

3.5.2 Current Status

3.5.2.1 RECAT Phase I

In 2011, EUROCONTROL and FAA published the following (non-public) documents for RECAT Phase I:

- RECAT Preliminary Safety Case, see (RECAT 2010a);
- RECAT Safety Assessment report, see (RECAT 2010b);
- RECAT Methodology report, see (RECAT 2010c);
- RECAT report extending RECAT to all ICAO aircraft types, see (RECAT 2010d) and
- RECAT report on Wake Turbulence incidents, see (RECAT 2010e).

The documents have been reviewed by stakeholders in the ICAO Wake Turbulence Study Group. The original objective of presenting the results to the ICAO Air Navigation Commission for acceptance in 2012 has been postponed.

For the US, FAA intends to introduce all solutions that are developed in RECAT into NextGen. Other ANSPs have shown interest to apply RECAT Phase I as well. EUROCONTROL is studying an amendment, called "RECAT B" that addresses also a potential reduction of separation for Category D aircraft as followers. The study shows a higher potential capacity benefit for the European airports of Paris, London and Frankfurt (approximately 3% more slots compared to 1.5%), see (Treve 2012).

The methodology that has been developed for definition of separation standards in RECAT Phase I is described in (Lang et al. 2009, Lang et al. 2010, and RECAT 2010c). Figure 7 shows the methodology and the underlying models in a block diagram. The methodology takes into account wake decay models derived from joint US and EU measurements. Aircraft characteristics that are relevant for re-categorization have been retrieved from public sources and stored in a database. These characteristics include physical characteristics, such as Maximum Take-Off Weight (MTOW) and wingspan, as well as aircraft performance characteristics, such as approach speed. ICAO separation distances are converted into separation times assuming standard approach speed profiles. Then, the evolution of vortex strength (circulation) over time is computed using a linear decay function that has been identified from wake vortex measurements at US and European airports.

For each aircraft pair, aircraft characteristics and the derived wake decay function are combined to determine the maximum wake vortex strength and rolling moment coefficient that can be encountered under ICAO separation standards. The primary severity metric is the maximum vortex strength. Additionally, the induced rolling moment coefficient is used to justify separation reductions for follower aircraft that are at the top end of the ICAO HEAVY category.

The methodology is applied to 61 aircraft that represent 85% of the traffic of the busiest EU and US airports.

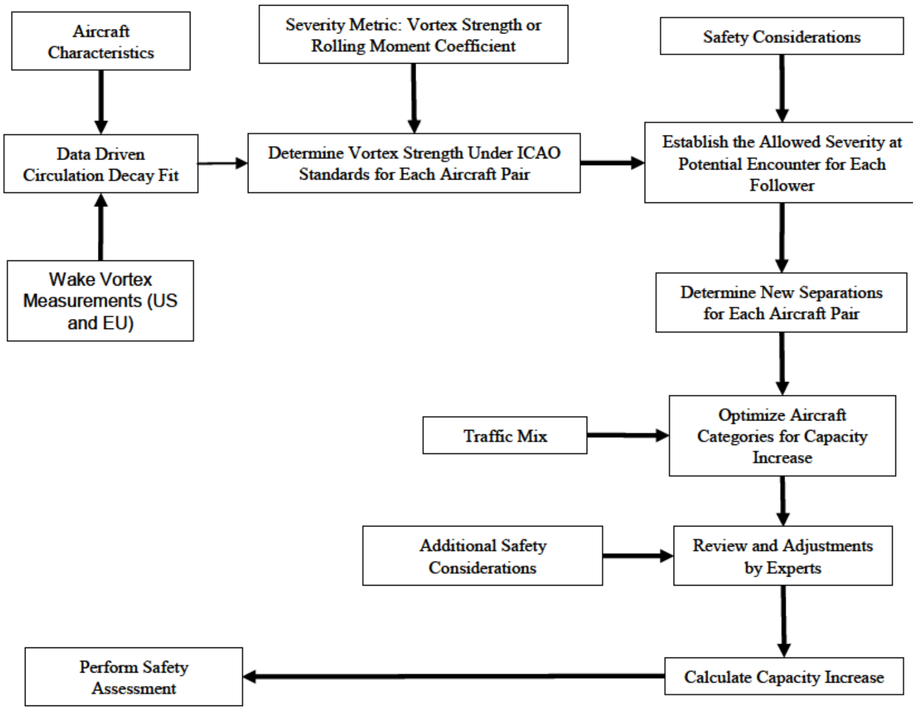


Figure 7: Flow chart showing the methodology used in RECAT Phase I, from (Lang et al. 2010).

Using this approach, an optimization was performed for 6 aircraft categories yielding the maximum capacity increase for both the U.S. and European peak traffic mixes, see Figure 8 and Figure 9. The 6 x 6 separation matrix that is larger than the current 4 x 4 ICAO separation matrix seems to be manageable for air traffic controllers.

A requirement of all RECAT phases is that the methodology has to be open, transparent and validated. Furthermore guidance on its application needs to be available so that ANSPs can use the method to assess the operational performance of RECAT for their airspace, and to study the effect of local procedures and new concepts. The future RECAT Phases, especially Phase III, may require and could benefit from more sophisticated methodologies.

		Follower					
		A	B	C	D	E	F
Leader	A		5.0NM	6.0NM	7.0NM	7.0NM	8.0NM
	B		3.0NM	4.0NM	5.0NM	5.0NM	7.0NM
	C				3.5NM	3.5NM	6.0NM
	D						5.0NM
	E						4.0NM
	F						

Figure 8: RECAT Phase I Separation Table, from (Delisi and Lang 2011).

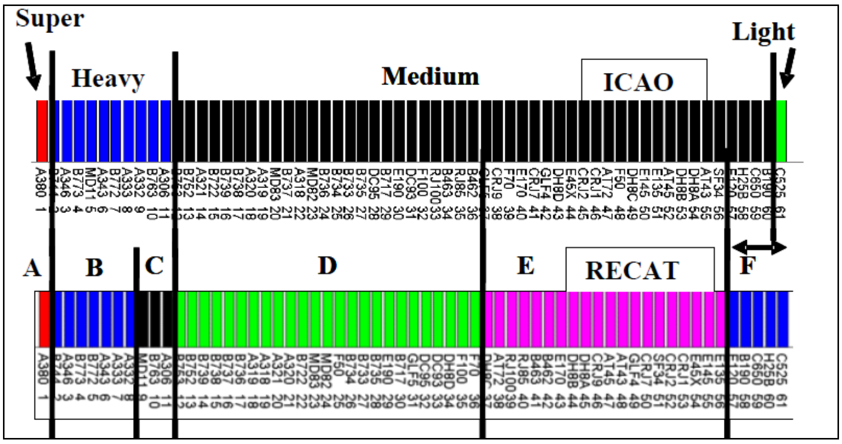


Figure 9: Comparison of: RECAT and ICAO Categories, from (Delisi and Lang 2011).

It is essential to note that both the current ICAO and the RECAT categorization systems can coexist and that each ANSP can decide whether, when and how to implement the RECAT system depending on the individual benefits. RECAT provides a global solution to reduce wake turbulence separation minima, but local implementations may differ among airports.

Furthermore, ICAO will not define the implementation of the systems if the proposal is accepted. For example, if an airport has more vortex encounters at the glideslope/localizer intercept due to a local procedure (e.g. MEDIUM aircraft turning on lower behind a HEAVY aircraft) then the local ANSP has to determine whether the procedure is acceptable or whether it should be changed.

3.5.2.2 RECAT Phase II: Leader/Follower Static Pair-Wise Separation

The tentative schedule for RECAT Phase II includes delivery of the recommendations to ICAO by late 2014 and first implementations in 2015, see Figure 6. FAA and EUROCONTROL intend to use the same methodology for RECAT Phase II as for Phase I. The goal is to implement static pair-wise separation minima that are independent of fleet mix. In contrast to the 6 category system of RECAT Phase I, the RECAT Phase II system can be optimized specifically to any individual airport in order to achieve further capacity gains. The methodology for Phase II shall use metrics and methods from Phase I, possibly refined and enhanced to include manufacturer provided aircraft performance data and recommendations from stakeholder. Separations for all potential aircraft pairs (not only 61) will be defined. Assuming approximately 1200 x 1200 potential aircraft pairings, 25 aircraft types may represent 99% of an airport's traffic mix. So a 25 x 25 matrix would be sufficient in that case.

As RECAT Phase I, RECAT Phase II can co-exist with the current ICAO rules. RECAT Phase II will provide available data for the ANSPs to decide about implementation of the system and will not define specifics of the implementation. Each ANSP is free when and how to implement it.

3.5.2.3 RECAT Phase III: Dynamic Pair-Wise Separation

The overall objective of RECAT Phase III is dynamic pair-wise separation. A detailed project schedule or methodology does not exist yet. However, some elements of RECAT Phase III are already underway, such as CREDOS, Heathrow TBS, WTMA-S. At later stages RECAT Phase III will include wind dependent and vortex decay driven solutions for which ground-based and airborne weather sensors and wake monitoring systems are needed. There are also plans to apply RECAT Phase III to en-route operations.

3.5.3 Research Needs

The effort in rule making for wake vortex separation standards offers capacity benefits while assuring or exceeding current safety levels. This progress can significantly be supported by continuing the international networking and cooperation between industry, airlines, airports, aircraft manufacturers, suppliers, air navigation service providers, authorities, pilot associations and research. The international network of experts from regulators, ANSPs, stakeholders and research that is sponsored by WakeNet3 Europe, WakeNet USA and WakeNet Global has in important role in distributing the required knowledge. A continuation of the European Wake Vortex Network when this network WN3E ends in June 2012 is strongly recommended.

ATM programmes like SESAR (EU) and NextGen (USA) are contenders to provide the required resources. A harmonized concept and roadmap that links NextGen and SESAR is needed to achieve a standard safety methodology as intended by RECAT.

Requirements on models, methodologies and data for RECAT Phase II and III need to be formulated in order to guarantee that models and methodologies, which are fit for purpose, are available when needed. Some requirements are listed in §5.5.3. As such research has a long lead time, three years or even more may be passing before applicable results are generated. Therefore it is essential to start the research and innovation process in time.

3.5.3.1 Definition of an operational concept for a dynamic wake vortex separation system

A dynamic wake vortex separation system shall provide information to avoid significant wake encounters in a fashion that changes depending on weather and operational factors. This requires research, innovation and standardisation activities that must be addressed by system developers, users, and regulators in the following areas:

- Operational concepts,
- System concepts (sensors, airborne and ground components etc.),
- Ground-based systems (wake vortex and meteorological sensors etc),
- Airborne systems (wake vortex sensor, crew interface.

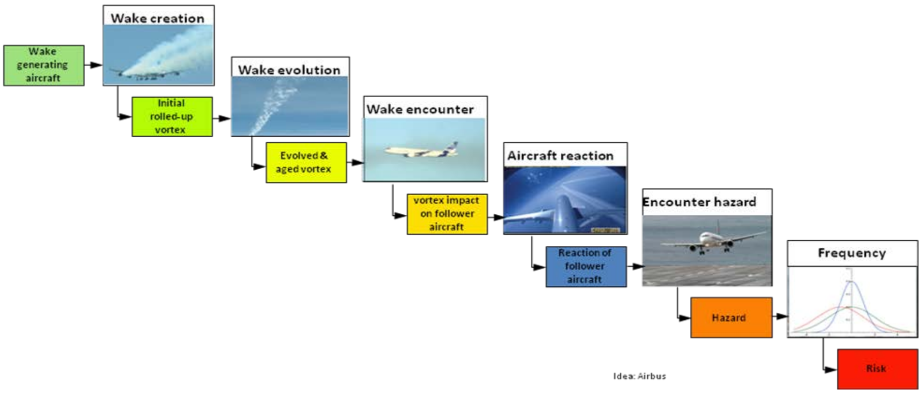
A key component of future concepts is the acquisition of meteorological data. Improved standardisation of the capabilities of meteorological sensors (methodology, quantities, resolution, accuracy etc.) is needed.

3.5.3.2 Validation of large and complex encounter models for risk assessment

The methodology of RECAT Phase I and Phase II use simple models for the definition of separation standards. That is due to the requirement that those models have to be accepted as state-of-the-art, they have to be public, understandable and available.

As the state-of-the-art in modelling has improved significantly over the last years (see §5 "Technologies"), the advantage should be investigated i) of using more sophisticated models with higher fidelity and ii) of including models for manual or automatic control of the airplane as well as models for severity assessment, which are not included yet. Simple models need to deliver conservative results because of inherent model uncertainties. Their inherent margins limit potential capacity gains. Enhanced models offer higher accuracy and can deliver the same safety levels with fewer margins.

The RECAT Phase I methodology models a limited part of the complete physical process from vortex generation to encounter hazard, thus it is not complete, see Figure 10. Models of the physical sub-processes, which are important for aircraft reaction and thus affect hazard and risk, are missing. This includes sub-models for manual or automatic aircraft control as well as sub-models for the assessment of the encounter severity.



Idea: Airbus

Figure 10: Models needed for a quantitative safety and risk assessment of new separation standards

RECAT Phase III (dynamic pair-wise separation) requires enhanced models and methods. Such models and the necessary expertise are available and offer higher prediction accuracy. Methodologies like WakeScene (see §6.2.2.4 and (Holzäpfel et al. 2009)), VESA (see §6.2.2.4 and (Kauertz 2010)), WAVIR (see §6.2.2.4 and (Speijker et al. 2004)) and ASAT; see (Ladecky 2003) that use large and complex models for safety and risk assessments of regulations on wake vortex separations are in development.

However, the models need to be validated against RECAT Phase III requirements, which are not defined yet. Requirements could be for example: models addressing the world's fleet of 9000 aircraft; models need to be conservative; they must be suited for fast-time simulations; they have to be transparent and understandable, and so on. RECAT Phase III requires such models in 2017. To be ready in time, model development and validation has to start now.

3.5.3.3 Metrics and criteria for severity assessment

Criteria for wake encounter severity assessment have to be derived with involvement of relevant stakeholders. It has to be assured that they are commonly accepted by all stakeholders. This includes analysing the data and results available worldwide so far and conducting additional human-in-the-loop tests under conditions and with parameters that have been agreed upon beforehand.

3.5.3.4 Wake vortex awareness and avoidance techniques

Wake vortex awareness and avoidance techniques should be developed and should be used to enhance regular airline pilot (and air traffic controller) training taking into account the improved understanding of encounter physics and operational implications.

3.6 Airborne wake encounter hazard mitigation

Main contributing authors:
Andreas Reinke, Sebastian Kauertz, Airbus

3.6.1 Overview

Safety and capacity improvements through mitigation of wake encounter hazards can also be provided by airborne applications. The following principles can be distinguished:

- Airborne wake turbulence separation management
    - Wake turbulence separation minima dynamically established onboard equipped aircraft responsible for their own separation. Minima adjusted as a function of the actual lead and follower aircraft characteristics, and depending on the prevailing meteorological conditions and the resulting wake vortex behaviour (transport and decay). Potentially supported by direct sensing of the wake position using novel airborne sensor technologies.
    - Delivery of wake turbulence separations either with the help of dedicated flight deck HMI in manual mode or automatically using autopilot and flight management functions.
- Tactical avoidance of wake encounters
    - Wake encounter conflicts detected dynamically onboard equipped aircraft depending on prevailing meteorological conditions and the resulting wake vortex behaviour (transport and decay). Potentially supported by direct sensing of the wake position using novel airborne sensor technologies.
    - Flight crew alerting and HMI such that the crew can decide on appropriate avoidance actions.
    - Flight crew alerting and HMI with additional automated identification of conflict resolution, optionally conducted in manual mode with support HMI or automatically using autopilot and flight management functions.
- Reduced vulnerability of follower aircraft to wake encounters if they occur, for example by
    - Pilot anticipation of an impending wake encounter leading to improved pilot flight control response to the wake encounter impact. E.g. through visualization of the wake vortex on the flight deck and dedicated alerting.
    - Dedicated aircraft stabilization by automated flight control activation in the event of a wake encounter.

The airborne wake turbulence separation management concept could replace today's rigid separation schemes in TMA operations. As such it would conditionally provide for arrival and departure throughput increases in favourable prevailing meteorological conditions to more efficiently handle peaks and queues in arrival and departure demand. As it would be aircraft specific some of the benefits typically associated only with pair-wise dynamic separations (see §3.4) can be delivered with this concept as well.

The concept of tactical avoidance of wake encounters is primarily a safety feature, especially useful in the cruise flight phase (also see §3.7). It can provide capacity benefits in airport operations when applied in the context of dynamic separations – either delivered using ground-based or airborne systems – and if its risk reduction potential is taken into account in the dynamic separation system.

The concept of reduced aircraft vulnerability promises the same principle benefits as the concept of tactical avoidance but has the additional benefit to not require potentially disruptive avoidance manoeuvres.

3.6.2 Current Status

Concepts for wake encounter hazard mitigation through airborne applications are specifically studied in the context of two research projects[1]:

- SESAR projects 9.11 & 9.30 (see §4.2.2.1)
- DLR project “Wetter & Fliegen” (Weather & Flying) and its successor “WOLV” (see §4.2.2.3)

Both projects address the operational concept as well as the development and validation of airborne wake vortex systems for tactical avoidance and reduced encountering aircraft vulnerability. The SESAR projects 9.11 & 9.30 are furthermore linked with the SESAR operational project 6.8.1 (see for example §3.4.2.1) with regard to the operational concept and application of the airborne system in the TMA.

Several new operational concepts are under development in the framework of SESAR and NextGen. Some of these new concepts are expected to have an impact on wake encounter risks. Those additionally envisioning to progressively transferring separation responsibilities from the ground to the air are candidates for inclusion of airborne wake encounter hazard mitigation concepts and applications.

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[1] Note that the Green-Wake project (see §4.2.2.2) is focused on technologies related to airborne systems.

3.7 New Operational Concepts

Main contributing authors:
Robert Luckner – TUB
Andreas Reinke – Airbus

3.7.1 Overview

With the deployment of new operational concepts especially for aircraft separations, as they are envisaged by SESAR and NextGen, the possibility of encountering wake vortices might increase. 4D-Reference Business Trajectories (RBT) might lead to an increase of crossing, climb and descent through other aircraft trajectories compared to today. In order to characterize the impact of these concepts and also the impact of different performance levels of Airborne Separation Assistance System (ASAS) applications on the Air Traffic System, research is recommended on:

- Simulation of future air traffic containing estimated traffic mix and 4D-RBT to assess the probability and frequency of unacceptable wake vortex encounters;
- Assessing the benefit of reduced ASAS self separation (SSEP) applications based on different performance levels of airborne wake vortex mitigation and alleviation systems;
- In combination with ASAS Self-Separation functions, the need arises to investigate and develop methodologies to mitigate hazardous or unacceptable wake vortex encounters en-route.

Furthermore, new operational concepts are required to address:

- Safety issues with helicopter wake turbulence, with helicopters as vortex generators should be addressed. Helicopter wake vortex has caused six accidents in the past five years in UK and Europe – currently there is limited guidance on wake vortex avoidance distances especially for light aircraft following helicopters; see (Luckner et al. 2011).
- Concerns that wind turbines in the vicinity of runways may affect aircraft,
- Wake encounters at takeoff and during flare when aircraft are close to the ground.

3.7.2 Research Needs

3.7.2.1 Wake vortex encounters in cruise

Wake vortex encounters in cruise are rare, however their occurrence is expected to rise with increasing traffic and their severity is expected to increase as aircraft weight differences are becoming larger (VLJs and HEAVIES above 500t MTOW). Currently, there are no wake vortex separations defined for cruise flight and it has to be investigated whether this is still adequate. To do so, measurements of wake vortex characteristics and evolution (decay and transport) and the corresponding meteorological conditions (wind, turbulence, eddy dissipation rate, temperature and temperature gradients) at high altitudes should be performed for model validation. Wake vortex encounters in cruise should be investigated in flight tests and in flight simulators taking the impact of simulator limitations into account. Wake vortex transport and decay models require knowledge of meteorological conditions (stratification level, turbulence).

3.7.2.2 Helicopter wake vortices

There is an operational need to quantify the distances and/or time values that prescribe the minima allowing helicopter operations (IFR landings and all take-offs) to be conducted independently and/or simultaneously with heavier fixed wing aircraft operations on the same and/or proximate runways. A 3 to 4 minutes separation is required for a helicopter that is departing from a helipad spaced less than 760m from a RWYs after a heavier fixed-wing aircraft depending on the airport layout.

Experience, so far, indicates that helicopters are more "resistant" to wake vortex encounters than fixed wing aircraft. This is nowhere quantified in a manner that would enable development and/or refinement of the existing ICAO wake turbulence separation minima in regard to helicopters as followers. RECAT effort should be extended to cover this missing facet of the ATM procedures related to wake turbulence.

3.7.2.3 Wind turbine wake turbulence

Guidance for wind turbine wake turbulence is missing as it is a relatively new topic. Its effects on aviation should be determined, particularly when wind turbines are sited in the vicinity of runways.

3.7.2.4 Enhancement of wake vortex decay in ground proximity

Incident reporting by pilots, field measurements at airports, and airspace simulations of take-off and departure indicate that a greater part of wake vortex encounters occur at altitudes below 300 ft. Within this altitude range clearance of the flight corridor by descent and advection of the vortices is restricted: stalling or rebounding vortices may not clear the flight path vertically and weak crosswinds may be compensated by vortex-induced lateral transport. Dedicated modifications of the ground surface geometry allow an acceleration and enhancement of vortex decay independent from environmental conditions (see §5.1.2.5). The installation of suitable obstacles following the runway tails may improve safety by reducing the number of wake vortex encounters and increase the efficiency of wake vortex advisory systems. While this approach has been demonstrated successfully in towing tank experiments and large eddy simulations the demonstration with a flight experiment is still pending. Optimum design and assembly of the obstacles also with respect to interferences with collision risk, instrument landing system, and height measurement by radar of landing aircraft need to be elaborated.

4. Enabling Systems

Main contributing authors:
Andreas Reinke – Airbus

All wake vortex related operational concepts as described in §3 of this report that are not purely procedural require some sort of automated support which is to be provided by dedicated systems. These concepts are hence enabled by the associated systems. For the majority of non-procedural concepts described in §3 the supporting systems are expected to provide condensed and highly elaborated information established using sensory information and models to human operators like ATC supervisors, ATC controllers and pilots for decision making. In the long-term such systems may also directly be linked to other systems that are automatically controlling aircraft operations (e.g. automatic in-trail operations).

Globally, ground-based and airborne enabling systems can be distinguished. While interoperability is mandatory, deeper collaboration of these two sides is not necessarily the optimum solution. While collaboration may theoretically provide some additional benefit, any concept requiring important systems installed on the ground as well as on-board aircraft will have limited benefits because of the high equipage costs and related low equipage levels, at least during the transitory phase of introduction. Since capacity benefits are only to be expected at constrained airports, the need to install airborne systems on a large number of aircraft – of which some will operate into these constrained airports only occasionally – does not seem economical. From this perspective the optimum solution is to equip large, constrained airports with dedicated ground-based systems while not requiring important and costly changes to participating aircraft. Airborne systems on the other hand enable dedicated means for wake encounter risk mitigation throughout the flight – hence including the important cruise flight phase – and at each airport to which the operate. The latter aspect will provide benefits also to those airports for which the installation of a presumably expensive ground-based system is not economically justified.

Enabling systems are a complex composition of (partly dedicated) sensors, dedicated models and algorithms, i.e. they are themselves relying on several enabling technologies and methodologies as described in §5 of this report. They have to be developed and validated with regard to their impact on safety and capacity and also need to be reflected themselves as part of the safety assessments associated to the operational concepts to which they contribute. Safety aspects are described in §6 of this report.

4.1 Ground-based Advisory Systems

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4.1.1 Overview

The main objective of a Ground-Based Advisory Systems is to punctually or permanently reduce landing and departure wake turbulence separations and, therefore, to increase the runway throughput in such a way that it safely absorbs arrival demand peaks and/or reduces departure delays without jeopardizing flights safety.

The Ground-Based Advisory System will be able to deliver in real time, the position and strength of the wake vortices, predict their behaviour, monitor the air traffic situation with regard to the hazard of wake encounters and possibly alert ATC controllers in case the flight safety is, or is predicted to be affected.

4.1.2 State-of-the-art

4.1.2.1 SESAR project 12.2.2 : Runway Wake Vortex Detection, Prediction and Decision Support Tools

The main objective of this project is to define, analyze and develop a verified wake turbulence system according to the operational concept developed by the SESAR Project 6.8.1. The aim is therefore to punctually or permanently reduce landing and departure wake turbulence separations and, therefore, to increase the runway throughput in such a way that it safely absorbs arrival demand peaks and/or reduces departure delays without jeopardizing flights safety.

This global objective will be achieved by means of developing a Wake Vortex Decision Support System (WVDSS). This later will be able to deliver, in real time, the position and strength of the wake vortices, predict their behaviour, monitor the air traffic situation with regard to the hazard of wake encounters and possibly alert ATC controllers in case the flight safety is, or is predicted to be affected. The WVDSS will take into account actual and forecast weather information as well as airport specific meteorological conditions, aircraft characteristics (generated wake vortex and encounter vulnerability), air traffic situation and airport runway layout. The WVDSS will be composed of several components; sensors, weather data base and wake vortex advisory system (WVAS). These components included in the WVDSS will be validated and deployed at airports in order to optimise the runway throughput and reduce delays.

As the WVDSS will be developed in conjunction with P6.8.1 (discussed in §3.4) it will be used for verification and validation purposes.

The P12.2.2 addresses the three steps of the SESAR concept story board:

- Step 1 refers to Time Based Separation (TBS) – Acquisition and processing of wake vortices information as well as headwind. The aim is to verify the position, strength and behaviour of the wake vortices depending on headwind strength in arrivals in order to evolve from distance based separation to time based separation. As well, a first release of the WVDSS prototype will be developed which will demonstrate this capability. This demonstration will include an in-situ verification campaign (XP1 in CDG).
- Step 2 refers to Weather Dependent Separation (WDS) – Prediction of wake vortex behaviour in changing weather conditions. The system will be updated with all the components linked to wind, weather nowcast and forecast, including real-time prediction of micro-scale terrain-induced turbulence close to the airport. The goal is to assess in real-time the position and strength of the wake vortices and to predict their behaviour for both departures and arrivals, in order to demonstrate the possibility to evolve from a time based separation to a weather dependent separation taking advantage of any favourable meteorological conditions (e.g. crosswind). This demonstration will include an in-situ

verification campaign (XP2 in CDG). All building blocks regarding weather monitoring will be developed / customized.

- Step 3 refers to Pair Wise Separation (PWS) – Demonstration of the capacity of the WVDSS to dynamically deliver separation for each aircraft pair. This requires an aircraft characteristics database and the customisation for different airports and runway configurations. The system will be refined to reach two main goals:
    - Perform a first demonstration of the pair wise separation concept. With a partial aircraft wake vortex characteristics database provided by P6.8.1, it will be demonstrated that the WVDSS could determine a dynamic pair wise separation, taking in account the real-time weather conditions as well as the aircraft sensitivity to wake vortex.
    - Demonstrate the system adaptability to other runway layouts.

The demonstrations of step 3 will be performed in platform tests and verified in an in-situ campaign. Building blocks related to pair wise separation (aircraft characteristics database, algorithms…) will be developed or customized.

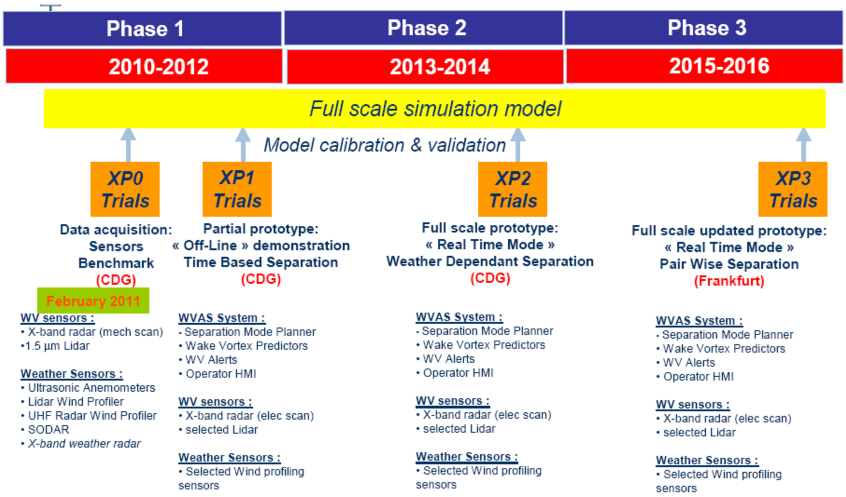

Figure 11: Project Overview SESAR WP 12.2.2.

Current Status

The global architecture of the WVDSS is depicted in Figure 11. It is composed of several components, for instance meteo sensors, meteo nowcast and forecast, wake vortex sensors, WVAS, likewise interface with the external weather observations, ATC system and stakeholders' HMI.

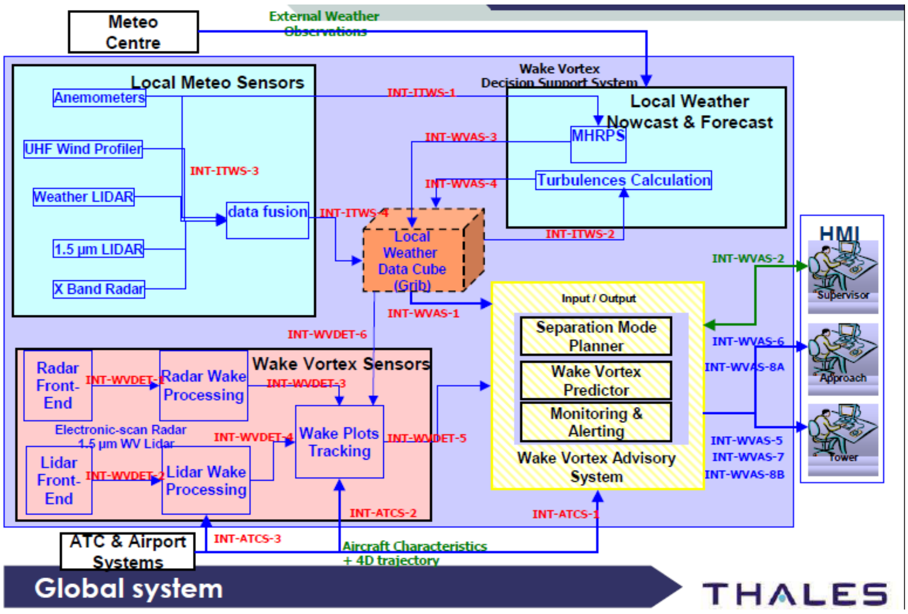

Figure 12 : Global Architecture of WVDSS

Ground-based Wake Vortex Advisory System (WVAS) aims at processing meteorological information and air traffic situation in order to provide ATC stakeholders the means to decide and apply reduced aircraft separation instead of current ICAO separation relative to wake vortex issue. The WVAS is composed of several components, for instance an Input/Output module, Separation Mode Planner, the Wake Vortex Predictor and the Monitoring and Alerting functions. A set of warning functions is also in force in order to provide encounter advisories in case an aircraft is, or is predicted to be, within a wake vortex hazards.

Meteorological information are forecast as well as nowcast information, these latest provided by means of sensors spread over the airport area and final approach area; i.e. along the glide slope. These information are gathered in a Local Weather Data Cube for further use by WVAS.

The WVAS is promised to provide real improvement in the way to monitor wake vortices transport and decay looking for reducing separations between aircraft as well as to increase flight safety by monitoring flight progress, alerting ATC stakeholders' in case one aircraft is, or is predicted to be within a wake vortex hazard and then for the ATC controllers to initiate appropriate action to resolve the situation. Then, this system will enable to reduce separation between aircraft in the final approach or departure, therefore will allow to increase runway throughput, and as a matter of fact increase airports capacity and reduce delays without jeopardizing flights safety.

The WVAS will be able to:

- Propose the separation mode to the supervisor: e.g. ICAO separation minima or reduced separation minima and time applicability of separation mode
- Process wind data including turbulence information and aircraft trajectory to provide spacing (chevron position for display purpose)
- Monitor wake vortices (wake vortex predictor output, decay and transport) against aircraft trajectories and provide encounter advisories to controller HMI for display purpose in case of actual or predicted wake vortex hazard
- Manage the wake vortex data (4D data) from wake vortex sensors function. In case of discrepancies between wake-vortex sensors and predictor an alert being generated

There are a number of tasks which have been achieved in 2010 and 2011 as part of Phase 1 of the work package:

- Preliminary system requirements definition
- System requirements definition for phase 1 (Time Based Separation)
- Preliminary system architecture analysis
- Initial technology studies
- Testing platform and tools requirements for phase 1 (Time Based Separation)

A sensors benchmark campaign has been conducted at Paris Charles de Gaulle airport (XP0 trials) and weather related studies will be performed in conjunction with SESAR project 15.4.9a.

Currently, the WVAS is in the development phase. It is foreseen that the components part of the WVAS i.e. I/O module, Separation Mode Planer, Wake Vortex Predictor and Monitoring and Alerting will be integrated as well as being connected to Local Weather Data Cube, Wake Vortex Sensors, Air Traffic Situation and Human Machine Interface by mid-2012. Off-line experimentations are planned for Q3 and Q4 2012 in Paris CDG.

Capacity Analysis

This SESAR Work Package takes up the findings of numerous weather dependent projects as ATC-Wake and CREDOS but also benefits from knowledge of the project partners (e.g. parts of DLR WSVBS will be further developed and tested during the project). The different evolution phases (Phase 1 to Phase 2) will provide demonstrations of system capabilities and evolve gradually from a Time-Based Separation to a Weather Dependent Separation to a Dynamic Pair Wise Separation concept as shown in Figure 11. Therefore, a need to assess the capacity benefit of the system will arise for each implementation phase.

4.1.2.2 Wake Vortex Prediction and Monitoring System (WSVBS)

The Wake Vortex Prediction and Monitoring System (WSVBS) (Holzäpfel et al. 2009, Gerz et al. 2009) has been developed to tactically increase airport capacity for approach and landing on closely-spaced parallel runways and single runways. The WSVBS supports dynamic adjustment of aircraft wake vortex separations dependent on weather conditions and the resulting wake vortex behaviour without compromising safety. WSVBS uses meteorological measurements and dedicated numerical weather prediction (see section5.3) in order to predict envelopes for probabilistic wake vortex behaviour (with P2P, see §5.1) and the resulting safety areas (with SHAPe, see §5.6) in several gates extending from final approach fix to threshold. A LIDAR monitors the correctness of WSVBS predictions in the most critical regions at low altitude. Integration with the DLR's arrival manager AMAN has also been demonstrated.

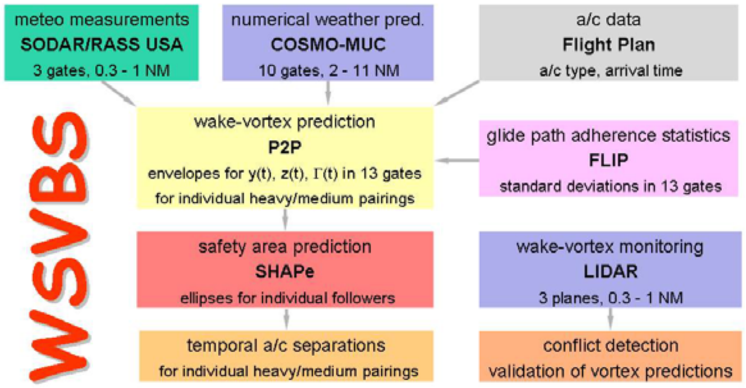

Figure 13: Flowchart of the WSVBS.

The aim is for a tactical increase in airport capacity for both approach and landing phases of flight. Every 10 minutes the WSVBS delivers minimum safe aircraft separation times for the next hour, which are translated into operational modes aiming at tactically improving capacity to reduce delays. During a performance tests at Frankfurt and Munich airports the system was stable and the predicted minimum separation times were confirmed by measurements.

The WSVBS system allows for various capacity-improving procedures to be applied, such the “Staggered” (STG) procedure, which allows parallel runways to be used independently from each other, but obeying the radar minimum separation; the “Modified Staggered Left” (MSL) procedure, whereby the aircraft on the right (windward) runway are separated by the radar minimum from aircraft on the left (lee) runway; and the “Modified Staggered Right” (MSR) procedure, whereby aircraft on the left (windward) runway are separated by the radar minimum from aircraft on the right (lee) runway.

Current Status

From scientific and technological perspectives, the WSVBS has reached a mature and useful state. The elements of the WSVBS are generic and can therefore be adapted to other runway systems and airports. Recently the components of the WSVBS have been extended to the prediction of dynamic and time-based separations for individual aircraft type pairings landing on single runways (dynamic pairwise separations). Dynamic pairwise separations correspond to the favoured procedure foreseen in the final development stage of NextGen and SESAR. Improved weather prediction has been achieved employing time-lagged-ensemble prediction systems with assimilation of local meteorological measurements.

The capabilities and functionality of the advanced WSVBS were demonstrated during a field measurement campaign at Munich airport between 23 June and 15 September 2010 (Holzäpfel et al. 2011).

There are a number of further activities planned for the WSVBS within the Weather & Flying project which include:

- The preparation for implementing the WSVBS at an airport.
- A risk analysis and an assessment of the capacity gain of the WSVBS.
- Components of the WSVBS are also to be developed and tested within WP12.2.2 of the SESAR SJU.

Capacity Analysis

The system was tested and evaluated at Frankfurt International Airport (FRA) in 2007 for the closely-spaced parallel runway system 25L/25R within a performance test that lasted for 66 days (Gerz et al. 2009). The tests revealed that separations could have been decreased for 75% of the time. Taking into account the usual traffic mix, a capacity gain of *3%* could be reached. Additionally, delays could be significantly reduced using the WSVBS. The capacity investigations are based on the real-time and fast-time simulation tools ATMOS II (Air Traffic Management and Operations Simulator) and SIMMOD of the DLR, where the potential capacity benefit for FRA was assessed.

To establish a baseline, the simulations were initially performed using ICAO separations. The simulations were then matched with separations derived from WSVBS and re-run. The simulations included actual aircraft types and flight characteristics spanning a realistic distribution of wake vortex categories, demand peaks throughout the day, weather data, and the WSVBS proposed minimum wake vortex separations. The fast-time simulations covered a period of one month. New fast-time simulations are also planned, which will be based on the WSVBS predictions of the three-month Frankfurt campaign.

Currently the capacity gain is seen as *tactical* by the project consortium, i.e. delays and holding patterns could be decreased and avoided. Based on potential experience within such an operational system, even an increased number of flights could be allowed, yielding a strategic capacity gain.

4.1.3 Research Needs

Nevertheless, beyond SESAR, some hot spots may arise when deploying the WVDSS in TMAs.

- Some areas will not be (or sufficiently) equipped by sensors. This would prevent having enough meteo or wind information to feed WVAS, as well, prevent having information on the wake vortex decay, especially in the ILS interception point upstream areas, these information being mandatory in order to organize and increase traffic capacity well ahead from the ILS interception. If not, it will not be possible to derive maximum benefit from capacity gain possibly got in along the glide because of the scattered arrival traffic converging towards the ILS interception point. Therefore it could impede from spreading the system in the extended terminal major areas (TMA),
- Some models used in the WVAS i.e. Wake Vortex Predictor might be put on the spot when it is facing to high traffic capacity, especially in very dense TMAs,
- The Human Machine Interface (HMI) must be subject to Human Factor analysis and suite the ATC controllers. WVDSS focuses on sensors, meteo and WVAS sub systems rather than HMI.

As well, it might be of interest to ensure interoperability between wake vortex advisory system and its sister system i.e. the weather hazard advisory system.

Therefore, it is suggested that several studies and research are made in the coming years:

4.1.3.1 Aircraft used as a sensor

To derive maximum benefit from capacity gain possibly got in along the glide requires spreading WVDSS in the extended TMA.

The use of aircraft as a meteorological sensor, studies of meteorological data and aircraft trajectories downlink from aircraft by means of ADS-B or Mode-S radar as well as processing these data in the WVAS will be a means to enhance and refine wake vortex predictions, monitoring and alerting functions. It will allow spreading the WVDSS over the extended TMA, as such it might be considered as an enabler to increase WVDSS use over the TMA.

Studies and research will cover : Definition, standardization and use of meteo and aircraft trajectories in Downlink Aircraft Parameters (DAP), use of DAP in WVAS components i.e. separation mode planner, wake vortex predictor, monitoring and alerting functions, refinement of WVAS processing to cope with extended TMA needs.

4.1.3.2 Wake vortex model performances

Deploying the WVDSS in complex medium or high sized TMA requires the capability to process in real time huge number aircraft trajectories as well as to compute wake vortex prediction. Time consuming algorithms must be efficient in order to be in line with real time constraints of an ATC system. Therefore, studies and research will cover benchmarking, possibly adaptation and refinement of wake vortex predictor algorithms must be conducted to guaranty that WVAS could to be used in a real time Safety Nets system.

Identification of the required accuracy of the meteorological measurements and predictions and of the wake vortex predictions in order to achieve the required capacity gains. This approach may answer questions like: “Is an intended concept of operations likely to be realisable at all?” and “To which extent must the performance of the different sub-models be improved to enable a particular concept of operations.”

4.1.3.3 HMI ergonomic

Conduct operational experimentation on WVDSS HMI will enable ATC Controllers to suit the HMI. Studies and research will cover HMI refinement driven by ATC Controllers.

4.1.3.4 Integrated Weather Hazard solution & Sub-System Interoperability

In addition, some sub-systems related to WVAS are currently under definition, research and development phases e.g. Weather Hazard Advisory System (WHAS) or Integrated Terminal Weather System (ITWS). Another means to increase flight safety will be to :

- Study and develop Advisory System i.e. ITWS, for wind-shear, convective storm, volcanic ashes advisories, based on experience gained through WVAS.
- Fed and enhance WVAS sub-system with ITWS outcomes e.g. wind-shear, convective storm, possibly volcanic ashes for studying the interoperability between the two sub-systems i.e. WVAS and ITWS.

4.1.3.5 Risk Analysis

For any operational concept there is a need to establish a generally accepted methodology for a comprehensive risk analysis. Such a methodology can also be used to adjust all components of a wake vortex advisory system to appropriate and consistent confidence levels. The required confidence levels have a strong impact on the potential capacity gain of a wake vortex system and thus on the business case of wake vortex advisory systems.

4.1.3.6 Warning System for Increased Safety

ATC has notified interest in a wake vortex warning system that may prevent wake vortex encounters for the currently used aircraft separations in order to further increase safety. For this purpose the components of a warning system would have to be adapted to predict corridors of maximum risk combined with a risk threshold controlling the issue of warnings.

4.2 Airborne Systems

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4.2.1 Overview

Airborne systems for wake vortex detection, prediction, warning, avoidance and impact alleviation are envisioned to enhance safety during all phases of flight. This specifically includes the cruise flight phase, during which relevant wake vortex encounters are reported regularly. Related operational concepts are treated in §3.6 of this report.

In general, three basic embodiments of airborne wake vortex systems can be distinguished:

- Wake encounter alerting with and without avoidance based on (probabilistic) wake vortex model predictions and enabled by advanced air-to-air data exchange
- Wake encounter alerting with and without avoidance based on mid to long range forward-looking wake vortex sensors
- Wake impact alleviation based on advanced flight control techniques enabled by short range forward-looking sensors and/or online wake characterization.

Hybrids of these basic embodiments are feasible, too. The five fundamental enabling technologies are hence:

- Operational, probabilistic wake vortex model. Research needs are addressed here as well as in §5.1.
- Mid to long range forward-looking, airborne wake vortex sensor. Research needs are addressed here as well as in §5.2.
- Advanced flight control techniques to suppress wake-induced disturbances based on new as well as existing air data sensors. Research needs are addressed in this chapter.
- Short range forward looking, airborne air data sensors. Research needs are addressed in this chapter as well as in §5.2.
- Online characterization of the wake vortex (determination of the wake properties like strength and position). Research needs are addressed in this section.

In addition to these fundamental enabling technologies a number of supporting technologies are also involved. These include:

- Real-time fusion of traffic data coming from multiple sources as well as their interpolation and extrapolation. Research needs are addressed in this section.
- Real-time fusion of meteo data coming from multiple, airborne and ground-based sources as well as their interpolation and extrapolation. Research needs are addressed here as well as in §5.3.
- 4D real-time conflict detection as well as 4D real-time, constrained conflict resolution. Research needs are addressed in this section.
- Real-time encounter severity estimation. Research needs are addressed in this section.

4.2.2 State-of-the-art

Today, no airborne wake vortex system exists. A number of patents related to airborne wake vortex systems have been filed since the 1990s. These primarily concern solutions related to the display of wake vortices on the flight deck, but also address other aspects.

In Western Europe, airborne wake vortex systems and their enabling technologies have been studied in a number of research projects, including:

- AWIATOR (2002-2007)
- I-WAKE (2002-2005)
- FLYSAFE (2005-2009)

Today, airborne wake vortex systems are specifically studied in the context of three research projects:

- SESAR projects 9.11 & 9.30 (see §4.2.2.1)
- Green-Wake (see §4.2.2.2)
- DLR project “Wetter & Fliegen” (Weather & Flying) and its successor “WOLV” (see §4.2.2.3)
- ALICIA (see §4.2.2.4)

In addition, airborne wake vortex systems will become relevant in the context of several new operational concepts developed in the frame of SESAR and NextGen, which envisage progressively transferring more and more separation responsibility from the ground to the air.

The “Integrated Wake Vortex Safety System”, proposed by the Russian State Institute of Aviation Systems (GosNIIAS), includes an important airborne part.

4.2.2.1 SESAR projects 9.11 & 9.30

Within the SESAR research programme the two projects 9.11 and 9.30 are directly related to development of airborne wake vortex systems, which are called Wake Encounter Prevention System (WEPS) in the context of these projects [Reinke 2010, Kauertz 2011]. Both projects are led by Airbus and build on earlier related research projects like I-WAKE and FLYSAFE, among others, to which Airbus was a contributor. The aim of the projects is to advance the definition and the operational concept of such a system up to a flight-test ready demonstrator. The provisional run-time of the projects is 2010 to 2015. Several parts of the work plan are sub-contracted to different European research institutions.

The SESAR projects 9.11 & 9.30 relate to wake avoidance based on vortex models (WEPS-P) and wake impact alleviation based on advanced flight control concepts enabled by sensor and wake characterisation (WEPS-C), see Figure 14. Wake avoidance based on mid- to long-range forward-looking wake vortex sensors is not considered.

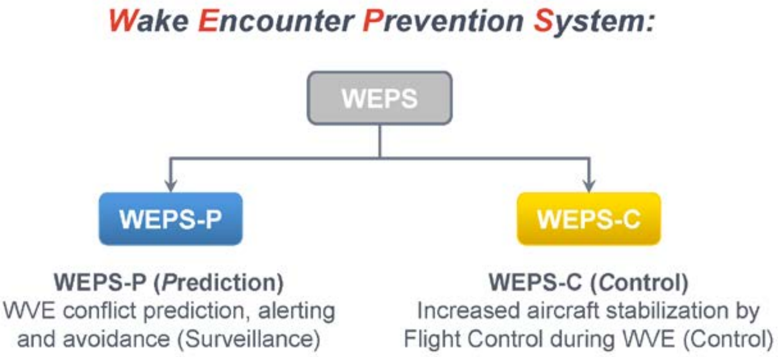

Figure 14: Sub-functions of WEPS

In order to verify and validate WEPS-enabled capacity increases and safety enhancements, both projects will set up technology demonstrator platforms. As part of these activities, a number of fundamental as well as supporting technologies will be addressed in some detail. These include: operational vortex models, advanced flight control techniques, online characterization of the wake vortex, consolidation of traffic and meteorological data, conflict detection and resolution, and encounter severity estimation.

The WEPS under evaluation in these projects is designed to mitigate the increase in wake encounter risk expected with the steadily growing air traffic density, and during all flight phases. It is related to new wake turbulence separation concepts for TMA operations as developed in the SESAR operational project 6.8.1 and is envisioned to complement future pair-wise separation schemes (see §3.4 and §3.5). One goal of these projects is to validate the system's risk reduction potential (safety aspect) and to verify its potential to reduce separations (capacity aspect) in combination with pair-wise separations.

WEPS is envisioned to reliably recognize imminent wake encounters, with a time horizon of a few minutes, to enable safe avoidance and/or dedicated alleviation by flight controls. In this sense, WEPS is of tactical nature, i.e. it is not intended to adjust an aircraft's overall flight plan, but rather to enable short-term, small-scale conflict resolution. WEPS is also not intended in a first step to provide the pilots with the means to determine what their separation should be. In general however it can be used to identify and indicate the required separations.

SESAR project 9.11 specifically concerns those parts of the system that are related to the model-based prediction of the wake behaviour, enabled by air-to-air data link exchange of relevant data. This part is termed WEPS-P, where the P stands for "Prediction in order to avoid". The global conceptual approach of WEPS-P is depicted in Figure 15. Apart from verification and validation activities, aspects of integration in current and future aircraft play an important role in the project as do necessary research activities related to new and major technical sub-functions.

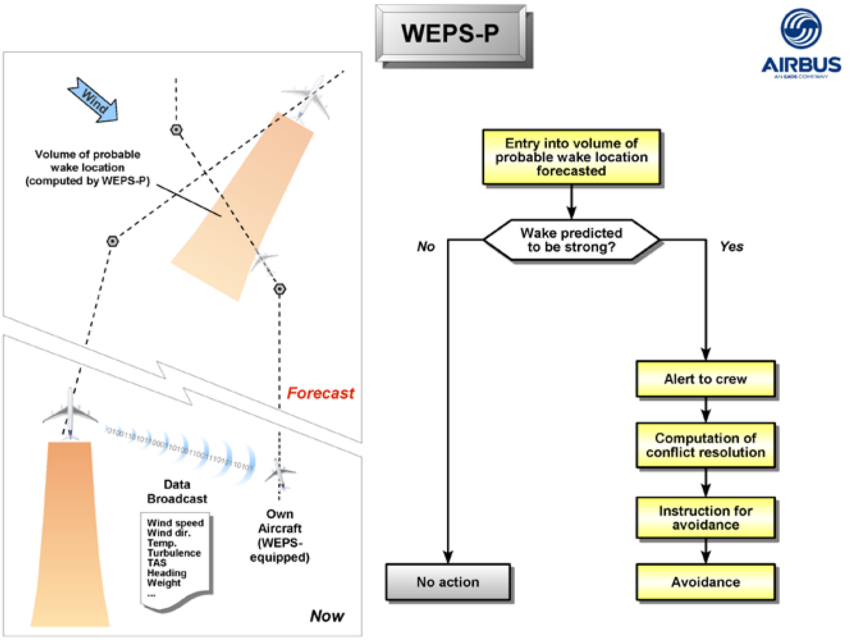

Figure 15: WEPS-P concept schematic

SESAR project 9.30 concerns those parts of WEPS that are related to the alleviation of wake impact on an encountering aircraft by means of flight controls and enabled by new forward-looking sensor technologies, e.g. LiDAR. This part is termed WEPS-C, where the C stands for "Control in order to alleviate". The global conceptual approach of WEPS-C – which is envisioned as an extension to WEPS-P – is depicted in Figure 16. The project focuses on application of a LiDAR sensor, while the development of such a sensor itself is not included.

Likewise to project 9.11, project 9.30 centres on verification and validation activities but also includes some research on fundamental technologies and integration. Both projects will also determine requirements on data link capabilities, i.e. the required extension of the transmitted data by additional parameters needed by WEPS.

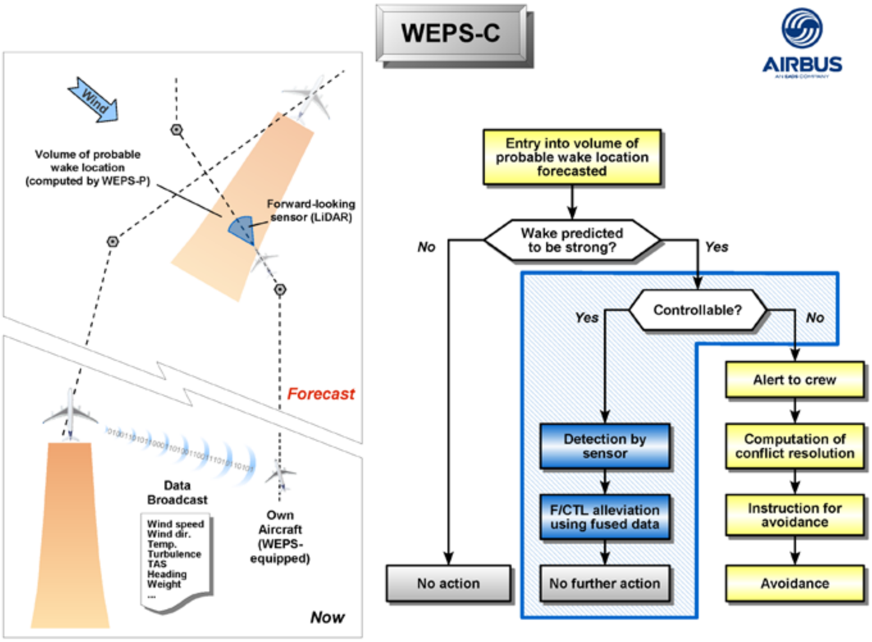

Figure 16: WEPS-C concept schematic

An early WEPS-P demonstrator system has been tested in flight by Airbus in 2010, see Figure 17. This test was performed in opportunity of dedicated wake encounter flights conducted in the framework of A380 wake turbulence separation assessment. It allowed testing a representative wake prediction and warning system in real time and using an air-to-air data link. Apart of testing the system's behaviour in a realistic environment, the test results also provide valuable information with regard to the accuracy of model-based predictions since the wake location and strength was explicitly probed in these tests.


- Installation on-board wake-encountering a/c (A320) during A380 Wake Vortex flight test campaign in Nov. 2010
- Real-time air-to-air data exchange via VHF between OBWPA and 2 wake-generating a/c (A380 & A340-600)
- Prediction and identification of conflicts
- Real-time display of predicted wake locations on dedicated screen in cockpit

Wake visualization seen from encountering aircraft

Real-time wake display on dedicated screen

Figure 17: Airbus flight test of airborne wake prediction

4.2.2.2 Green-Wake

Green-Wake is a project of the 7th Framework Programme to support the EC objectives of improving air transport safety and increasing airport capacity. The project started in November 2008 and has been extended to be completed by August 2012. The objective of Green-Wake is to develop and validate innovative technologies that will detect wake vortex and wind shear hazards in a timely manner and input demands to the aircraft's flight control system to automatically alleviate the threat to safe flight that these phenomena generate. As a result this will improve aircraft passenger safety and comfort and improve the operating efficiency of an aircraft, as well as airports, by providing a safe means to decrease separation between trailing aircraft.

To that effect Green-Wake will develop and test an Imaging Doppler LiDAR system that is capable of detecting and measuring wake vortices and wind shear phenomena of the order of 50 to 200 meters in front of an aircraft allowing action to be taken to reduce the hazard. The aim of the project is to develop a system suitable for integration into a commercial aircraft, but also to look at how data are to be presented to the aircrew. A demonstration of the Green-Wake wake vortex detection system is shown in Figure 18.

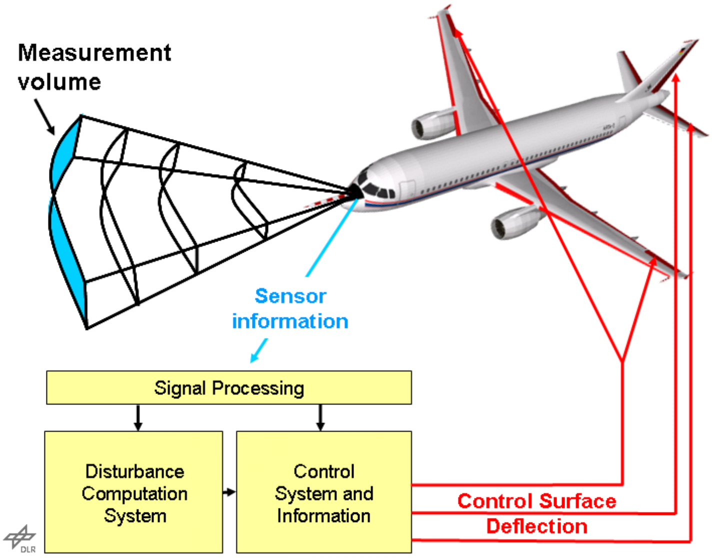

Figure 18: Concept of Green-Wake vortex detection system

Current Status

The consortium has completed an extensive review of the requirements and how the state-of-the-art technologies available can address the measurement application. The wake vortex and wind-shear simulator is nearing completion and the Doppler LiDAR system concept has been developed and a prototype is built during the remainder of the project.

The simulator is one of the three major outputs of the Green-Wake project. The LiDAR instrument, the main deliverable of the project, is currently built. A first version of the prototype has been evaluated and tested in the wind tunnel. The final ground based prototype instrument running in real time will produce a 3-dimensional hazard map, aimed at enhancing the presentation of hazard information. It will characterize the movement of the air and detect wake vortices and wind-shear at a range of up to 200 m.

Further Developments

Further information on the project and contact details for project representatives can be found on the GreenWake project website at www.greenwake.org. Details of related publications can be found in [Schmitt 2007], [Schwarz 2007], [Rahm 2007].

4.2.2.3 DLR project Wetter & Fliegen

The DLR internally funded project "Wetter & Fliegen" (Weather and Flying) is a four year project with a run-time from 2008 to end of 2011 with participation of several DLR institutes. A variety of airborne topics are studied in the framework of this project: sensor requirements for the direct use of forward-looking measurement data for flight control purposes, wake characterization methods as well as automatic control and wake warning and avoidance applications.

Airborne wake vortex warning systems

Airborne wake vortex warning systems serve to increase the pilots' situational awareness in case of a predicted, imminent or even current encounter. Concerning the latter, DLR has concluded from simulator studies with an Airbus A330 model that this aircraft's autopilot usually can handle a wake vortex encounter better than a pilot flying manually; nonetheless pilots tend to disconnect the autopilot because of uncertainty whether there is a malfunction in the flight control system [Vechtel 2010]. Here the indication of a wake presence appears helpful, as it does in support of wake alleviation functions (such as a special wake vortex mode of the controller). The necessity of displaying further information (e.g. encounter geometry) needs to be investigated.

If a hazardous wake encounter is predicted, best use can be made of a wake warning system if it can be employed to perform evasive manoeuvres. It is obvious that a depiction of the encounter geometry and surrounding obstacles increases the pilot's situational awareness during execution of the manoeuvre. Even if wake evasion is not possible due to the flight situation, an indication of a possible threat due to wake vortices can increase flight safety.

DLR is working on a Wake Encounter Avoidance and Advisory system (WEAA) which has the aim to avoid potentially hazardous wake vortex encounters by modifying the flight path as required. A conceptual system design has been performed, a simplified version of which is depicted in Figure 19. The basic idea behind this system is that evasive manoeuvres should be performed without the necessity to obtain an ATC clearance and just by subsequently informing ATC similar to TCAS manoeuvres. DLR aims at a proof-of-concept for selected system components with evaluation through flight simulation.

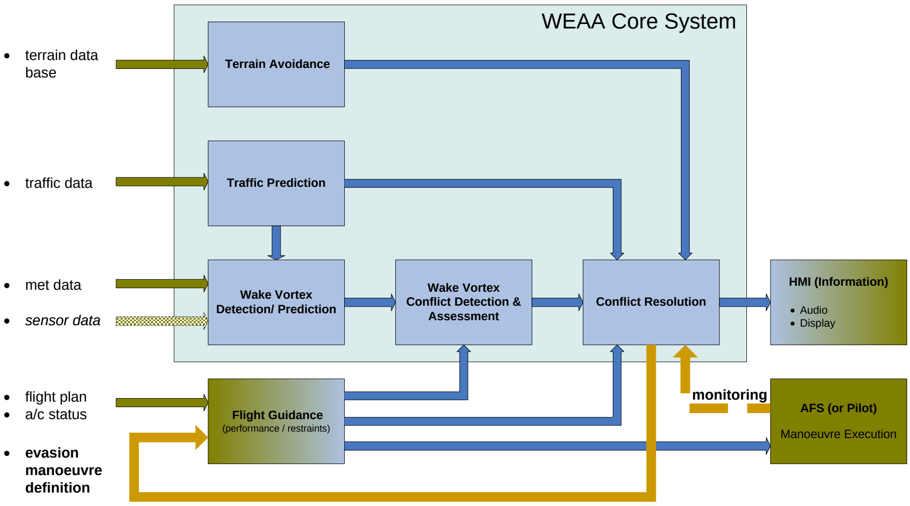

Figure 19: Simplified overview of conceptual architecture of DLR's Wake Encounter Advisory and Avoidance system (WEAA) [Vechtel, Bauer, 2010], [Schwarz et al. 2010].

The system

- performs data fusion of own aircraft data (flight state, flight plan, system states), traffic data obtained via ADS-B and meteorological data for wake prediction (at least wind vector) in real time;
- predicts wake vortices from performance data and planned trajectories of surrounding aircraft using meteorological data;
- performs a conflict detection, using prediction of own trajectory, followed by hazard assessment where required;
- generates an evasion trajectory, taking into account terrain data (from EGPS/TAWS database), which is designed to avoid triggering TCAS or GPWS warnings;
- provides guidance for the necessary evasive manoeuvres to the pilots, e.g. on PFD and VSI; and
- gives an overview display of the situation to increase the pilot's situational awareness, e.g. on the ND.

First implementations of trajectory generation algorithms have been developed. An operational concept development and display design for the HMI have been carried out [Raab 2010] and initial evaluation has been carried out in a simulator study. The work is on-going in the successor project "WOLV" which starts in 2012.

LiDAR sensor and vortex characterisation

Regarding the derivation of forward-looking sensor requirements driven by an automatic wake vortex control system, numerous offline simulations have been conducted in order to determine the performance of the controller as function of the sensor characteristics (such as sampling rate, measurement errors and resolution) and field of view. However, it is already foreseeable that the line-of-sight velocities available from current forward-looking sensors (e.g. as provided by LiDAR) cannot directly be used for an automatic control system.

Experience with on-board measurement is available from wake vortex encounter flight experiments at DLR. The encounter aircraft usually was equipped with one or multiple sensors (five-hole probes or vanes) that recorded three-dimensional airflow vectors while passing through the vortices (in-situ). The analysis method developed by DLR utilises an analytic wake vortex model and estimates its respective model parameters (i.e. circulation, vortex locations and spatial orientation) from the recorded flight test data. The applied wake vortex model with the identified parameters subsequently allows a very accurate reconstruction of the measured wake vortex flow field (Figure 20).

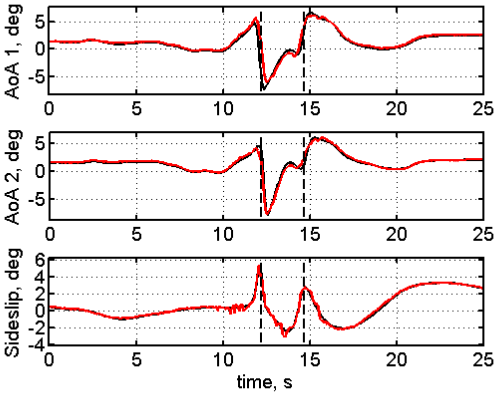

Figure 20: Fuselage vane signals (angle of attack and sideslip) measured in flight test (red line) and reconstructed signals using the identified analytic wake vortex model (black line).

This wake characterisation method developed by DLR is very versatile and not limited to three-dimensional flow-vectors as input. In order to achieve forward-looking detection capabilities, the algorithms were adopted to operate even with one-dimensional line-of-sight velocity measurements of a forward-looking LiDAR (Light

Detection and Ranging) sensor [Fischenberg 2009, Hahn et al. 2010]. In the considered configuration, the sensor scans a spherical pattern in front of the aircraft and measures the respective line-of-sight flow components at several discrete measurement locations (Figure 21).

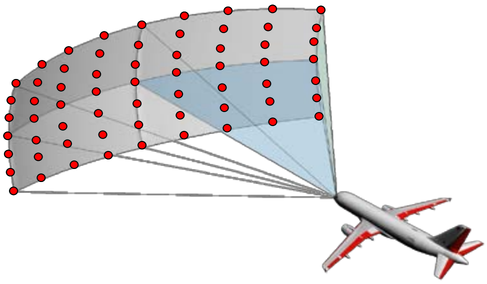

Figure 21: Spherically shaped scan pattern of an on-board forward-looking LiDAR sensor

Compared to the three dimensional flow vectors from the in-situ measurements using dedicated five-hole probes for research, the single line-of-sight velocities measured by LiDAR provide much less information about the flow field in front of the aircraft. The flow profile of a vortex is inherently predominantly two-dimensional so that especially for near axial arrangements the measured line-of-sight velocity components are very small. Consequently, large scan angles of the measurement pattern are necessary to assure that the LiDAR is able to measure flow components of a wake vortex even for shallow encounter angles.

The DLR characterisation method again utilises an analytic wake vortex model to reconstruct the flow field based on the measured line-of-sight velocities of the LiDAR. An a-priori analysis of the measurement data generates initial values of the model parameters. A subsequent Online Identification iteratively optimises these parameters in order to achieve the best possible reconstruction of the measured line-of-sight velocities (Figure 22). A patent application for the method was filed [Fischenberg 2009].

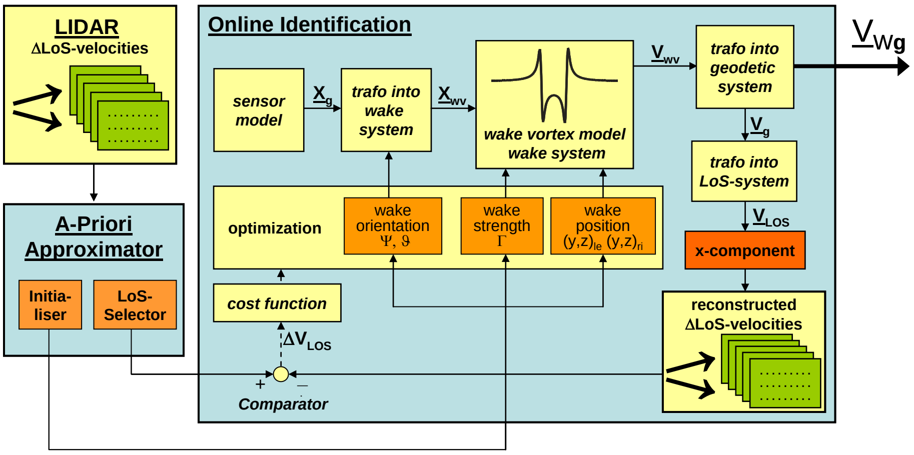

Figure 22: Outline of DLR's forward-looking wake vortex characterisation method

Wake impact alleviation

Regarding automatic control applications DLR has gained experience in the last years with automatic control specifically for wake vortex impact mitigation using forward-looking sensor data, designated as feed-forward control concept (see Figure 23). Assuming ideal knowledge of the 3-dimensional wind field in front of the aircraft, an Aerodynamic Interaction Model is used for the determination of the forces and moments induced by the wake vortex. The required control deflections needed for a (partial) compensation of the induced moments are calculated by inverting the aerodynamic control derivatives.

Several flight tests have been conducted on the DLR research aircraft ATTAS with the emphasis on the pilot evaluation of different in-flight simulated wake vortex encounters with and without automatic assistance [Hahn and Schwarz 2008], [Hahn et al. 2010]. In the most recent flight tests the automatic system was enhanced by using the Direct Lift Control (DLC) Flaps of the ATTAS in order to assess the benefits of the load factor compensation [Hahn et al. 2010] (see Figure 23). The resulting pilot ratings were compared to the results obtained in preceding flight tests (see Figure 24).

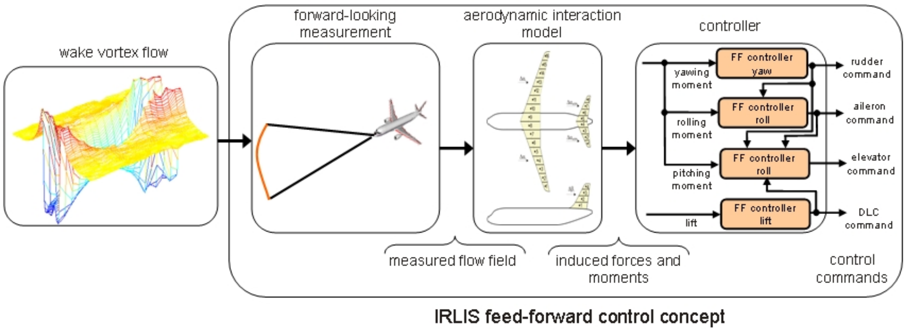

Figure 23: Principle of the feed-forward control assistance system

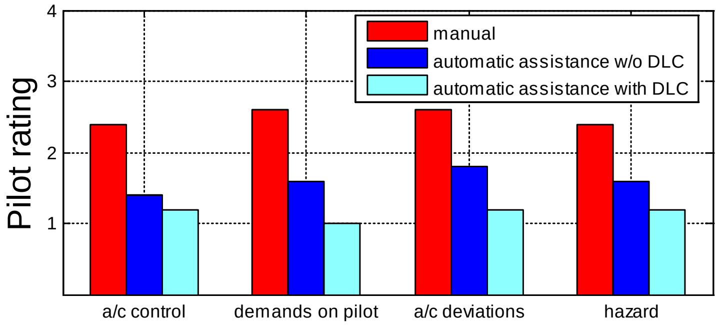

Figure 24: Average pilot ratings for in-flight simulated wake vortex encounters

Additionally, within the project “Wetter und Fliegen” DLR is working on an automatic control system for wake vortex mitigation feeding back conventional sensor data available on modern passenger aircraft. The research work in this area concentrates on the design of the structure and the gains of such a control system specifically used as a wake vortex alleviation system.

4.2.2.4 ALICIA project

ALICIA is a research and development project funded by European Commission under the Seventh Framework Programme, operational between 2009 and 2013. ALICIA aims at developing new and scalable cockpit applications which can extend operations of aircraft in degraded conditions. Stated commercial aircraft operational capabilities that shall support the achievement of ALICIA’s objective include “Fixed wing transport aircraft shall be able to support and improve flight crew situation awareness of approach and landing hazards (e.g. low visibility, visual illusions, energy management on contaminated runway, terrain, obstacles, wake vortices, microburst, etc.).”.

4.2.3 Research Needs

The airborne wake vortex detection / characterisation, warning conflict resolution and impact mitigation is a quite novel field and hence only little research work is known until today. The development of systems that reliably predict wake vortices in front of aircraft is highly desirable. By reducing the probability of wake vortex encounters, such systems would contribute to safety enhancements of the commercial air transport system. Furthermore, forward-looking detection systems are seen as a key technology to enable a reduction of today’s wake turbulence separation requirements in order to increase airport and airspace capacities.

The majority of research needs related to airborne wake vortex systems concern the different enabling technologies, for example, the associated wake vortex sensor. Related technology research needs are addressed in §5.2 of this report. Research needs specific to the underlying operational concepts are listed in §3.6.

4.2.3.1 Airborne, short-range forward-looking air data sensors

Continued research is needed to advance the technology of forward-looking air data sensors. Airborne, short range, forward-looking air data sensors are required to enable novel technologies for the suppression of wake impacts, especially those affecting the roll axis, by flight control. Such sensors need to reliably measure air velocities in front of an aircraft during all phases of flight and with high availability and accuracy in the order of 1 m/s or below. LiDAR is regarded as the potential enabling technology.

- Development of short-range LiDAR air data sensor demonstrator and flight tests

  Apart from measurement accuracy, frequency, range and availability, relevant requirements also exist with regard to size, weight and power consumption of such sensors. Important research efforts are required to achieve such sensor maturity. Also, for the purpose of testing such a new sensor itself as well as for the verification and validation of all connected aircraft functions – including coupled flight control systems – and in order to reduce any later certification risks, it is necessary to develop a technology demonstrator, to install it on a flight test aircraft and to evaluate the overall system operation through flight trials.

4.2.3.2 Airborne, mid- to long-range wake vortex sensors

Continued research is needed to identify and advance fundamental technologies for the mid- to long-range detection, tracking and possibly characterisation of wake vortices. Such a sensor would enable novel airborne wake vortex concepts permitting wake avoidance based on measurement instead of model predictions, with the associated increase in accuracy and acceptance.

- Assessment of sensor technologies suitable for the mid- to long-range detection, tracking and characterisation of wake vortices.

  Candidate solutions need to be identified and assessed taking into account functional as well as aircraft installation requirements. Sensor technologies also suitable for other surveillance functions like weather, turbulence, volcanic ash, obstacle detection etc. should be preferred. Promising solutions should be evaluated using technology prototypes. Complementary and/or alternative technology solutions should be investigated.

- Evaluation of advanced sensor-model-fusion technology to improve mid- to long-range sensor capability with regard to wake vortex detection, tracking and characterisation.

  Sensor capabilities may be improved by combining sensory information with wake vortex model predictions based on data link. Associated concepts should be developed and evaluated with regard to their potential to reduce sensor weight and power consumption.

4.2.3.3 Real-time, on-board meteo data fusion

Continued research is needed with regard to the real-time provision of fused meteorological data required for wake vortex predictions. It is necessary to investigate how this can be derived on-board an aircraft using meteorological data disseminated through data links from multiple, dissimilar sources. Such meteo functions need to provide estimates of wind speed and direction (wake transport by wind) as well as atmospheric turbulence (effect on wake decay) in the vicinity of the aircraft. Optimally, such functions also provide reliable accuracy estimates for use in probabilistic vortex models.

- Identification of data requirements with regard to parameter definitions, update rates, accuracies and reliabilities.

  Comprehensive data requirements need to be established taking into account the functional architectures of related airborne systems, their capabilities, and wake vortex model requirements.

- Identification of potential data sources, data links and associated standards
- Methods for the fusion as well as temporal and spatial extrapolation of such meteo data

  Methods need to be developed and validated that allow fusion as well as temporal and spatial extrapolation of meteo data stemming from different and dissimilar sources (e.g. air-to-air and ground-to-air data links).

Further related research needs are detailed in §5.3 of this report.

4.2.3.4 Operational, probabilistic wake vortex prediction models

Airborne wake vortex systems need operational vortex models for all phases of flight. These models need to be sufficiently fast in order to support airborne, real-time applications. They need to be flexible with regard to varying levels of input data availability and accuracy. They need to be validated for different levels of application (safety net, capacity increase) and different phases of flight.

- Can all necessary input data, especially met and traffic data, be made available on-board the aircraft with the required accuracy, reliability and update rate?
- Solutions requiring minimum computational effort need to be established.

Further related research needs are detailed in §5.1 of this report.

4.2.3.5 Online wake characterisation

Additional research is needed towards the real-time, online characterization of a wake vortex (determination of the wake properties like strength and position) based on multiple information sources including existing as well as novel aircraft sensors and using enhanced technologies like model-sensor filters. Such wake characterisation can provide significant benefits over directly using sensor measured velocities in combination with novel wake encounter alleviation flight control techniques. Today, detection methods and algorithms are still in an early stage of development. Potential is seen in the further adaptation of the detection algorithms to the individual properties of specific sensor technologies. Since recent development work still is based on numerically generated measurement databases it is highly desired to work with genuine measurement data or even to move to hardware-in-the-loop experiments in the future.

4.2.3.6 Alerting and conflict resolution

Additional research is needed with regard to the appropriate way of alerting pilots, the identification of a resolution manoeuvre and the necessary guidance for such a manoeuvre in case of airborne wake vortex system activation.

- Human-Machine Interface and Human Factors of wake vortex alerting as well as conflict resolution.

  What is the best way (Human-Machine Interface and Human Factors) to warn the pilot and suggest a conflict resolution (visually and/or aurally)? It must be analysed how visual/aural warnings could be optimised to give the pilot the best situational awareness.
- Concept and algorithm for the creation of avoidance trajectories taking into account terrain (TAWS), other traffic (TCAS) and own aircraft capabilities.

  Identification of an evasion trajectory for conflict resolution has to be optimised regarding computational effort (computation time) and deviation from the planned flight path. An optimised concept/algorithm for evasion trajectory generation needs to be developed which takes into account terrain (TAWS), other traffic (TCAS) and own aircraft capabilities. The benefits and feasibility to perform evasive manoeuvres in 3-D need to be evaluated (i.e. not only lateral or vertical evasion). Finally research is necessary to confirm whether a tactical approach (i.e., no change in flight plan) is generally sufficient for the avoidance manoeuvre.

4.2.3.7 Flight control alleviation of wake-induced disturbances

Additional research is needed with regard to new fly-by-wire flight control concepts allowing improved stability of wake encountering aircraft.

- Evaluation of adapting flight control feed-back gains in wake encounter situations.
- Evaluation of novel flight control concepts for improved stabilisation in wake encounter situations.

  Up to now evaluations of the feed-forward automatic assistance have mainly been performed using idealized measurement data. This especially concerns the assumption of the availability of the complete 3-dimensional velocity vector. In fact today's forward-looking sensors are only capable of providing reliable line-of-sight measurements. Therefore a future research field is the combination of on-board detection algorithms, such as the online identification method described in [Fischenberg 2009], and the feed-forward control assistance system as described in this section. In this case the required velocity vectors are derived from a wake vortex model whose parameters are identified by using forward-looking measurements.

  Another open issue for the application of such a system is the prevention of unintended commands that might even increase the effect of the wake vortex induced aircraft reaction, and the robustness of the approach (a vortex must not be interpreted into a (turbulent) flow field when there is none).

  Further research is needed for the integration of wake vortex mitigation systems in modern highly augmented and automated aircraft, because previous research work was concentrating on aircraft with conventional mechanical flight control systems.

  The use of manual augmented control laws, such as the C*-law, and automatic control algorithms has great impact on the aircraft reaction during a wake vortex encounter. This raises the following questions: What is the best piloting technique for (highly) augmented aircraft during a wake vortex encounter? And what are the benefits of adapting the feedback gains of the manual or automatic control laws during a wake vortex encounter?

  First simulation trials have indicated that the pilot's reaction might be more appropriate if the pilots knew that the aircraft reaction results from a wake vortex encounter. Consequently an aural or visual warning might improve the pilot's reaction during the encounter. The design, the integration into the current cockpit architecture and the evaluation of such a system are future research topics, even if initial steps have been taken by [Raab 2010]. This system should also indicate the status of the automatic assistance system

- Evaluation of the impact of the vortex flow field on aircraft air data sensors and associated effects on flight control stabilisation capabilities.

  Specifically the two following interactions between the flow field and the control system also need further consideration

  - Local stall effects: Current Δ-aerodynamic models for vortex induced forces and moments are limited to the linear region of the lift curve, as stall effects cannot be taken into account. Is this sufficient in all cases, especially when slowly flying aircraft encounter high vertical wind velocities? It is especially necessary to ascertain that the authority of the control surfaces, in particular the ailerons, is not negatively affected.
  - Effects of vortex field on flow sensors: The high local velocities affect the alpha and air speed sensors of the aircraft; additionally the barometric height measurement is perturbed if the vortex core with its changes in static pressure is encountered. The effects on the flight control system need to be investigated (e.g. an angle of attack protection might be inadvertently triggered; the aerodynamic state assumed may not be representative of the aircraft).

4.2.3.8 Harmonized and integrated operational concepts

Additional research is needed to assure harmonization between airborne and ground-based wake vortex advisory systems and their contributions and roles as part of new wake vortex separation rules. Research is also needed to allow airborne wake vortex system operations and hence benefits in the context of existing and future air traffic operational concepts.

- Integration of airborne wake vortex avoidance systems with ATC in general and interoperability with new ground-based wake vortex advisory systems.

  The capabilities of new airborne wake vortex systems need to be taken into account in related ATC operational concepts. Research is needed to assure harmonised operations yielding maximum benefits. Harmonised definition and application of pair-wise dynamic separation concepts within SESAR, NextGen and in other world regions needs to be assured.

- Acceptability and operational treatment of small-scale tactical avoidance manoeuvres as a result of wake vortex avoidance.

  Small-scale avoidance manoeuvres are an important possibility to reduce the risk of severe wake encounters, especially en-route. The effects on flight safety need to be studied and system requirements need to be derived.

- Harmonization and integration with other operational concepts

  Conceptual research related to the integration of new airborne wake vortex system capabilities with the manifold new aircraft operational concepts envisioned as part of SESAR and elsewhere (e.g. ASAS Self Separation, 4D-Business Trajectories, Wake Vortex Free Approach) is required. New technologies under research for stand-alone wake vortex detection, prediction, alleviation and avoidance systems are expected to be well suited to also assure wake encounter safety in combination with such new operational concepts but additional effort is required to identify integration options, to integrate these functionalities and to assure harmonised concepts. Required Performances should be set up for different ASAS-SSEP levels. This would allow the integration of technologies available in the near term into airborne systems for lower required performance levels. Technologies available in the long term could then be integrated to reach higher performance levels.

4.2.3.9 Safety assessment

Additional research is needed to identify how the capabilities of airborne wake vortex systems and vulnerability of follower aircraft can properly be taken into account in wake vortex safety assessments (see §6.2) and using which metrics (see §5.5.2.5).

- Definition of means of compliance and safety case requirements

  Probably the biggest hurdle towards the development of airborne systems aiming at reducing wake turbulence separation requirements while assuring today's safety level is the uncertainty with regard to means of compliance and safety case requirements. While there have been recent advances related to wake turbulence safety assessments (e.g. A380, WIDAO), these primarily take into account the characteristics of the wake vortex but not specifically the capabilities of the follower aircraft. Industry will remain cautious towards developing new aircraft wake vortex systems as long as it is unclear if and how such systems' new capabilities will be taken into account in future separation standards and how such systems can be qualified.

4.2.3.10 Required operational environment

Additional research is needed to fully define the required operational environment.

- Availability of additional air-to-air and potentially ground-to-air data link capabilities specifically required by airborne wake vortex systems.

Research need to identify harmonized system needs.

- Definition of performance levels and requirements for wake vortex related operational concepts

  Research is recommended on the impact of wake vortex separations on these new ATM concepts, themselves based on different performance levels of evolving airborne wake vortex mitigation and alleviation systems. While dedicated systems (e.g. on-board wake vortex mitigation systems) should be linked to operational concepts (e.g. ASAS applications with wake vortex recognition) already in the short term, it should be noted that systems in the mid and long term are expected to satisfy the operational concept requirements based on different technologies (e.g. wake vortex prediction, wake vortex detection, usage of available and upcoming data links or a combination of different technologies, etc.). Therefore, research is also recommended on defining performance levels in terms of accuracy, integrity, continuity and availability for wake vortex related operational concepts.

4.2.3.11 Validation of operational efficiency

Additional research is needed to fully validate the operational efficiencies of airborne systems.

- Evaluation of system demonstrators in an operationally relevant simulated environment including normal and abnormal operational circumstances

  The operational efficiency, benefits and acceptance of airborne systems depend on their ability to prevent a significant number of wake vortex encounters while at the same time not leading to undue numbers of false alarms. Whereas the probability of prevention is linked to the risk reduction provided by such systems (and hence its operational benefit with regard to safety and capacity), too high levels of false alarms will render such system simply unacceptable. Hence, representative systems need to be tested in normal as well as abnormal operational conditions using ground-based simulations in addition to analysis. Acceptable false alarm rates need to be established through pilot evaluations.

5. Technologies and Methodologies

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The chapter Technologies is leading through the multifaceted disciplines that shall enable the implementation of wake vortex concepts by the provision of models, instrumentation, and understanding. Also the approaches discussed in §6 Safety significantly depend on the available technologies. On one hand, the capabilities of the respective technologies control the feasibility of the concepts and systems; on the other hand, the delineated concepts and systems may trigger developments of technologies. Anyway, technologies research may reveal fascinating insights in various disciplines like vortex dynamics, remote sensing, weather prediction, aerodynamics, flight dynamics or even human (pilot) behaviour models.

5.1 Wake Vortex Behaviour Modelling

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5.1.1 Overview

Wake vortex behaviour modelling is the technology relating to the operational (thus necessarily simplified) modelling of aircraft wake vortex behaviour: the transport and the decay of the port and starboard vortices of the two-vortex system formed after complete rollup of the wake behind an aircraft. Those vortices are influenced by various parameters: the characteristics (weight, span, flight speed, attitude, span loading) of the aircraft that generates them, the local meteorological conditions (cross wind and head wind, wind shear, turbulence, stratification) in which they then evolve, and the ground proximity conditions which also affects their transport and decay.

Depending on application, *operational* refers to such software tools being useable for off-line studies or for real-time systems.

The operational models developed are physics-based (hence they are also called “physical models”) and aim at predicting the behaviour of the wake vortices in one plane crossing the flight path. The models are expressed, typically, as ordinary differential equations (ODE; with added stochastic components in some cases), and that are integrated in time. Some models also take into account the uncertainty/variability of the impact parameters: they are then denoted probabilistic.

Operational wake vortex models are still being further developed and used essentially in Europe and in the USA. Two platforms have also been developed that use the European models in several gates to rebuild the 3-D wake generated by an aircraft evolving in given meteorological conditions, also enabling analyses relating to potential wake vortex encounter.

For some applications, wake vortex behaviour modelling also refers to modelling the expected topology of the wake vortices (e.g., amplitude of the Crow instability development, topology of the vortex rings formed after reconnection and their decay).

Also the use of velocity field databases in flight simulators, obtained from very detailed large-eddy simulations (LES) of wake vortices in specific conditions, can be considered as some kind of “operational modelling”. As such databases can be very large (e.g., 1 GB for one 3-D velocity field at one time), they must be reduced to a smaller set for real-time access in the flight simulator. In some cases (e.g., Crow instability in weak atmospheric turbulence and without or weak stratification), the database itself can be reduced to a simplified mathematical model which fits properly the main vortex 3-D topology; the model can then, in turn, be used to feed the flight simulator with velocity fields computed using an efficient Biot-Savart evaluation.

Finally, this section also describes recent developments achieved with LES and the analysis of field measurement data.

5.1.2 State-of-the-art

There are two European operational wake vortex models:

- the Deterministic/Probabilistic Two-Phase wake vortex decay and transport model (D2P/P2P) of DLR, and
- the Deterministic/Probabilistic wake Vortex Model (DVM/PVM) of UCL

and three US models:

- the AVOSS Prediction Algorithm (APA), a deterministic wake vortex model developed by several groups and researchers,

- the Vortex algorithm Including Parameterized Entrainment Results (VIPER), a deterministic model recently developed by NWRA for the FAA,
- the TASS Driven Algorithm for Wake Prediction (TDAWP), a deterministic model developed by NASA with still limited functionality.

These models forecast, deterministically or probabilistically, the transport and decay of wake vortices generated in one slice across the flight path.

Two platforms have also been developed. Each one uses a European operational model in several gates to rebuild the 3-D wake generated by an aircraft evolving in given met conditions, also enabling potential encounter analysis:

- WakeScene (see §6.2), developed by DLR, that uses the D2P/P2P and
- WAKE4D (see §6.2), developed by UCL, that uses the DVM/PVM.

The European operational models were continuously developed, improved and used, also in the framework of several large-scale projects. The projects in which the models were, and are still, used are listed below.

- Wirbelschleppe I & II (1999-2007) “Fundamental and applied wake vortex research”, DLR Project
- S-Wake (2000-2002): “Assessment of wake vortex safety”, FP5
- C-Wake (2000-2003): “Wake vortex characterization and control”, FP5
- I-Wake (2002-2005): “Instrumentation systems for on-board WAKE-vortex and other hazards detection, warning and avoidance”, FP5
- ATC-Wake (2002-2005): “Integrated Air Traffic Control WAKE vortex safety and capacity optimization system”, FP5
- AWIATOR (2002-2007): “Aircraft WIng with Advanced Technology Operation”, FP5
- FAR-Wake (2005-2008): “Fundamental Research on Aircraft Wake Phenomena”, FP6
- FLYSAFE (2005-2009): “Airborne Integrated Systems for Safety Improvement, Flight Hazard Protection and All Weather Operations”, FP6
- CREDOS (2006-2010): “Crosswind Reduced Separations for Departure Operations”, FP6

  In the EU project CREDOS the D2P and DVM models have been used within the WakeScene-D package to estimate the probability to encounter wake vortices during departures in different traffic and crosswind scenarios. Comprehensive sensitivity analyses have been conducted and crosswind scenarios for reduced separations have been evaluated (see §3.1).
- TBS (2006-2008): EUROCONTROL “Time-Based Separation project”

  The WAKE4D-DVM/PVM was used in the first phase of the EUROCONTROL project “Aircraft Wake Vortex Modelling in support to Time-Based Separations on Final Approach''. This work was a partnership between UCL and M3Systems. The WAKE4D platform was used for a comparative risk analysis. The wakes generated by various aircraft in various wind conditions were simulated. A risk metric using the highest possible circulation of the potentially encountered vortices was also computed and was used to compare applying the current distance-based separations in still air conditions to applying the time-based separation (Desenfans 2010).
- Green-Wake (2008-2012): “Demonstration of LiDAR based wake vortex Detection System incorporating an Atmospheric Hazard map”, FP7
- WIDAO (2007-2010): “Wake-Independent Departure and Arrival Operations (WIDAO) at Paris CDG airport”, EUROCONTROL and DSNA project

The WAKE4D-PVM was also used for a fast-time study that aims to quantify the impact on landing medium aircraft safety of wake turbulence generated by heavy aircraft departing on parallel runways. Different scenarios of departure were investigated and the impact on the wake frequency/severity curves of the potentially encountered vortices was studied. The curves correspond to the complementary cumulative density function (CCDF) of the circulation. This study was performed for the CDG airport in the framework of the EUROCONTROL and DSNA WIDAO project. The purpose of the project was first to quantify the increase of frequency and severity of potential wake vortex encounter (WVE) by medium landing aircraft if the departing heavy aircraft are lined up shifted ahead of the currently used runway entry. It also aimed to compare the results with the frequency/severity curve of potential WVE at ICAO separation in trail behind a heavy aircraft. In that project, more than 4000 departing aircraft were considered in about 2000 different wind conditions and for two pairs of runways.

- RECAT (started in 2008): “Re-categorization of the Wake Turbulence Separation Minima”, Joint EUROCONTROL-FAA project

  In the framework of the joint EUROCONTROL-FAA RECAT project (see §3.5), Phases II and III, DLR and UCL (Gerz et al. 2011, Winckelmans 2011) proposed that the operational models should be used, in addition to the very simplified model (fitted on measurements close to the ground) with assumed linear decay which was used in Phase I.

- Wetter & Fliegen (2008 - 2012): “Airport and aircraft wake vortex, thunderstorm, and winter weather systems”, DLR Project

- SESAR P6.8.1 (started in 2010): “Wake vortex data analysis and modelling”, led by EUROCONTROL

  In the framework of SESAR P6.8.1, described in Sections 3.1 and 3.4, and in collaboration with EUROCONTROL, it is planned that UCL will also compare the results of their models (DVM/PVM in WAKE4D) to those of large-scale measurement campaigns (e.g., the Heathrow campaign).

- SESAR P12.2.2 (started in 2011): “Runway Wake Vortex Detection, Prediction and Decision Support Tool”, led by Thales

  As subcontractors to Thales, UCL and DLR integrate their wake vortex prediction platforms (WAKE4D and WakeScene) into the WVDSS platform described in §6.2.2.4. In the framework of the project, the predictor will also be benchmarked and validated. The final platform will also integrate the concept and system defined, also with EUROCONTROL, in the project P6.8.1.

- SESAR P9.11: “Aircraft Systems for Wake Encounter Alleviation” and P9.30:” Weather Hazards / Wake Vortex Sensor”, led by Airbus and started in 2011

  As subcontractors to Airbus, UCL and DLR bring their probabilistic models (PVM and P2P) of wake vortex behaviour in and out of ground effect, and adapt them to the requirements of a real-time, airborne warning system WEPS-P (Wake Encounter Prevention System based on Prediction, see §4.2). The models will also be verified against wake measurements.

- WSVBS

  The P2P model has been applied for performance tests of the WSVBS (see §4.1.2.2) at Frankfurt airport in winter 2006/07 and at Munich Airport in summer 2010 and spring 2011 for landings on single runways as well as closely-spaced parallel runways either for aircraft weight class combinations or dynamic pairwise separations.

- Wake vortex encounters in cruise flight

  In a cooperation between DLR and NCAR (National Center for Atmospheric Research) funded by FAA the probability to encounter wake vortices en route will be estimated employing the P2P and the WaVoP (Wake Vortex Prediction) model. WaVoP is an adaptation of CoCiP (Contrail Cirrus Prediction Tool, Schumann 2011) which supports the identification and quantification of potential encounters employing air traffic density and weather data bases.

5.1.2.1 Deterministic and Probabilistic wake Vortex Model (DVM / PVM)

UCL's Deterministic wake Vortex Model (DVM) is a deterministic model based on the method of discrete "vortex particles" that models the primary wake vortices (generated by an aircraft) as well as the "secondary" vortices (generated when the vortex comes into ground effect, IGE). The DVM takes into account the influence of the generating aircraft characteristics (position, aircraft configuration, span, weight, and airspeed), the atmospheric conditions (the vertical profiles of head-, crosswind, wind shear turbulence and temperature stratification, see also §5.1.2.7), and the ground proximity (see §5.1.2.5). A simplified model of the Crow instability growth is also included and was also validated using LES results (see §5.1.2.7). The wake vortex evolution (i.e. transport and decay) is computed, using simplified physical models, in a plane ("computational gate") that is perpendicular to the trajectory. Results are the time evolution of the vortex position and strength. Two initialization options are available in the DVM. Either a vortex sheet (with a certain circulation distribution model) is discretised using vortex particles, or a chosen circulation distribution model (i.e., one-scale models: the low-order algebraic model (Burnham-Hallock) or the high-order algebraic model; or even the more complex, two-scale model of Proctor-Winckelmans) of rolled up vortices is used and is itself discretised. The model has been improved, calibrated, assessed and validated against data of US and EU measurement campaigns and results of Large Eddy Simulations (LES), also in the framework of EC funded projects. Figure 25 provides an example of comparison between DVM predictions and measurements (form the EDDF-1 database) for a NGE/IGE case.

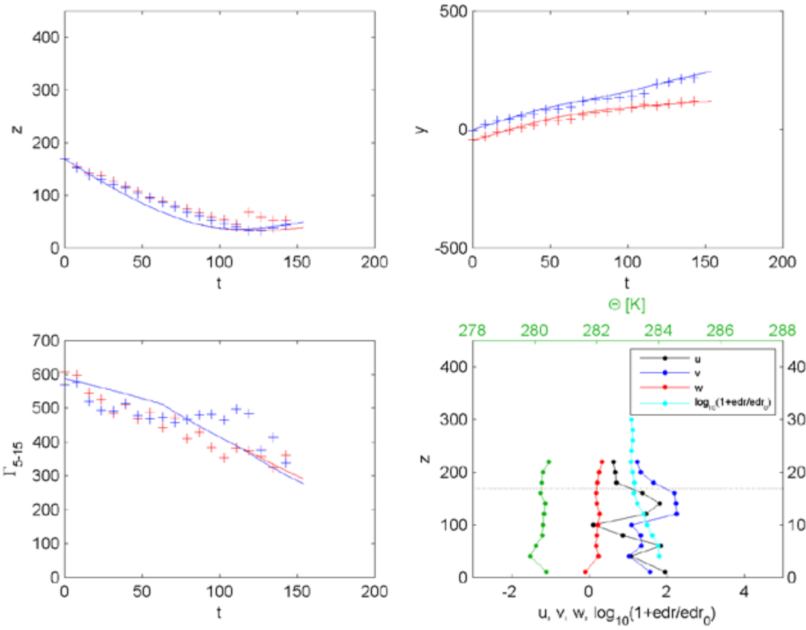

Figure 25: Example of comparison between EDDF-1 measurement data (crosses) and DVM prediction (solid). Red and blue colours are used respectively for the starboard and the port vortices. The measured met data are also provided ($edr_0 = 10^{-5}$ m^2/s^3).

The Probabilistic wake Vortex Model (PVM) uses the DVM as sub-tool in a Monte Carlo approach with variations of the impact parameters (inputs, i.e. aircraft characteristics and weather profiles, and model coefficients). Those parameters are varied depending on their natural variations (for the met data), their uncertainty (for the met and aircraft data) and their calibration (for the coefficients of the physical models). So each PVM run uses many DVM runs. The total number of DVM runs used is large, yet is not directly related to the number of varied input parameters. This enables to obtain the statistics of the results (vortex positions and circulation) in one computational gate. The PVM also uses the bootstrap resampling technique that enables to obtain conservative statistical results while limiting the number of DVM runs.

The WAKE4D, and its subcomponents DVM and PVM, have been used in fast-time and real-time simulations of WVEs as well as a vortex forecast function in experimental detection, warning and avoidance systems in aircraft and on ground. A Graphical User Interface (GUI) was also developed for easy use of the DVM/PVM. This GUI is also useful for demonstration or training purposes. These developments were aimed at allowing more easily a transfer of the simulation tools to other users. The WAKE4D and its subcomponents DVM and PVM are described in detail in (Winckelmans et al. 2010, De Visscher et al. 2010 and Winckelmans et al. 2011)

5.1.2.2 Deterministic and Probabilistic 2-Phase Model (D2P/P2P)

DLR's Deterministic 2-Phase model (D2P) computes the transport and decay of the wake vortex pair in a 2D plane (gate). It takes into account the aircraft characteristics: weight, wing span, flight speed, position, height above ground, flight path angle, and bank angle. The model considers the vertical profiles of the meteorological quantities: head wind, cross wind, wind shear, turbulence (TKE, EDR), and temperature stratification (gradient of potential temperature). All parameters are normalized based on initial vortex separation, b_0, and initial circulation, Γ_0. The probabilistic version P2P is based on the uncertainties of wake vortex evolution found in LES and field experiment data. Uncertainty allowances are modelled by conducting three model runs with different fixed and dynamic uncertainty parameters. Finally, the probabilistic envelopes for vortex position and strength are calibrated employing field measurement data. The model has been validated against data of over 10,000 cases gathered in two US and six EU measurement campaigns. With a computation time below 0.01 s on a standard personal computer, P2P is suited for fast-time simulations. The D2P and P2P have been used in fast-time and real-time simulations of WVEs and in risk analysis tools (see §5.5) as well as in airborne and ground based experimental wake vortex prediction and avoidance systems (see sections 4.2 and 3.4). The model design and applications to field measurement data are described in detail in (Holzäpfel 2003, Holzäpfel and Robins 2004, Holzäpfel 2006, Holzäpfel and Steen 2007, Frech and Holzäpfel 2008, Holzäpfel 2011).

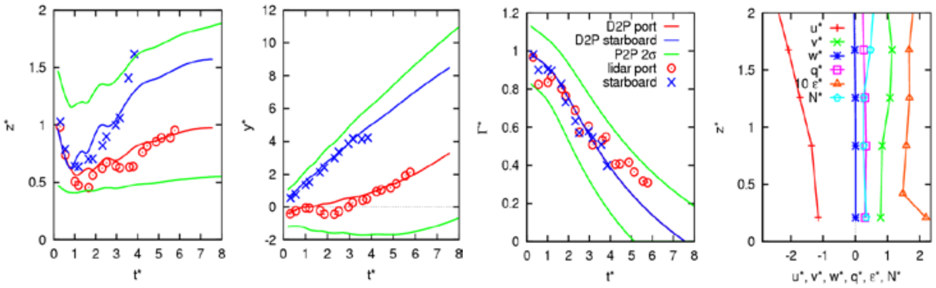

Figure 26: P2P prediction of wake vortex behaviour in ground proximity. Measured (symbols) and predicted (lines) evolution of normalized vertical and lateral positions and circulation. Red and blue lines denote deterministic predictions; green lines are envelopes for 95.4% probability. Right: Vertical profiles of normalized environmental data.

Figure 26 left shows exemplarily the asymmetric rebound of the wake vortices in a crosswind situation close to the ground. Also the measured vortex divergence (second from left) and the circulation decay (third from left) are well predicted by the D2P. One LiDAR measurement point of vertical position is situated outside of the predicted probabilistic envelopes (2σ corresponding to 95.4%) of wake vortex behaviour.

Currently, the vortex model is further improved. The Probabilistic 3-Phase (P3P) wake vortex model is based on core elements of the P2P model and improves vortex position and circulation prediction in particular in the late stages of the vortex life (far field of the wake) where vortex rings are forming. The P3P model combines the circulation evolution phases of gradual diffusion, rapid decay and ring diffusion.

5.1.2.3 Description of the US operational models

The APA 3.2 model predicts wake vortex trajectories and circulation within a plane perpendicular to the path of the generating aircraft (Sarpkaya et al. 2001, Robins and Delisi, 2002). Atmospheric inputs include vertical profiles of the ambient crosswind, temperature, and turbulence intensity (represented by EDR). The initial wake is represented as two vortices whose initial strength and position are dependent upon input conditions.

If the wake is out of ground effect, the APA model utilizes a decay and transport model, such as developed by Sarpkaya (Sarpkaya 2000). For in ground effect, APA utilizes image vortices to represent the effect of an impenetrable ground, and the introduction of secondary vortices that cause wake vortex rebound. The method for vortex decay while in ground effect depends on a formula derived from a TASS LES study (Proctor et al. 2000). The latest APA version, Suite 4.0, is similar to APA 3.2, but allows the option of using Sarpkaya, TDAWP, or D2P as the OGE module.

The TDAWP model is a deterministic wake vortex model. It has separate prognostic equations for vortex descent rate and 5-15 m average circulation, and it applies these separately to both the port and starboard vortices (Proctor et al. 2006). The formulation is driven by parametric studies from LES using TASS (Proctor and Switzer 2000). The TDAWP formulation includes the effects of crosswind shear on vortex descent rate, thus allowing the prediction of vortex tilt and the change in lateral separation due to crosswind. Ground effect is not yet included in the model.

The VIPER model is being developed for the FAA by NWRA (Delisi 2011). It will be used to predict the evolution of aircraft-generated wake vortices under a variety of atmospheric conditions and aircraft flight regimes for evaluating new, proposed operational procedures. It is based on control-volume analyses and the fluid laws for conservation of mass, momentum, and angular momentum. An IGE model is currently being developed to be combined with the OGE model.

5.1.2.4 Multi-Model Ensemble

In a recent study the prediction skills of several deterministic wake vortex models have been compared (Pruis and Delisi 2010, Pruis 2011). It is found that the models are generally pretty good. However, a “best” fast-time numerical wake vortex model cannot be determined due to uncertainties in accuracy of the input environmental and aircraft conditions. As a consequence, it is suggested to utilize multiple fast-time wake vortex models and to determine the probabilistic estimates of wake vortex behaviour using the model ensemble. Such multi-model ensembles have proven to be successful for probabilistic weather prediction (see § 5.3). The finding that the uncertainties and variability of the initial and environmental conditions have a dominant impact on wake vortex prediction skill is well known; see e.g. (Holzäpfel 2009, Winckelmans et al. 2009, Winckelmans and Bourgeois 2010).

5.1.2.5 Wake vortex interacting with the ground and the wind: simulations and modelling

In the FAR-Wake project, significant researches were achieved on wake vortex physics and operational modelling NGE/IGE, also for cross-wind or headwind (Holzäpfel et al. 2008). They were supported by the results of Large Eddy Simulations (LES) performed in the framework of the project (Giovannini et al. 2007) and by the data of the WakeFRA 2004 measurement campaign (Holzäpfel & Steen 2007). In addition, complementary studies were performed to analyse the result sensitivity to the crosswind amplitude and to the generation altitude. The IGE models of the DVM and of the D2P have then been further improved.

LES studies of wake vortices IGE: sensitivity analysis to the crosswind amplitude and to the generation altitude

In addition to the work performed in the FAR-Wake project (Giovannini et al. 2007), further wall-resolved LES investigations of wake vortices IGE and with realistic turbulent crosswind were carried out by UCL, in collaboration work with Airbus, using an improved subgrid-scale model (Bricteux et al. 2009), valid for both vortex flows and wall-bounded. Four cases were considered with various wind amplitudes and release altitudes. A visualization of the flow field for the case with the strongest investigated wind is provided in Figure 27. DLR has also conducted wall-resolved and wall-modelling LES of wake vortex evolution in ground proximity with and without wind. Figure 28 left shows the interaction of the primary wake vortices with the turbulent structures generated by some crosswind at the ground surface.

In Figure 27 and 21 left, one observes the vorticity sheet, generated at the ground, by the presence of the primary vortices that detaches from the ground and starts rotating around the primary vortices. Triggered by crosswind streaks those secondary vorticity sheet transforms into so-called omega loops wrapping around the primary vortices and initiating vortex decay.

UCL performed detailed analyses of the wake vortex transport and decay. In particular, the circulation distribution, Γ(r), of the longitudinally averaged vortex (flow averaged over the computational plane of the longitudinal direction) was evaluated as a function of time, enabling to obtain both $\Gamma_{5\text{-}15}$ and Γ_{tot} of each “mean vortex”. In addition, the circulation distribution was also measured in each computational plane which enables also deriving the statistics of $\Gamma_{5\text{-}15}$ and Γ_{tot}. The results allow the estimation of the spread that can be expected in LiDAR measurements derived values of $\Gamma_{5\text{-}15}$ or Γ_{tot} (as a LiDAR measurement scans a plane, not a mean vortex). Further, the results were used to calibrate the DVM/PVM transport and decay parameterizations (see below). The report by UCL to Airbus (Bricteux et al. 2009) will be used to produce a publication. Some of this work was also presented at an ASME conference (Bricteux et al. 2009).

DLR further investigated the influence of the introduction of obstacles at the ground surface (see Figure 28 right, Stephan et al. 2012). It can be seen that the obstacle may substantially accelerate vortex decay in the critical area close to the threshold where most vortex encounters occur. Such a setup specifically exploits properties of vortex dynamics to accelerate wake vortex decay in ground proximity with the following characteristics: (i) early detachment of strong omega-shaped secondary vortices, (ii) omega shape causes self-induced fast approach to the primary vortex, (iii) after the secondary vortex has looped around the primary vortex, it separates and travels both ways along the primary vortex, again driven by self-induction, (iv) the artificially generated secondary vortex connects to the regular ground effect vortex and thus obtains continued supply of energy, (v) the highly intense interaction of primary and secondary vortices leads to rapid wake vortex decay independent from natural external disturbances.

Good agreement with towing tank experiments has demonstrated another proof of concept (Geisler & Konrath 2012). In a next step the obstacles have been optimized with respect to size and shape. LES indicate that plate lines cause even slightly stronger effects than much more massive block-shaped obstacles (Stephan et al. 2012). The beneficial effects are robust with respect to headwind and crosswind. The time for decay to 50% of the initial vortex strength can be halved by the introduction of the barriers.

In summary the introduction of plate lines at the ground supports the selective generation of secondary vortices and enables a smart utilization of vortex properties in order to generate fast approaching and rapidly spreading disturbances leading to premature vortex decay in ground proximity. The installation of suitable obstacles at runway tails may improve safety by reducing the number of wake encounters and increase the efficiency of wake vortex advisory systems. A respective patent entitled “Surface Structure on a Ground Surface for Accelerating Decay of Wake Turbulence in the Short Final of an Approach to a Runway” has been filed under number DE 10 2011 010 147. Flight experiments will be conducted at Oberpfaffenhofen airport (Germany) in order to demonstrate the real-life functionality of plate lines for the release of premature wake vortex decay in the most critical flight phase prior to touchdown.

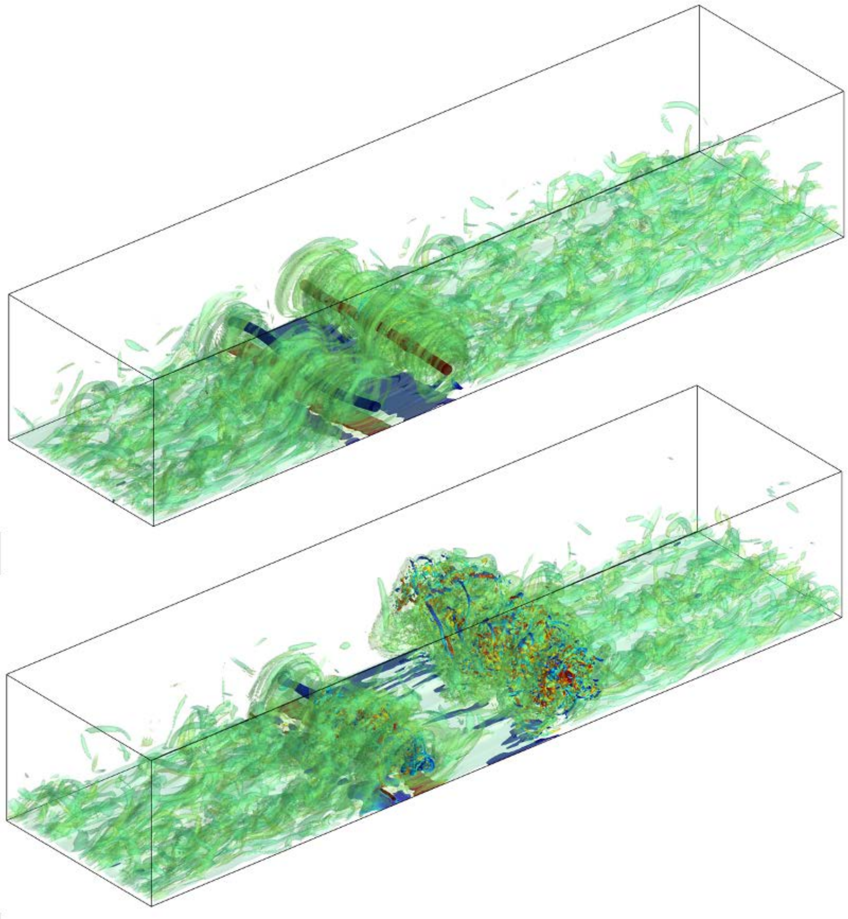

Figure 27: Wake vortices IGE and with turbulent cross-wind $v(h_0) = 2\ V_0$ and with $h_0=b_0$: Iso-surfaces of vorticity norm coloured by the axial vorticity ω_x at time $t/t_0 = 1.0$ (top) and $t/t_0 = 2.0$ (bottom; by that time, the downwind vortex has already much decayed and lost coherence).

Modelling of ground effects on wake vortex behaviour

UCL developed and validated an improved model for wake vortex behaviour In-Ground Effect. It models the flow dynamics using vortex particles both for the primary and secondary ground-generated vorticity. It is able to dynamically reproduce the combined effects, on the wake vortex behaviour, of the ground proximity and of the wind (both head- and crosswind components). The agglomeration of secondary separated vortex particles limits the number of used particles (and hence the computational time) while maintaining a sufficiently good representation of the flow dynamics. The further reorganization of the secondary particles, after the primary vortex rebound, also permits to mimic the turbulent reorganization of the secondary vorticity around the primary vortices at those times and its interaction with those, leading to a much enhanced decay IGE. The DVM, and in particular the IGE model, was calibrated and assessed based on LES results and on measurement data from the WakeFRA 2004 campaign. It was found to properly reproduce the wake vortex behaviour both in terms of transport and circulation decay for times up to t/t_0 = 4-5, the typical times of interest for operational applications (for large aircraft, t/t_0 = 4 corresponds roughly to 120 s). As the model is based on physical concepts, one expects it to be also valid for conditions different from those tested here. Further details on the model and its validation are found in (De Visscher et al. 2011, De Visscher 2012).

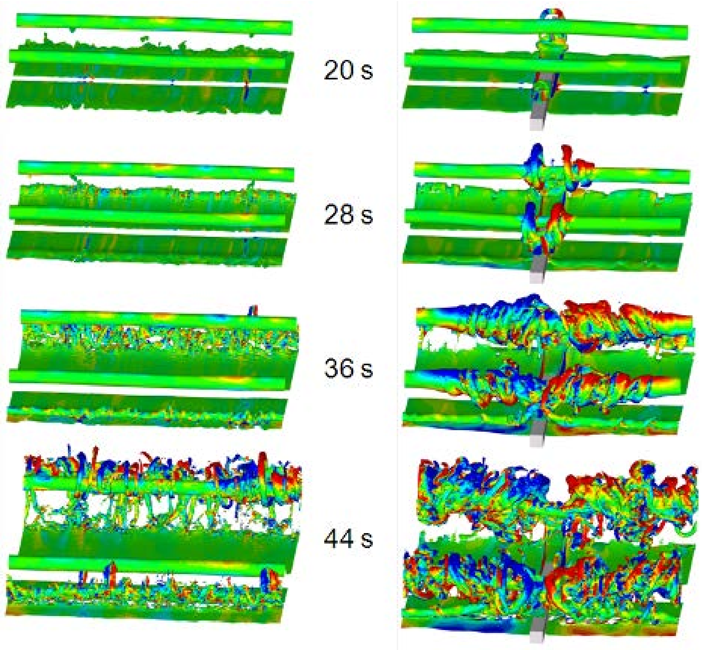

Figure 28: Wall resolving LES of wake vortex evolution in ground proximity with turbulent crosswind of 0.85 of initial vortex descent speed at initial vortex altitude of b_0 and vortex time scale t_0 = 26.3 s (wind direction points into image plane). Left without and right with obstacle at the ground surface (square profile with side length 0.19 b_0).

5.1.2.6 Wake vortex transport and decay depending on the cross-wind, also combined with ground effects

These investigations were performed in the framework of the FP6 CREDOS project than ran from 2006-2010. The involved partners were DLR, UCL and Airbus.

Use of the EDDF-1 and EDDF-2 databases

In the framework of the CREDOS project, two measurement campaigns of wake vortices generating by departing aircraft were performed: EDDF-1 and EDDF-2. The databases were analysed and used to assess the performance of the operational prediction models (DVM/PVM and D2P/P2P). The use of the two measurement campaign databases is described in (CREDOS deliverable D2-5 by De Visscher et al. 2009). Selected highlights of the results are reported in the following.

The EDDF-2 database contains about 10,000 wake vortex cases generated by heavy and medium aircraft at various height (up to 150 m) and in a large range of meteorological conditions. This hence enables to perform well-converged statistical analyses. The wake vortex lateral transport was statistically correlated with the crosswind, using different (operational or not) “crosswind definitions”.

For each crosswind definition, the envelopes containing the wake vortices with various probability levels were built at different times. An example of the obtained envelopes is shown in Figure 29. A simple mathematical model was proposed and calibrated for the evolution, as a function of the crosswind, of the envelope containing the vortices (with a certain probability level). Finally, an analysis of the wake vortex circulation decay, depending on the wind amplitude, was also performed: those results can also be related to the recent Large-Eddy Simulation (LES) studies carried out by UCL on wake vortices IGE and with different crosswinds (see details above).

The prediction models DVM/PVM were also assessed employing both the EDDF-1 and the EDDF-2 databases. The simulations were run using inputs as close as possible to the measurement conditions, and also using the “declared” measurement uncertainties. The results were compared with the provided experimental data, and quantified comparisons on the wake vortex positions and circulations were provided and discussed, using statistical means. The difference between the LiDAR processed $\Gamma_{5\text{-}15}$ circulation (as provided in the EDDF-1 database) and the LiDAR processed total circulation Γ_{tot} (as provided in the EDDF-2 database) was also highlighted. An example of comparison between EDDF-1 measurement data and DVM prediction is shown in Figure 25. Also studied was the influence, on the DVM results, of the extrapolation of the met data, when not available. Due to the high variability of the met and wake vortex data in both databases the obtained differences between the measurements and the model predictions were found to be higher than those obtained with the WakeFRA 2004 data and results of LES. Considering the quite high variability of the present data, the agreement between the DVM predictions and the measurements data was considered as quite good. For the PVM it appeared that the predicted envelopes, obtained using the declared measurement uncertainties, were reliable. In order to obtain "better" predicted results, yet of course larger envelopes, one should rerun the PVM using input uncertainties which better reflect the true uncertainty of the provided data.

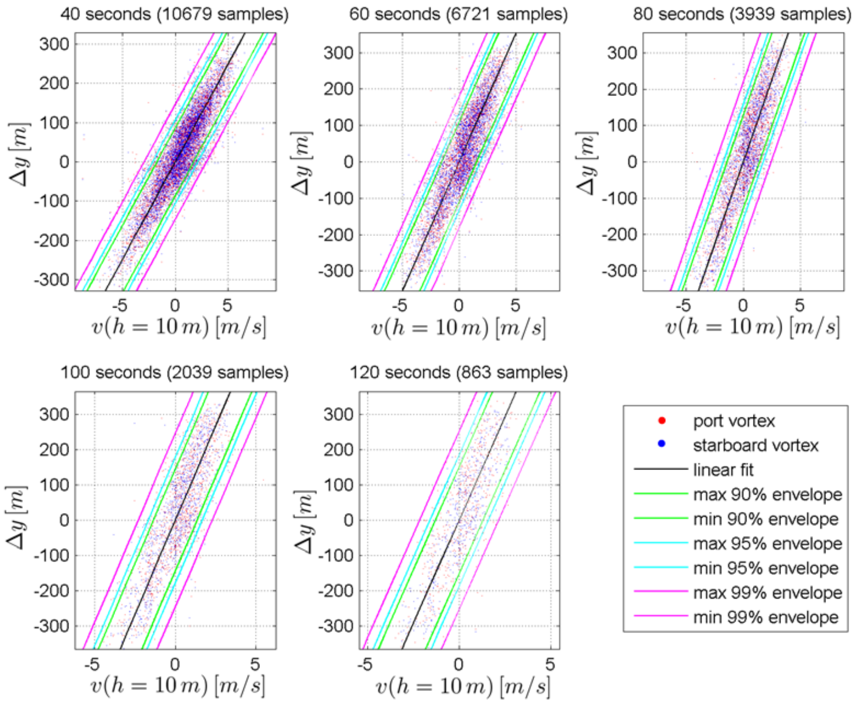

Figure 29: Evolution of the vortex net lateral displacement as a function of the crosswind (at 10 m height) at different vortex ages. Linear fits (black) show the mean evolution whereas coloured envelopes delimit 90% (green), 95% (cyan) and 99% (magenta) of the examined vortices.

Different parameterizations and inputs of the D2P/P2P model were tested to investigate the effects of the onset of ground induced rapid decay, the headwind/tailwind modelling, the crosswind shear model, the vortex decay models, the input wind profile (SODAR/RASS or WTR/RASS). A scoring procedure was used to compare the obtained results. The comparison of scoring results indicated on average better model performance for EDDF-1 than for EDDF-2, although wake vortex prediction OGE is subjected to larger uncertainties than IGE and although the measurement conditions during EDDF-1 were complicated by very strong winds. With the WakeFRA data significantly higher prediction skill was achieved (Holzäpfel & Steen 2007). The scoring results also confirmed that crosswinds measured by LiDAR yield superior prediction skill of lateral transport compared to WTR/RASS measured crosswinds; this is as expected.

Then the two deterministic models DVM and D2P were compared in a "benchmarking exercise", based on a small subset of the EDDF-1 database. For the benchmark, Airbus selected 16 cases representing different crosswind and headwind classes. Both wake vortex models were run from identical initial conditions specified by Airbus and based on aircraft and LiDAR data. The predicted vortex characteristics (lateral and vertical positions and circulation) of both models were confronted to the LiDAR measurements, comparing the running average of vortex characteristics (predicted by both models and “measured”) and computing the rms deviation between the predictions and the measurements. An assessment depending on crosswind and headwind categories was also performed. It was noted that the sample size is not sufficient for robust conclusion. However, for both models, the vortex predicted characteristics were in the range of the scatter of the LiDAR data. It was concluded that both models represent well the wake vortex transport and decay. It is indicated that the models could indeed be used for the prediction of vortex trajectories under cross wind conditions, together with the appropriate probabilistic versions (PVM and P2P) or using an appropriate safety margin to be defined and applied.

DFS, DLR, and UCL employed different approaches in order to estimate crosswind threshold values supporting vortex-free corridors for departing aircraft (Dengler et al. 2010). Although several competing effects as wake vortex transport in and out of ground effect, temporal and spatial wind variability, and the spreading of aircraft trajectories after take-off complicate the analyses, all three approaches lead to similar crosswind thresholds. Employing standard instrumentation at 10 m height a minimum crosswind threshold of 3.9 – 5.0 ms^{-1} has been identified to clear a safety corridor of 200 m width from wake vortices with a 95% probability within 60 seconds. Crosswind thresholds can be reduced if the wind is measured close to the air mass in which the vortices evolve. A definite crosswind threshold for operational use cannot be deduced solely from this study since critical factors like risk and safety assessment have not yet been taken into account.

Monte-Carlo simulations of departure under crosswind conditions

Another contribution of CREDOS was the use of both D2P and DVM modules in the WakeScene-D software package of DLR, as part of the work in CREDOS on "Risk Modelling and Risk Assessment" (CREDOS deliverable D3-9 by Holzäpfel and Kladetzke 2009, Holzäpfel et al. 2009). This used the updated and validated wake vortex behaviour models to realistically simulate takeoff scenarios with complex flight path, involving wake vortex evolution and decay in and out of ground effects. A description of WakeScene is given in §6.2.

The Monte Carlo simulations of the departure scenarios showed that the use of different wake vortex models (P2P or PVM) did not change the conclusions with respect to the suggested crosswind thresholds. This indicates that, on one hand, the models have reached a valuable level of maturity and that, on the other hand, the results of relative safety assessments could be quite robust with respect to peculiarities of the employed submodules.

Measured vortex tracks of about 10,000 departures from runway 25R of Frankfurt airport have been compared with WakeScene-D simulations. For lateral vortex transport, which for crosswind departures constitutes the most important quantity, good agreement between the characteristics of measurement and simulation has been achieved. This indicates that WakeScene-D with its wake vortex models allows investigating realistic wake vortex behaviour in domains and height ranges that are far out of reach of measurements.

5.1.2.7 Wake vortex behaviour depending on combined turbulence and stable stratification: simulations and modelling

LES investigations of wake vortices evolving in stably stratified and weakly turbulent atmospheres were conducted by UCL (De Visscher et al. 2009, De Visscher and Winckelmans 2010, De Visscher 2012). Those simulations aim to be as realistic as possible (very high Reynolds number, tight vortex cores $r_c/b_0 = 0.050$). Different stratification cases were investigated, from neutral to very high and with weak to very weak ambient turbulence levels. In order to best represent the combined atmospheric conditions, the stratified and turbulent realistic fields are obtained using LES of forced turbulence, evolving until it reaches a statistically converged equilibrium state. The computational domains were $(4\ b_0)^3$ and $(8\ b_0)^3$, thus also defining different integral length scale L_0 of the turbulence. An example of the flow field is provided in Figure 30 for a case with turbulence and low stratification level in a computational domain allowing the development of the Crow instability.

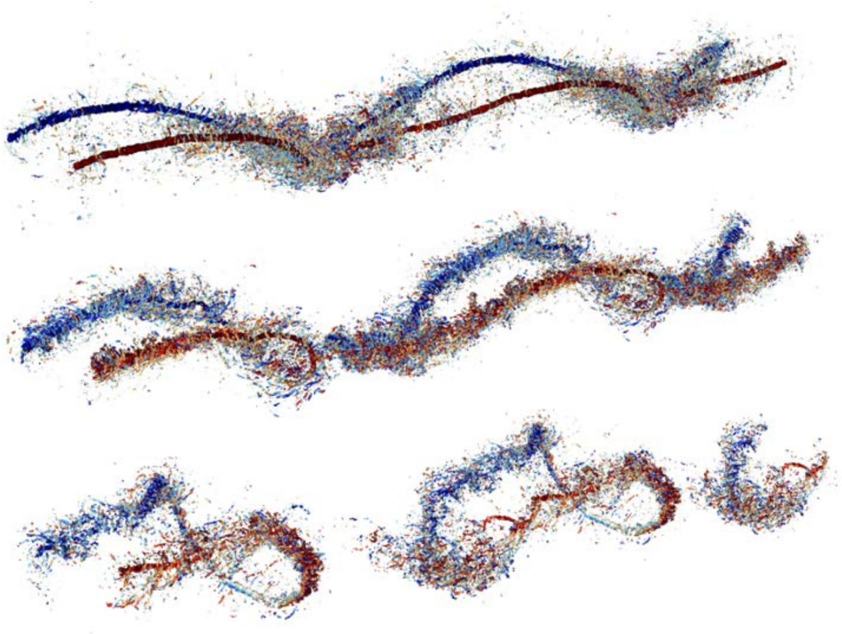

Figure 30: Case of weakly turbulent and stratified atmosphere with N*=0.35: iso-surfaces of λ_2 coloured by the axial vorticity ω_x at times t/t0= 3.0 (top), t/t0=4.0 (middle), and t/t0=5.0 (bottom).

When the stratification level is from medium to high (N* > 0.75), the instabilities have short to medium wavelengths and the turbulence integral scale has a weak impact. When the stratification is absent or low (e.g., N* <= 0.75), the long wavelength Crow type instabilities are also triggered and this leads to vortex linking.

The influence of solely turbulence on wake vortex behaviour (transport, decay and topology) was then also investigated by UCL using LES (De Visscher 2012). The vortices were observed to link and form vortex rings only in weak turbulence cases, whereas, in moderate to strong turbulence, smaller wavelength instabilities also significantly develop and prevent the vortices from linking.

Stratification, turbulence and the Crow linking process all significantly influence the vortex decay. In weak stratification and weak turbulence, the decay is very slow until the time of vortex reconnection. The Crow linking then induces a decay that is much non uniform along the vortex and it must be measured and characterized in various cross-planes (e.g., measure the circulation distribution, $\Gamma(r)$, perpendicular to the detected deformed vortex core line in each cross-plane, and thus obtain local values of $\Gamma_{5\text{-}15}$ and Γ_{tot}): some planes exhibit a very fast second phase decay whereas others only see a slight increase of their circulation decay rate. For higher stratification levels, the strong interactions of the turbulent baroclinic vorticity structures with the wake vortices induce a fast decay of their circulation, which is much uniform along the vortices. For cases with moderate to strong turbulence, the smaller wavelength instabilities also induce an additional decay all along the vortex tubes. This quantification of the circulation decay is very important from an operational point of view. The mean circulation evolution is indeed a relevant measure of the vortex strength (and hence of the related hazard) only for cases of moderate to strong turbulence and/or moderate to strong stratification. For vortices evolving in calm and weakly stratified (or neutral) atmospheres, the use of the complete circulation decay envelope (i.e., as obtained in all cross-planes) is required for any potential encounter analysis. Examples of circulation decay for a case with low and high stratification levels are shown in Figure 31.

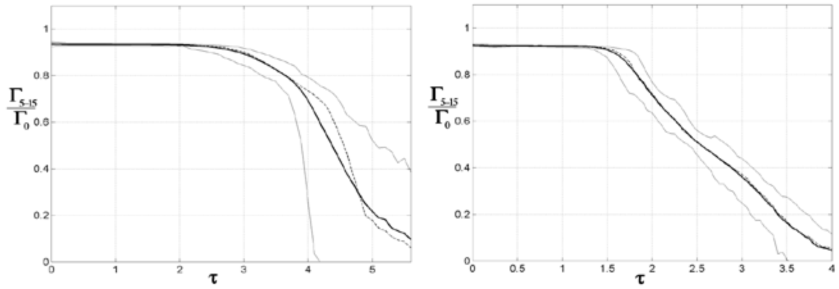

Figure 31: Comparison of the circulation decay of WV evolving in a weakly turbulent (ε* = 2.4·10^{-4}) and stratified atmosphere for N*=0.35 (left) and N*=1.0 (right). The mean (solid line), the median (dash line) and the 95% envelope (thin lines) are computed using the circulation evaluated in several cross-planes.

The results of these studies were compared and used to propose improvements of the DVM stratification transport model. The comparison between LES results and DVM results are provided in Figure 31. Note that ε* is defined as $\varepsilon^* = \varepsilon \cdot b_0/V_0^3$.

Two models were also proposed for the effects of combined stratification and turbulence on the circulation decay. The first model is valid for cases of weak turbulence and for all the investigated stratification levels. It represents the decay of the longitudinally-averaged circulation. In case of Crow linking, it then represents the mean decay of the circulation evaluated in all cross-planes (those who cut the vortex ring and those who don't and hence have a zero circulation). The second proposed model only represents the circulation decay of the parts of the vortices that are still alive, thus providing the upper bound. Examples of comparison between LES and DVM (using the first decay model) results are provided in Figure 32: .

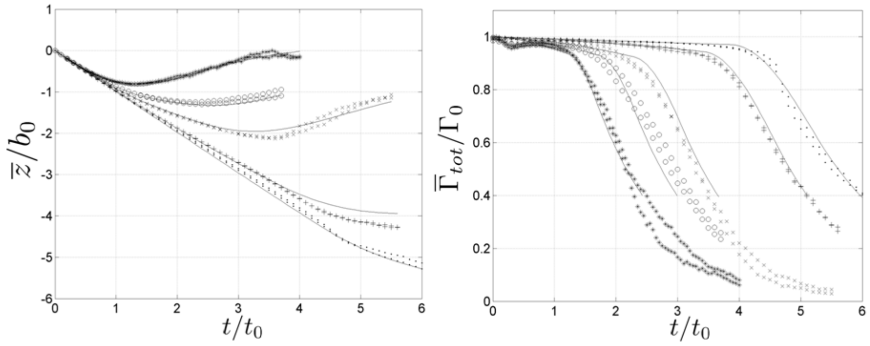

Figure 32: Average vertical displacement (left) and average total circulation (right) for cases with ε* = 2.4 10^{-4} and N*=0 (.), 0.35 (+), 0.75 (x), 1.0 (o) and 1.4 (+). The DVM results are also displayed (solid).

For the PVM model, a decay pdf and decay envelopes will be used for the strong decay phase, and containing the characterization results obtained from the different cross-planes. For the medium to high stratification levels and/or moderate to strong turbulence levels, those envelopes are found to be tight (confirming the longitudinal uniformity of the decay) while they are quite spread for the low stratification and weak turbulence levels.

It is also important to stress that the resulting detailed velocity fields of such LES correspond to wake vortices in specific and realistic conditions. As such, they can also be stored and used as input in “fast time velocity field evaluation” routines for flight simulator encounter studies (see §5.5, and (De Visscher and Winckelmans 2010, Vechtel 2010, Vechtel 2011, Bieniek and Luckner 2011)). Such LES fields have also been used with good success as databases for LiDAR simulator studies (Brousmiche et al. 2009, Brousmiche 2010, Lugan et al. 2010, Holzäpfel et al. 2003) and also for radar simulator studies (Vanhoenacker-Janvier et al. 2010).

DLR has also conducted LES of wake vortex evolution in environments with various degrees of atmospheric turbulence and stable stratification (Hennemann and Holzäpfel 2009, Hennemann 2010, Holzäpfel et al. 2010, Hennemann and Holzäpfel 2011, Misaka et al. 2012). Prior to the inset of the counter-rotating vortex pair the atmospheric turbulence was allowed to develop a state with a distinct inertial subrange and a constant eddy dissipation rate, ε*. Different size distributions of turbulent eddies leading to different turbulent integral length scales, $L_{t,}$, result from the initialisation of turbulence energy spectra with different peak wave numbers.

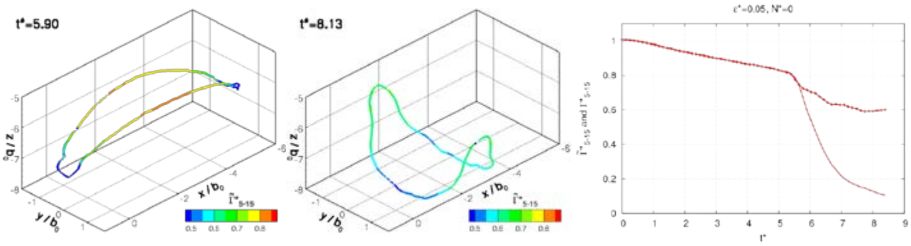

Figure 33: Wake vortex topology with colour-coded circulation in a neutrally stratified environment with weak to moderate turbulence ($\varepsilon^* = 0.05$, $L_t/b_0 = 0.41$) shortly after linking (left) and in vortex ring regime (centre). Corresponding temporal circulation evolution (right) averaged over “cross-planes” (line) and along vortex tubes (symbols).

A post processing method has been developed that is capable to identify the vortices even in progressed states of vortex decay where the coherent vortex structure is getting lost. In a next step this method allows determining circulation along the vortex centre lines (see Figure 33, left). In contrast to the two-phase circulation decay characteristics as obtained from the “cross-plane view and characterization”, the vortex circulation estimated perpendicular to the detected deformed vortex core line may reveal a three-phase decay sequence (see Figure 33, right). The initial phase of gradual decay termed “diffusion phase” is followed by a “rapid decay phase” which typically commences at the time when the vortices link. In neutrally stratified environments long-living vortex rings are observed with gradual vortex decay. This third phase may be termed “ring diffusion phase”. The evolution of the vortex topology from the initial sinusoidal oscillations, the subsequent vortex linking and vortex ring formation up to the axial contraction and the lateral spreading of the vortex ring can be explained phenomenological by mutual velocity induction.

Concerning the operational characterization of the decay in the case with low or without stratification (i.e., neutrally stratified), one can adopt different views. If one switches from a “cross-plane view and characterization” (thus with min and max second phase circulation decay depending on the plane considered) during the phase of linking to a “vortex ring view and characterization” after, then one finds that the decay is again fairly uniform, and again quite weak, along each vortex ring, corresponding to a third “ring diffusion phase”. If one remains in the “cross-plane view and characterization”, then there is no clear third phase, as in Figure 31. Both view points are of interest to the operational modelling.

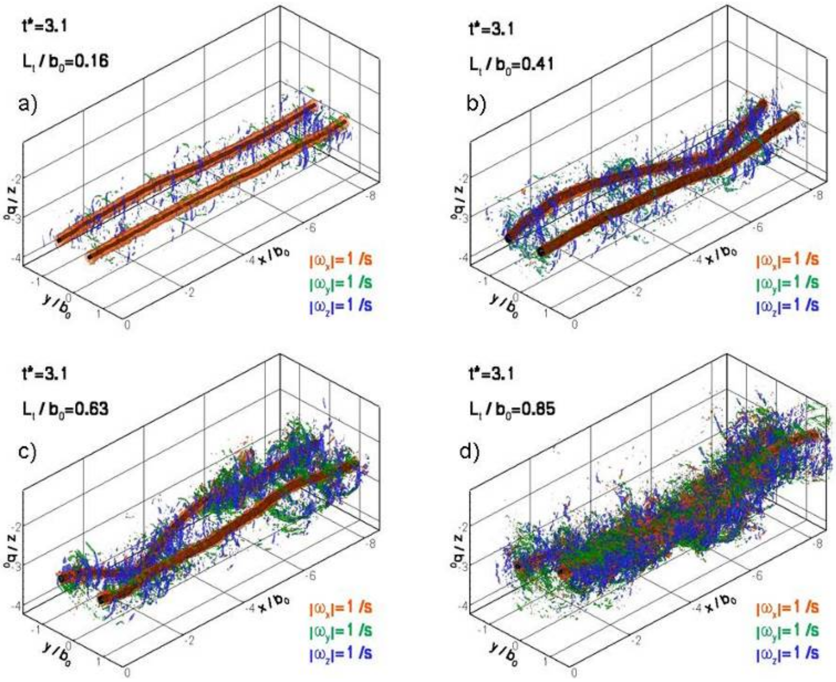

Figure 34: Vortex topology and secondary vorticity for different integral turbulence length scales prior to onset of rapid decay ($\varepsilon^* = 0.23$, $N^* = 0$, reprinted from Hennemann & Holzäpfel 2011).

The ratio of the integral length scale of turbulence and initial vortex separation, L_t/b_0, may have a strong effect on vortex decay characteristics and vortex topology. With increasing L_t/b_0 ratios the decay rate already in the diffusion phase is increased and the vortex topology is becoming more complex. Figure 34 shows that increasing L_t/b_0 ratios increase the amount of secondary vorticity generated from environmental eddies which in turn reduces the energy of the primary vortices. DLR has also been working on subgrid-scale models and has found that the Lagrangian Dynamic Model (Meneveau et al. 1996) is well suited to predict sustained tight vortex cores in turbulent environments.

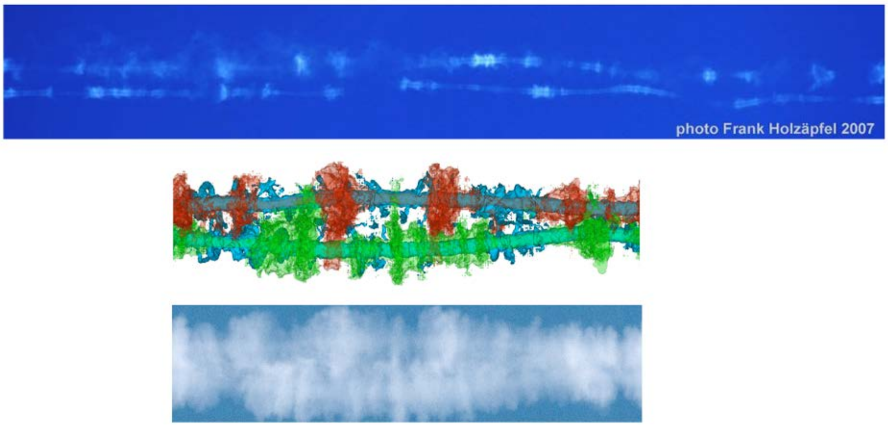

Figure 35: Vortex bursting phenomenon. Top: photograph; centre: LES, isosurfaces of vorticity magnitude (blue) and of passive tracer distributions (red and green) ($t^* = 4.6$, $\varepsilon^* = 0.01$, $N^* = 0.35$, $L_t/b_0 = 0.95$, reprinted from Misaka et al. 2012); below: visualisation based on radiative transfer simulation with libRadtran/MYSTIC (Tobias Zinner, Moritz Schönegg, MIM, LM Universität München).

Turbulent exchange processes of passive tracers within the descending vortex oval and between the oval and its environment have been investigated (Holzäpfel et al. 2010). The dispersion of the ice crystals during the vortex descent is an important parameter in order to quantify the vertical extent, optical thickness, and lifetime of the contrails produced during cruise. Currently, it is not yet clear how strong the contribution of contrails to global warming might be.

Figure 35 shows a photo (top) and simulations of the apparent axial redistribution of ice crystals along the vortex tubes, a phenomenon termed vortex bursting, puffs or pancake vortices (Spalart 1998). In Holzäpfel et al. 2010 and Misaka et al. 2012 it is revealed that the mechanism of vortex bursting is related to collisions of secondary vorticity structures propagating along the vortex lines and that vortex bursting is not related to local vortex decay. Also the formation of vortex funnels can be explained by these propagating coherent secondary vorticity structures (Misaka et al. 2012).

From LiDAR observations it is known that wake vortices may frequently live much longer than anticipated by the aircraft separations that have to be obeyed during approach and landing or during departures. One potential reason why flying is safe nevertheless is the fact that the vortices do not remain straight but are rapidly deformed by the relatively strong turbulence prevailing in the atmospheric boundary layer. The deformation of vortex segments may reduce the impact time of adverse forces and moments experienced by an encountering aircraft and thus may alleviate the severity of the encounter (see §5.5).

The vortex deformation found in LES with various degrees of turbulence and stratification was characterized in terms of curvature radii (Hennemann and Holzäpfel 2011). At a late stage of vortex evolution the established statistics indicate a predominance of curvature radii on the order of one initial vortex separation, b_0, for a variety of environmental conditions. It still has to be investigated thoroughly whether such strongly deformed vortex segments may still pose a risk to follower aircraft. Encounter flights of the DLR research aircraft Falcon behind an A380 indicate that already pronounced sinusoidal oscillations prior to vortex linking might significantly reduce the severity of encounters.

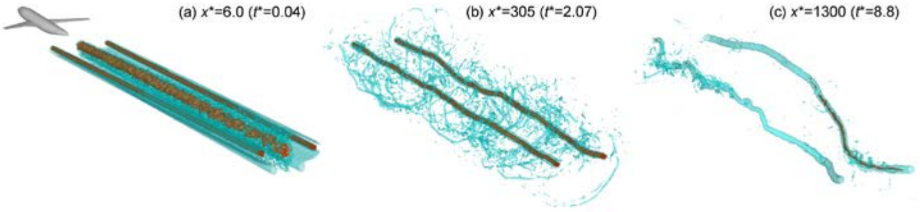

Figure 36: Evolution of aircraft near wake and the resulting wake vortex pair at cruise conditions. Two different levels of vorticity magnitude are shown by red and blue transparent surfaces.

Wake vortex evolution depends not only on environmental conditions but also on the specific aircraft geometry and the configurations for cruise, take-off or landing. A novel wake initialization approach is developed by DLR where a realistic aircraft wake is generated in a LES domain by sweeping a high-fidelity RANS flow field through the domain. This also requires new developments for the boundary conditions supporting spatial LES throughout wake vortex lifetime. Using this approach simulations have been performed from the roll-up until final vortex decay for long range aircraft models in clean and high-lift configuration (Misaka et al. 2012).

Figure 36 shows the wake roll-up and the subsequent evolution of a vortex pair behind the DLR-F6 wing-body model in weak ambient turbulence. Wingtip vortices and fuselage wake have high vorticity magnitudes in the beginning. The fuselage wake with its pronounced axial velocities decays relatively quickly while the wingtip vortices preserve the high vorticity. The decayed fuselage wake and the vorticity from the inboard wing wrap around the wingtip vortices adding disturbances around them. Remarkably, this leads to an increased circulation decay rate in the early diffusion phase as it is observed in LiDAR measurements. A stable vortex pair appears at t*=2.1 and at t* = 8.8 the vortex pair is highly disturbed and almost decayed.

5.1.3 Research Needs

5.1.3.1 “Validation” of the wake vortex models

A large number of questions regarding wake vortex modelling have been raised again and again and so far no answer is in sight that would be considered appropriate by a majority of stakeholders: Are the wake vortex models mature enough to be applied in a wake vortex advisory system? Have the wake vortex models been sufficiently validated? How and when can this be achieved? What is the necessary number of data against which the models need to be validated? How can it be assured that the models are capable to predict wake vortex behaviour under unusual meteorological conditions and all flight phases? Are they applicable to cruise conditions? It appears very difficult to answer these questions.

It is thus of primary importance to define, with stakeholders, the required validation level and the appropriate metric to be used to compare predictions and measurements. Finally, and most important, a correct validation, can only be performed with high quality, experimental and/or numerical (LES), databases.

- Define the required “validation level”

  So an inversion of the questions might be useful. One could prescribe alternatively the wake vortex prediction accuracy needed for a particular concept, system or safety assessment. Then the models would have to prove whether or not they are capable to achieve the required accuracy. This approach would correspond not only to the validation of the wake vortex models themselves but to that of the complete set-up, i.e. including inputs of meteo and aircraft parameters.

- Define a proper metric of comparison

  Different metrics have been developed and used to compare experimental or LES results to those of operational models. For instance, one can perform a comparison case by case. In cases for which long wave (e.g., Crow type) instabilities also occur, one can then also consider the distribution of the circulation decay (or at least the envelopes) along the direction of flight, as various parts of the vortices do not decay at the same rate.

  Alternatively, one can compare the statistics (mean, median, envelopes) of an experimental database to those of the model-predicted database. This last measurement is indeed less sensitive to the individual measurement errors but rather shows the general ability of the model to represent the wake vortex behaviour in various conditions.

- Need of high quality measurement databases

  Any validation exercise requires a high quality measurement database, both for the vortex characteristics (position and circulation) and the meteorological data. Ideally, each measurement is provided together with an estimate of its measurement error.

5.1.3.2 Vortex models and wake vortex encounter studies

The results of LES and of simplified operational models should be used in encounter studies. This can be done in flight simulators and compared to the results of flight experiments. Finally, encounter simulation studies can only be performed if the core radius size, the topology, and the velocity distribution of the wake vortices are known with sufficient precision.

- Wake vortex models in flight simulators

  Promote the operational use of the LES methodologies and available LES databases in flight simulator studies, also in support to severity characterization of wake vortex encounters, new operational concepts, and also in support to new/improved LiDAR system and/or LiDAR signal processing developments. The induced velocity fields obtained from the results of the prediction platform WakeScene or WAKE4D can also be used. The resulting encounter could then be compared when using either the LES or the wake vortex model results.

- Flight experiments

  Flight experiments should be conducted where wake vortex characteristics are estimated simultaneously from (i) in situ measurement (nose booms), from (ii) the aircraft reaction during the encounter, and (iii) from remote sensing with airborne LiDAR. Simultaneous video recordings of the visualized wake (contrail or smoke) from the encountering aircraft and from larger distance would provide information on the prevailing vortex topology. Complementarily, the particular wake vortex evolution under the prevailing meteorological conditions could be investigated with LES. The application of all these key technologies to identical wake vortex segments could enable comprehensive and substantial insights into physical wake vortex parameters, accuracies of the respective measurement instrumentations and encounter modelling (aerodynamic interaction model, wake parameter identification). This would further be a valuable method for validation and/or improvement of the participating methods.

- Determine vortex core sizes and tangential velocity distributions for real aircraft in cruise and high-lift conditions.

  This is an important question for the characterization of the encounter hazard also in context with the A380 wake vortex separations (see, e.g., Bieniek and Luckner 2011, Winckelmans and Chatelain 2011). Different methods could be employed: (i) highly resolving simulations considering the flow around the aircraft and the roll-up process, (ii) dedicated remote sensing measurements with e.g. LiDAR or (iii) with aircraft in-situ measurements employing a nose boom rake or (iv) tower fly by measurements with dedicated sensors.

  This could also be done by pursuing the simulations of far wake vortex systems in turbulent equilibrium and on fine grids, also taking into account Reynolds number effects: to determine r_c “as determined by the fluid mechanics in the far wake and also based on energy arguments (themselves related to induced drag)”, and hence participate to resolving the discussion on this important issue. Use the results for operational modelling of r_c and for support to wake vortex encounter studies (evaluation of induced rolling moment, flight simulator studies using improved wake vortex models).

5.1.3.3 Further improvement of the wake vortex behaviour modelling

The wake vortex models are already quite mature. They can hence be used as such. However, some further studies would enable a better characterisation and hence a better modelling of the wake vortex behaviour. These studies should include the further characterisation of the vortex behaviour OGE in turbulent, stratified (stable or unstable) and sheared atmospheres and of the vortex behaviour IGE with head- and crosswind.

- Effects of stable stratification and turbulence on wake vortex behaviour OGE

  The enhanced characterization (from LES results on various sizes of periodic domains) and operational modelling (in DVM/PVM and D2P/P2P) of wake vortex transport, topology and decay should be finalized for cases with and without stable stratification and submitted to various turbulence levels, and also to various integral length scales (yet always limited by the size of the simulation box). For significant stratification the long wavelength Crow-type instability does not develop and the decay is essentially uniform along the vortex, as the result of short and medium wavelength instabilities. For low stratification the long wavelength Crow-type instability does develop, resulting into vortex linking and subsequent non-uniform decay along the vortex. For relatively weak turbulence long-lived vortex rings may form yielding a third phase of decay. It should also be investigated whether for large integral turbulence length scales ($L_t/b_0 > 1$) the effect of turbulence can be characterized solely by eddy dissipation rate.

- Effects of convective boundary layer on wake vortex behaviour OGE

  Further work would also be needed on the characterization and operational probabilistic modelling (in PVM and P2P) of wake vortices submitted to a highly unstable and buoyant atmosphere.

- Further improvement of the modelling of wake vortex behaviour NGE/IGE

  Further work on the enhanced characterization (from LES results) and operational modelling (in DVM/PVM and D2P/P2P) of wake vortices submitted to wind NGE/IGE: cross-wind cases of various strengths, head wind cases of various strengths and combined cases.

5.1.3.4 Modelling of the Near-wake behaviour

- Further improve the operational modelling (in DVM/PVM and D2P/P2P) of the wake generated by aircraft in approach and takeoff configuration.

The merging of the outer flap vortices and the tip wing vortices form the “primary outer two-vortex system” (Γ_1 and b_1) which typically survives in the extended near wake and in the far wake. The HTP vortices, possibly combined with the inner flap vortices, form the “secondary inner two-vortex system” (Γ_2 and b_2) which may not survive as it quickly moves upward as a dipole which is fast dissipated. The transport and decay of the surviving two-vortex system (Γ_1 and b_1) is then what needs to be modelled by the operational models. In particular, the effective spacing factor, $s= b_1/b$, can then, on some aircraft, be larger than that corresponding to cruise conditions.

5.1.3.5 Miscellaneous

- It should be investigated in which limits the classical normalization of wake vortex parameters based on initial vortex separation, b_0, and on initial circulation, Γ_0, is valid. The question arises in particular when considering wakes generated near the ground.
- The LES methodology considering the effects of peculiarities of specific aircraft designs on the resulting wake vortex characteristics in the far field should be further developed. The method should be capable to simulate the flow around specific aircraft geometries (including fuselage, tail plane, jet engines, flaps, slats, landing gear, …) and also consider different flight manoeuvres. This would be helpful to answer questions regarding the proper normalization (see above), merging or separation of individual vortices, appropriate real-time modelling, entrainment of jet exhaust, vortex core sizes and resulting tangential velocity profiles, and circulation evolution in the early diffusion phase. This refined method for initialization of wake vortices certainly requires careful validation.
- Further characterize, from LES, the difference between the averaged vortex (e.g., by removing the meandering) and the instantaneous vortex: effect on r_c and on $\Gamma(r)$.
- Further discuss and study the cost (also computational) and the related benefits of operational probabilistic envelopes for wake vortex transport and decay: pdf, mean, percentiles at various levels (e.g., 95% and 99%), etc. This, of course, is highly related to each application.
- Further study the benefit of parallel computing in operational models, using either CPU or GPU or both. This can become important for real-time application of models that use a Monte Carlo approach, even with a re-sampling procedure (such as the PVM).

5.2 Wake Vortex and Wind Sensors

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5.2.1 Overview

5.2.1.1 Ground Sensors

A new generation of low cost sensors has recently emerged for wind monitoring, boosted by technological breakthroughs (e.g. electronic scanning High Power X-band Radar, Electromagnetic Multi-Static Radars, Coherent 1.5 mm LiDAR, UV LiDAR, Forward-Looking Interferometer,…). A mixed of these sensors could be jointly used for wind assessment and for wake-vortex monitoring for ground Runway Wake Vortex Detection, Prediction and Decision Support Tools (e.g. SESAR P12.2.2) or for Airborne Alert Systems. In these future systems, that should be operational in all weather conditions, wind retrieval (wind amplitude/direction, Eddy Dissipation Rate (EDR) characterizing ambient air turbulence) with high spatial resolution and fast update rates will be required as input to the “Wake Vortex Predictor”. Wake-vortex detection, localization and strength assessment (circulation) will be a second fundamental requirement for safety net. In the following a survey of candidate technologies will be described based on state-of-the-art and survey of emerging technologies.

For “Wake-Vortex Predictor”, accurate information on 3D wind vector field and on EDR are required, at a very high tempo (< 1 minute) compliant with tactical operations. In this context, new solutions need to be introduced in a stepwise approach based on extension of weather observation infrastructure, improvement of weather nowcasting and development of high resolution forecasting (by assimilation of high density of data). Other sources of wind & EDR data could be envisaged like extension of ground-air data link capacity.

In the table below, we provide a tentative list of relevant observables with some estimates of required quality criteria.

WakeNet3-Europe has organized a dedicated workshop on "Wake Vortex & Wind Monitoring Sensors in all Weather Conditions”, hosted by Thales Research & Technology the 29th & 30th March 2010: http://wakenet.eu/index.php?id=125

This workshop was made of invited international guest keynote speakers & experts from Europe, USA & Asia to present their last technological sensor developments and end-users to report last sensors trials on airports. 34 talks covered the international state-of-the-art and testified the world wide interest for topics covered by WakeNet3-Europe. The number of talks was equally distributed between academic labs, SMEs, Industries and end-users.

Quantity	Unit of measurement	Targeted accuracy	Update rate	resolution/volume
longitudinal wind (profile)	m/s	1 m/s	60 s	30 m / 50 km range x 1500 m altitude
cross wind (profile)	m/s	1 m/s	60 s	30 m / 50 km range x 1500 m altitude
vertical wind (profile)	m/s	0.3 m/s	60 s	30 m / 50 km range x 1500 m altitude
turbulent kinetic energy (profile)	m^2/s^2	0.002 m^2/s^2	60 s	30 m / 50 km range x 1500 m altitude
eddy dissipation rate (profile)	m^2/s^3	order of magnitude (log. scale)	60 s	30 m / 50 km range x 1500 m altitude
vortex core lateral position	m	50 m	10 s	25 m / Along runways x 200 m in altitude
vortex core vertical position	m	50 m	10 s	25 m / Along runways x 200 m in altitude
vortex strength (circulation)	m^2/s	10 % of value	10 s	25 m / Along runways x 200 m in altitude

Table 2: Relevant observables parameters

Based on results of this workshop and international technology survey, candidate sensor technologies could be based on different approaches:

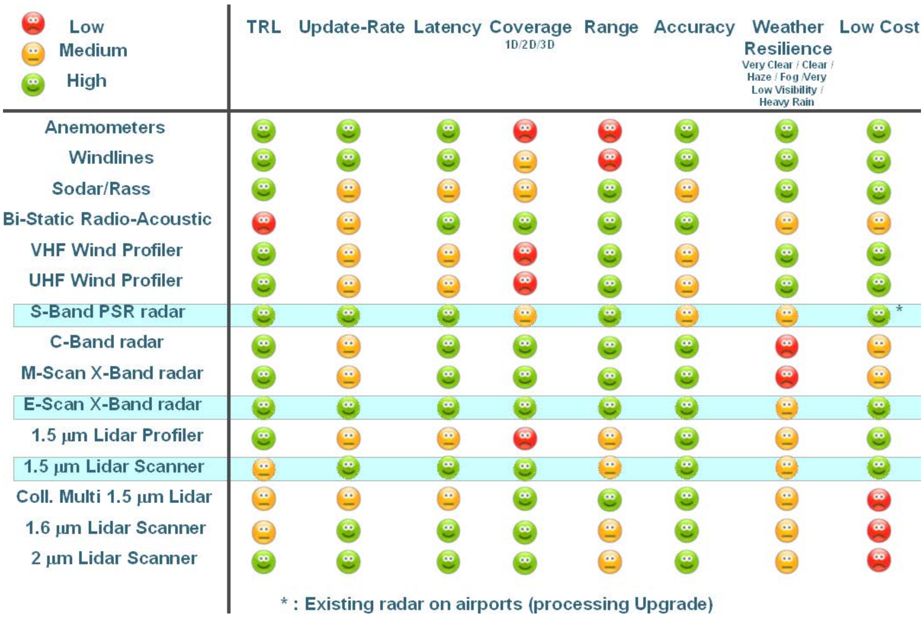
- sensor mode: active or passive (mainly acoustic methods), collaborative or multi-sensor
- sensor configuration: mono-static or multi-static
- sensor exploration: 1D profiler, 2D/3D scanner (mechanical or electronic scanning)
- mono or multi beams
- measurements on scattering or air index variations

Following figures give a survey of available sensors for wind and wake-vortex monitoring. Main sensors are Electromagnetic sensors: Radar, Infra-Red LiDAR and UV LiDAR. Some acoustic sensors are also candidates but less efficient and limited to short range detection.

Figure 37: Survey of wind monitoring sensors.

Figure 38: Survey of wake vortex sensors.

Following Figure 39 shows a comparison of candidate Ground wind measurement instruments according to the following criteria: TRL (Technology Readiness Level), update-rate, latency, 1D/2D/3D coverage, range, accuracy, weather resilience, and costs. The best ranked technologies are 1.5 µm LiDAR scanner and electronic scanning X-band radar complemented by the upgraded weather channel of the primary surveillance ATC radar.

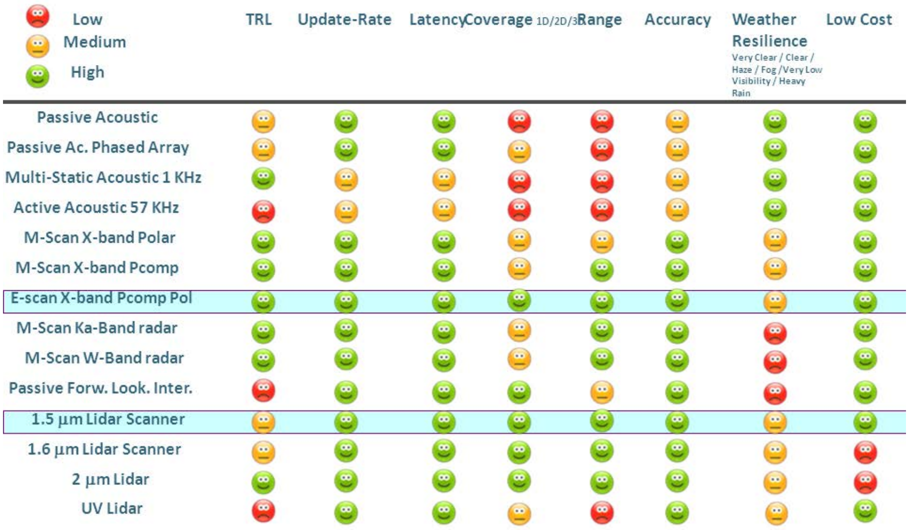

🔴 Low
🟠 Medium
🟢 High

	TRL	Update-Rate	Latency	Coverage 1D/2D/3D	Range	Accuracy	Weather Resilience Very Clear / Clear / Haze / Fog /Very Low Visibility / Heavy Rain	Low Cost
Anemometers	🟢	🟢	🟢	🔴	🔴	🟢	🟢	🟢
Windlines	🟢	🟢	🟢	🟠	🔴	🟢	🟢	🟢
Sodar/Rass	🟢	🟠	🟠	🟠	🟢	🟠	🟢	🟢
Bi-Static Radio-Acoustic	🔴	🟠	🟢	🟢	🟢	🟢	🟠	🟠
VHF Wind Profiler	🟢	🟠	🟠	🔴	🟢	🟠	🟢	🟢
UHF Wind Profiler	🟢	🟠	🟠	🔴	🟢	🟠	🟢	🟢
S-Band PSR radar	🟢	🟢	🟢	🟠	🟢	🟠	🟠	🟢 *
C-Band radar	🟢	🟠	🟢	🟢	🟢	🟢	🔴	🟠
M-Scan X-Band radar	🟢	🟠	🟢	🟢	🟢	🟢	🔴	🟠
E-Scan X-Band radar	🟢	🟢	🟢	🟢	🟢	🟢	🟠	🟢
1.5 µm Lidar Profiler	🟢	🟠	🟠	🔴	🟠	🟢	🟠	🟢
1.5 µm Lidar Scanner	🟠	🟢	🟢	🟢	🟠	🟢	🟠	🟢
Coll. Multi 1.5 µm Lidar	🟠	🟠	🟠	🟢	🟢	🟢	🟠	🔴
1.6 µm Lidar Scanner	🟠	🟢	🟢	🟢	🟠	🟢	🟠	🔴
2 µm Lidar Scanner	🟢	🟢	🟢	🟢	🟠	🟢	🟠	🔴

* : Existing radar on airports (processing Upgrade)

Figure 39: Comparison study of Ground wind sensors.

Following Figure 40 provides a comparison of candidate Ground wake-vortex sensors. Again, a sensors suite consisting of a 1.5 μm LiDAR scanner and electronic scanning X-band radar is a good compromise for wake-vortex monitoring in all weather conditions.



🔴 Low
🟠 Medium
🟢 High

	TRL	Update-Rate	Latency	Coverage 1D/2D/3D	Range	Accuracy	Weather Resilience Very Clear / Clear / Haze / Fog /Very Low Visibility / Heavy Rain	Low Cost
Passive Acoustic	🟠	🟢	🟢	🔴	🔴	🟠	🟢	🟢
Passive Ac. Phased Array	🟠	🟢	🟢	🟠	🔴	🟠	🟢	🟢
Multi-Static Acoustic 1 KHz	🟢	🟠	🟠	🔴	🔴	🟠	🟢	🟢
Active Acoustic 57 KHz	🔴	🟠	🟠	🔴	🔴	🟠	🟢	🟢
M-Scan X-band Polar	🟢	🟢	🟢	🟠	🟠	🟢	🟠	🟢
M-Scan X-band Pcomp	🟢	🟢	🟢	🟠	🟢	🟢	🟠	🟢
E-scan X-band Pcomp Pol	🟢	🟢	🟢	🟢	🟢	🟢	🟠	🟢
M-Scan Ka-Band radar	🟢	🟢	🟢	🟠	🟢	🟢	🔴	🟢
M-Scan W-Band radar	🟢	🟢	🟢	🟠	🟢	🟢	🔴	🟢
Passive Forw. Look. Inter.	🔴	🟢	🟢	🟢	🟠	🟢	🔴	🟢
1.5 μm Lidar Scanner	🟠	🟢	🟢	🟢	🟢	🟢	🟠	🟢
1.6 μm Lidar Scanner	🟠	🟢	🟢	🟢	🟢	🟢	🟠	🔴
2 μm Lidar	🟢	🟢	🟢	🟢	🟢	🟢	🟠	🔴
UV Lidar	🔴	🟢	🟢	🟠	🔴	🟢	🟠	🟢

Figure 40: Comparison study of ground-based wake vortex sensors.

Taking into account jointly cost constraint and system requirements for wind and wake vortex monitoring in operational all weather conditions, a good compromise is achieved by low-cost multifunction radar/LiDAR scanners. The combination could be a high-power 1.5 mm LiDAR scanner in clear air or very clear air and a low-cost E-scanning X-band radar with pulse compression in low visibility (fog, heavy rain). Main advantages of this combination are: measurement of wind, wind shear, and wake vortices under all weather conditions, 3D scanning, high update-rates, high resolution and accuracy, low cost and compact integrated systems. Developments of this kind of sensors need specific studies to increase their technology readiness level (TRL).

LiDAR and Radar Sensors need Electromagnetic Simulator integrating Fluid Mechanical models of wake-vortex and air turbulence mixing humidity and aerosol concentration models. The simulation of sensors allows tuning of sensor parameters and modes and optimal sensor deployment on an airport. Different 1.5 μm LiDAR Wake Vortex Simulators have been developed in Europe by UCL and ONERA / Leospere. A simulation of an aerosol-independent, 355nm UV direct detection LIDAR has been developed by EADS.

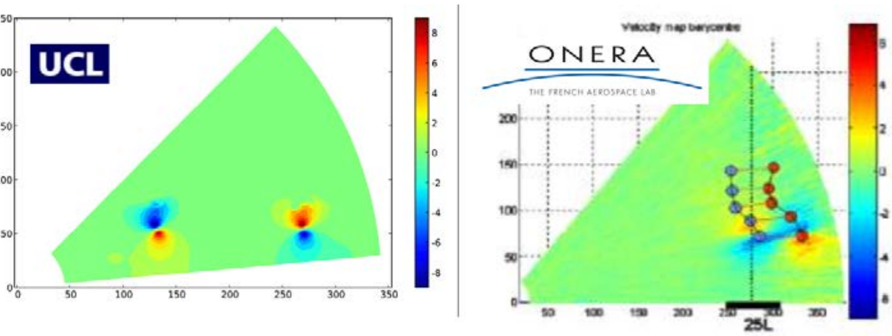


Figure 41: Wake-vortex LiDAR sensor simulation.

Radar wake-vortex simulation activities are relatively new with only very few laboratories active in this domain : NUDT in China, ONERA in France and UCL in Belgium :

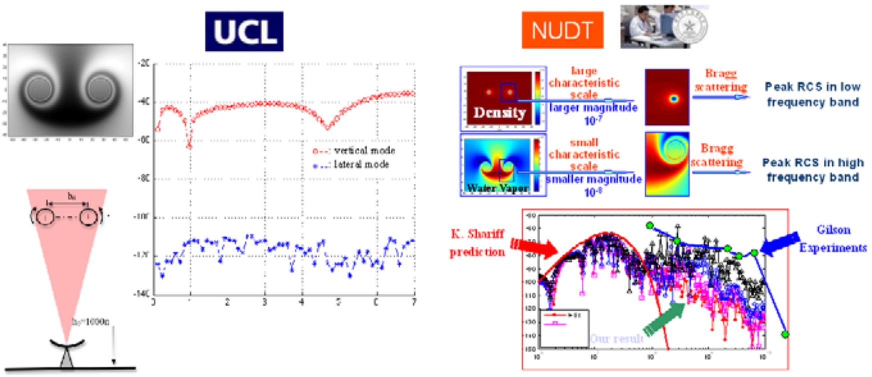


Figure 42: Wake-vortex radar sensor simulation

As described above, for the detection of wake vortices in all weather conditions a combination of LiDAR and RADAR sensors is most promising. While LiDAR sensors are adequate for good weather conditions, RADAR sensors outperform LiDAR sensors in bad weather conditions, i.e. in rainy and foggy conditions.

The combination of LiDAR and RADAR is challenging, since the detection of wake vortices with both sensors differs in space and time. Thus, a fusion of both sensors is needed, which takes into account the different scanning planes in space and time. Therefore, also the different behaviour of the wake vortices in space and time has to be considered for creating a spatially and timely combined sensor output. Based on the sensors´ output, a short time prediction of the wake vortex behaviour can be conducted.

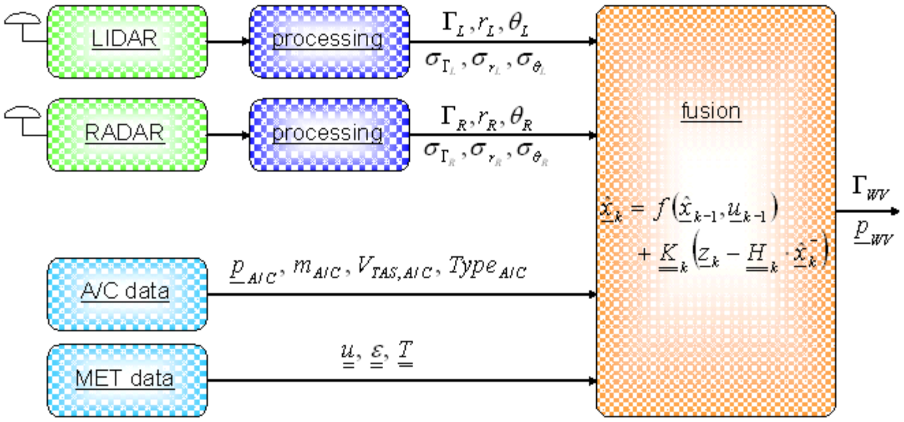


Figure 43: Radar/LiDAR Multi-sensors Collaborative system layout for Wake-Vortex Tracking

For this hybridization, a Kalman filter framework can be used like in classical tracking problems. Such filters work in two consecutive steps: a propagation part, where the system state is estimated based on model assumptions, and a measurement update part, where the system state is corrected by a physical detection of an object. TU Braunschweig in Germany studies this kind of system.

5.2.1.2 Airborne Sensors

A potential future forward-looking LiDAR system will perform 3 dimensions air speed measurements, 50 to 150 meters in front of an aircraft, to support several aircraft flight control functions. In order to validate this concept and extract the corresponding LiDAR requirements, LiDAR simulation models have been developed by Thales, EADS, and DLR. These LiDAR models are integrated into existing aircraft flight dynamic loops. Using these LiDAR models will provide the impact of the LiDAR system characteristics on the overall performances of the flight control loop, for different applications and for different aerodynamic and atmospheric situations.

The LiDAR system characteristics that can be tested are:

- The geometric conditions of the measurement (number of measurement axis, position of the different Line Of Sight with respect to the aircraft, position of the measurement points on the different LOS)
- The technological characteristics of the LiDAR system (Laser wavelength, laser pulse duration and energy, pulse repetition rate, spatial resolution, dimensions of Receiver optics)

The different aerodynamic and atmospheric conditions that will influence the performances of the LiDAR system (regarding air speed measurement) are:

- The structure of the air velocity field ahead of the aircraft (depends on the application under consideration: Gust Load Alleviation, or Turbulence Active Control, or Wake Encounter Prevention System / Control)
- The atmospheric conditions : air temperature and density, aerosols back scattering coefficient level

The atmosphere has two main elastic backscatter mechanisms that may be used for analysis (non elastic backscatter mechanisms are not considered here):

- *Mie backscatter*: corresponding to the aerosol or other particles, whose size is of the order of that of the wavelength or greater. The energy of the Mie backscatter signal is proportional to the concentration of aerosol. The spectral bandwidth of the Mie backscatter is narrow, similar to that of the laser, due to very low thermal motion of the aerosols
- *Rayleigh backscatter:* corresponding to the molecules (mainly the molecules of nitrogen and oxygen). The energy of the Rayleigh backscatter is proportional to the atmosphere density. The spectral bandwidth of the Rayleigh backscatter is relatively broad, due to the random movements of the air molecules caused by thermal motion (at a speed close to the speed of sound)

Both the Rayleigh and Mie backscattered spectra are frequency-shifted equally due to the Doppler frequency shift, which is proportional to the relative Line-Of-Sight speed of the LiDAR system with respect to the region of the atmosphere under analysis.

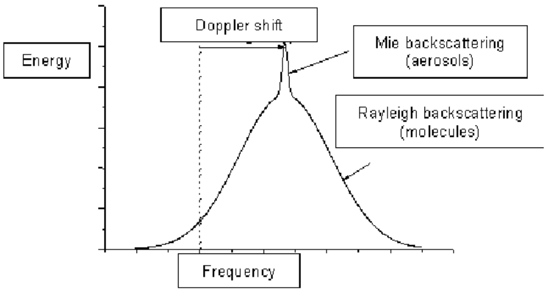


Figure 44: Spectrum of back-scattered light

The measurement of the air speed along the LOS is obtained through the measurement of the backscattered light Doppler shift. To get this Doppler shift, the backscattered light is subjected to spectral analysis. The average speed of the atmospheric molecules or aerosols induces a Doppler shift that can be seen in the spectrum of the backscattered light. The frequency shift amount Df is linked to the laser frequency fL, air speed Vr and light speed c. In addition to this average Doppler shift, individual speeds of aerosols or molecules induce the broadening of the spectral line. This is negligible for the aerosols but induces the large width of the Rayleigh line.

For LiDAR application, it is necessary to know quite accurately the position of the measurement point under consideration (that is, its distance from the LiDAR system on the LOS). 2 different methods may be used for that purpose:

- The optical system itself can be used to direct and focus the light to a specific place, which is then selected because it presents the maximum efficiency regarding the system sensitivity. This type of distance selection can be used with a Continuous Wave (CW) laser. However, this method has 2 main drawbacks:

- The distance selectivity may not be sufficient. For example, other points on the LOS (clouds for example, when compared with clear air) may present a much higher reflectivity than the expected measurement point, with respect to the incident light. The actual measurement point is then difficult to identify clearly
- The position of the measurement point cannot be changed easily, since the optical systems may not be modified easily while in flight
- The LiDAR measurement distance d is defined by precisely measuring the time t between the laser pulse emission and the backscattered light detection: d = c x t / 2, where c is the speed of light (c » 3.108 m/s). For example, for d = 50ms, t » 333 ns. The advantage of this method is that it provides a nearly perfect rejection for out of range back-scatter, and also allows as many as desired measurement points on the LOS. The drawback is that it requires the use of a pulse laser, which will inevitably broaden the emitted light spectrum and then make the backscattered light spectral analysis more complicated in case of a coherent detection system.

Choice of the laser wavelength

Laser in human eye visible and near IR spectrum (400 to 1400 nm) is excluded for safety reasons: these wavelengths are focused on human eye retina and then present a specific hazard. Allowed exposition levels are very low. Infra Red (IR) past 1400 nm or Ultra Violet (UV) below 400 nm are stopped before the retina and so they are much safer for most applications. Allowed acceptable exposure levels are much higher. The LiDAR simulation model has been designed for both IR and UV wavelengths. Each of these 2 options has specific advantages and drawbacks.

IR LiDAR (typical l = 1.55 µm)

- IR technologies and components are been used for telecom applications for many years, and have benefited (and still do) from the huge developments done for this market. Components and sub-systems (laser, detectors, optical components, etc) can be found at much lower price, much higher integration stage and much higher technological maturity than for the UV counterpart.
- In the IR LiDAR case, coherent detection is used. The backscattered signal is mixed with a local oscillator (which may be a fraction of the laser light, or a frequency shifted version of it), which results in beating at a frequency equal to the difference between the one of the local oscillator and the one of the backscattered signal. This low frequency beat is transformed in an electric signal through a diode detector, then digitised and numerically processed, in order to estimate the air speed information.
- IR light allows the use of coherent detection, which is both more simple and more accurate than direct detection in the case of a UV LiDAR
- However, an IR LiDAR uses only Mie backscattering, the Rayleigh backscattered energy being at a too low level in the case of IR light. Then, the level of back scattered light relies on the presence of aerosols, which may not be ensured over all locations, altitude, atmospheric conditions and flight conditions, depending on the specific characteristics of the LiDAR and the intended measurement range.

UV LiDAR (typical l = 355 nm)

- UV technologies did not benefit from the same developments as the IR. UV LiDAR components maturity level (cost, integration, volume, reliability, etc) is still behind the maturity level or IR components. Nevertheless, newest developments of high power, pulsed, single frequency fiber lasers might be used to frequency multiply into the UV range.
- In the case of a UV LiDAR, direct detection must be used. With the present available technology, this can be done only by using an interferometer. There exists several types of such interferometers, each having advantages and drawbacks (such as improvement or degradation in presence of Mie

Contribution, requirement over the detectors, maturity level, etc).The light coming out of the interferometer is sent to a detector, which provides an electrical signal suitable for electronic processing.

- UV LiDAR has to use direct detection to perform the necessary spectrum analysis. This requires the use of sophisticated optical components such as interferometers.
- However, a UV LiDAR can use both Mie and Rayleigh backscattering. So, even if the aerosols concentration is low, a UV LiDAR will still be able to use the Rayleigh contribution (molecular backscatter) which is always available and hence provide a measurement at all altitudes. The Mie contribution, if present, will only improve the accuracy of measurement.

5.2.1.3 Survey of Sensors R&D Roadmap in US NextGEN Program

In this first part, finally, we will make some comparisons with technological issues developed in US NextGEN (Next Generation Air Transportation System) roadmap where 2 projects of Electronic scanning radars (MPAR and CASA) have been scheduled with a De-risking budget of 215 M$ for developing technological demonstrators. Upgrade of ATC Air Field Surveillance Radar (ASR) radar weather channel is also identified in US roadmap with development of a new WSP (weather Signal Processor) for ASR radars. For ADS-B Downlink, "Aircraft Derived Meteorological Data via ADS-B Data Link for Wake Vortex, Air Traffic Management, and Weather Applications" OSED has been recently defined by US RTCA SC-206 SG-1 Subgroup for Wake, ATM, & MET. The NextGEN Roadmap is described in public NAS Enterprise Architecture / Infrastructure Roadmaps, Version 5.0, approved by FAA, 19th January 2011 :

- NextGen Surveillance and Weather Radar Capability
  - Next generation primary radar system in 2017 by evaluating Multi-Function Phased Array Radar Technology (MPAR) : new radar technology that will deliver highly accurate severe weather information simultaneously with three dimensional aircraft surveillance
- Weather Processing
  - Wind Shear & Atmospheric Turbulence Detection Algorithm
  - ASR 8/9/11 Weather Channel Upgrade + Nat. Weather Radar Improvement (NEXRAD)
  - Nextgen Weather Processor
  - Convective Forecast Improvement
- Wake Turbulence Meteorological Research
  - Research on meteorological sensing supporting wake turbulence encounter avoidance concepts
  - Research on direct and remote wind and eddy dissipation rate (EDR) sensing
  - Conduct research on meteorological modelling and model validation in support of wake turbulence avoidance concepts.
- NextGen Network Enabled Weather : NNEW & Wx Data Cube
  - Dissemination of observations and forecasts via netcentric access with an component called the 4-D Weather Cube (4-D Wx Cube).

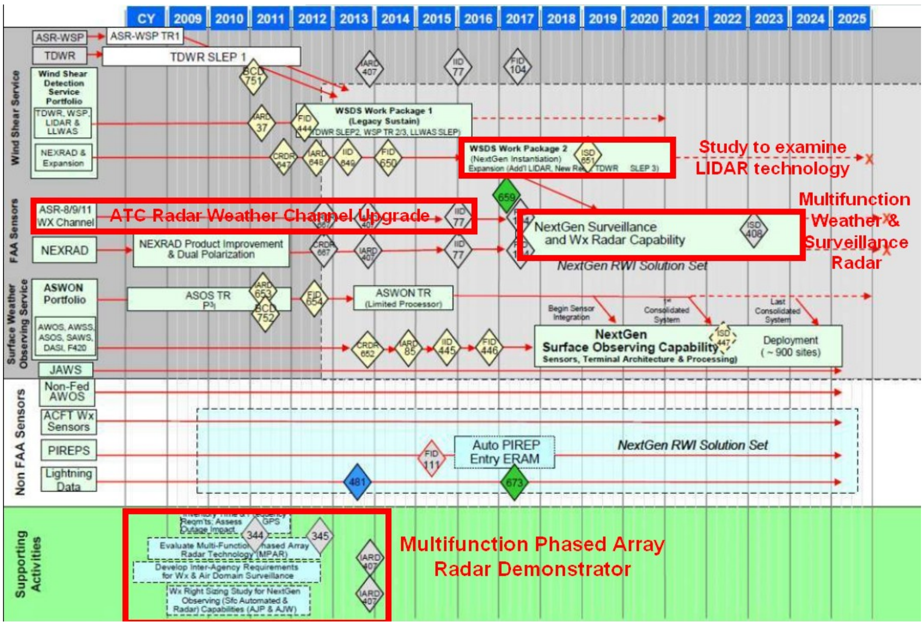


Table 1: US NextGEN Roadmap on Weather Aviation

5.2.2 State-of-the-art

In this state-of-the-art, we will describe different ongoing projects on wind and wake-vortex sensors in US, Russia, Japan and Europe.

5.2.2.1 US NextGEN ASR Radar weather-channel

- Partners : RAYTHEON (US), Northrop (US)
- Funding : FAA (NextGEN)
- Run-time : Until 2015
- Principal goal : Development of Weather Signal Processor for ASR Radar Weather channel
- Topics and achievements in the scope of the project :

  Multifunction Radar for wake-vortex, wind hazards and surveillance is a new concept for airport. For the time being, the only operational weather Radar for airport is US TDWR (Terminal Doppler Weather Radar) in C band. This Radar was developed during 80's to monitor low altitude phenomena such as wind shifts over the runways, wind shear along the immediate approach and departure corridors, and downbursts.

  US FAA program have upgraded Primary Surveillance Radar ASR-9 with advanced Weather Channel Processing integrated in WSP (Weather Systems Processor). The purpose of the WSP is to provide low-cost, high-quality, wind-shear detection equipment at medium-density air traffic airports not equipped with TDWR. The WSP is an "outboard" processing add-on to the ASR-9. Accurate microburst outflow wind measurement requires processing of data acquired nearly simultaneously from the ASR-9's high and low elevation beams. Development of Enhanced PSR Radar (ASR-9 & ASR-11) Weather Channel is studied for new US NextGEN program.

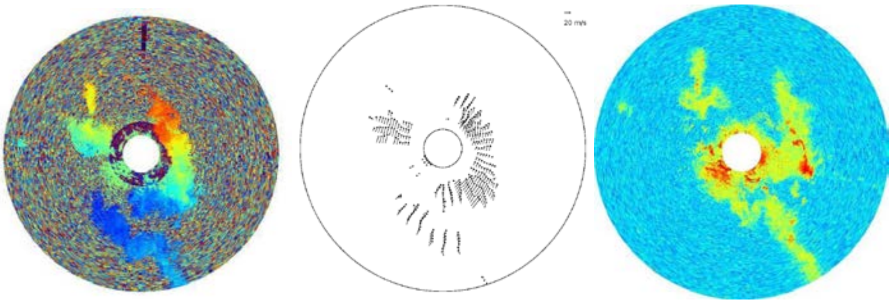


Figure 45: Wind field monitoring with PSR radar weather channel. Left: Doppler radial velocity in rain cloud. Centre: Wind field assessment based on Doppler information. Right: Atmospheric turbulence map based on high resolution Doppler processing.

5.2.2.2 US & Japanese Elec-Scanning Solid state Weather X-band Radar

- Partners : TOSHIBA (Japan)
- Funding : ENRI (CARATS)
- Run-time : started in 2011
- Principal goal : Development of Solid state E-scan Weather Radar

- Partners : RAYTHEON (US), EWR (US)
- Funding : FAA, NSF (NextGEN, included in MPAR Demonstrator, CASA program)
- Run-time : started in 2010
- Principal goal : Development of Multifunction X-band Radar (Weather, Surveillance)
- Topics and achievements in the scope of the project :

  CARATS is in Japan an equivalent of European SESAR program. In the framework of CARATS, new X-band solid-state weather radars are developed for decrease of running cost and effective use of frequency resources. In Japan, Toshiba has developed high power solid-state transmitter. Peek-transmitting power of solid-state weather Radar is less than that of a weather Radar of electron tube type, but this Radar can transmit much longer pulse than conventional Radar. Compared life aspect, magnetron and klystron need to be replaced every half year to 2 years. Very recently, TOSHIBA has developed a technology for active phased array weather Radar (APAWR) of X band with Digital Beam Forming (DBF), Solid state 450 W Power & 1° beamwidth.

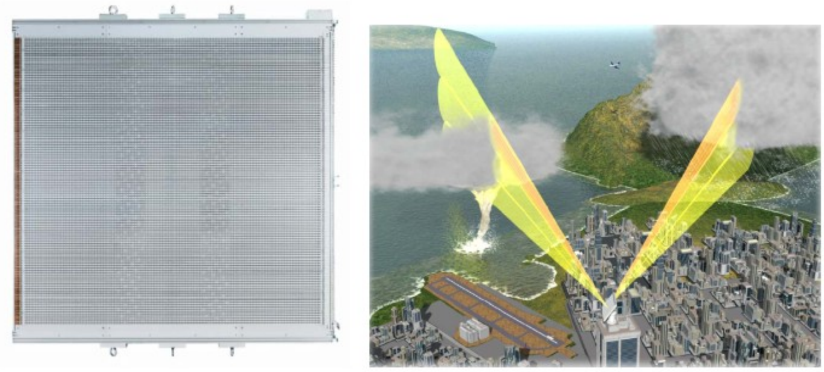


Figure 46: First Experimental X-band Solid-State Phased Array Radar with 1D Elec-Scanning (APAWR, TOSHIBA)

The Center for Collaborative Adaptive Sensing of the Atmosphere (CASA), an Engineering Research Center chartered by the National Science Foundation, is investigating the feasibility of small low-cost X-band Radars and the associated software architecture and data handling issues that would enable future deployment of such networks. CASA's concept envisions an observing technology based on low-cost, dense networks of Radars that operate at short range, communicate with one another, and adjust their sensing strategies in direct response to the evolving weather and to changing user needs.

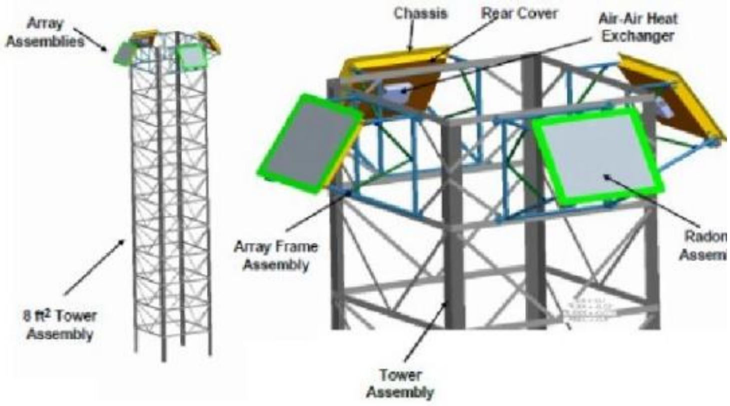


Figure 47: CASA radar panels placed on existing infrastructures

In CASA, RAYTHEON 2D Electronic Scanning Full Digital Array Prototype is Full 2D (azimuth and elevation) electronic scanning with beam width from 1° to 2°. RAYTHEON Panel Arrays incorporate the keys to affordable sensors: modular, scalable "Building-Blocks" ("Function-Specific" PWB's, Facilitates Integration and Test; "throw-away" assemblies), "Computer-Board"-like assembly (flexibility in choosing the right MMIC technology for the application, new MMIC technologies are readily incorporated, digital beamforming opportunities).

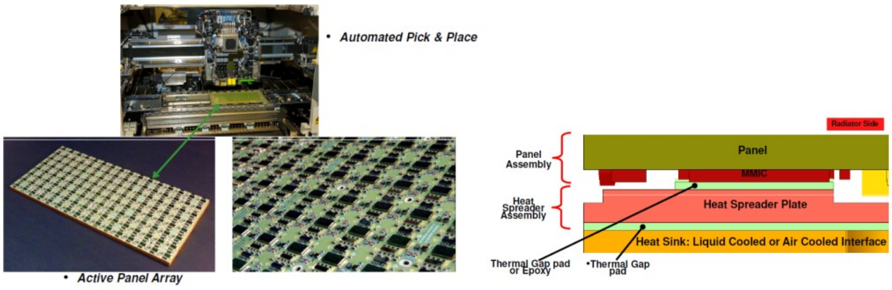


Figure 48: (at left) Panel Array:"Computer-Board"-Like Assembly (Flip-Chip-on-Printed Wiring Board: Package-Less TR Channel), (at right) Common Heat Spreader for Air or Liquid Cooled Interface (Thermal Performance of TR MMICs: Identical Thermal Resistance to Heat Sink)

Focus areas for achieving low cost affordable arrays, have been the development of a fabrication and assembly process for the panel array using computer board processes. The panel array consists of a mixed-signal multilayer printed wiring board fabricated in a single lamination step, and the SiGe T/R MMIC provides the full functionality of a T/R module integrated into one chip. CASA final 2D Electronic Scanning Full Digital Product Requirements is10 W's to 100 W peak power per panel ~2° x 2° average beam width ~ 1m x 1m array

In CASA program, US EWR Company has developed portable X Band Solid State weather Radar, with pulse compression technology. In October 2011, the first EWR prototype of X-band Phased Array Radar of 1.2 Kw solid state with 1D Electronic scanning in elevation through Radiating Panel rows command by Phase shifters has been presented for Meteorological Technology World Expo in Brussels. This prototype has simultaneous weather and air surveillance, multiple programmable volume scans, vertical rotating panels and horizontal phase tilt in single and multiple face configurations.

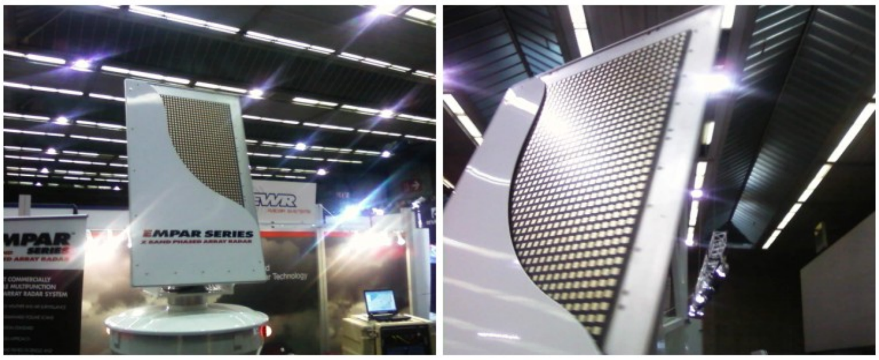


Figure 49: US CASA project and EWR EMPAR prototype of 1.2 Kw Solid-state X-band Phased Array radar with 1D E-scan in elevation

Different prototype of Electronic Scanning X-band Radar are under development for CASA program

- 1D Electronic Scanning Phase Tilt Phased Array studied by UMASS University
- 2D Electronic Scanning Full digital Array studied by RAYTHEON

UMASS 1D Electronic Scanning Phase Tilt Phased Array Prototype. This prototype is characterized by Planar microstrip array, 64 columns across (100 cm, 2° beam), 32 series-fed elements per column (50 cm. 3.8° beam), 2 W T/R Module per column, Duty Cycle 30%, Gain~38 dB, Peak SLL -22 dB Taylor (Elev), any in Azimuth, Beamwidth 2-4 deg (Azim) 4 deg (Elev), Azimuth plane scan range 90º (± 45º) (Electronically), Elevation plane scan range 0- 90º (Mechanically), Polarization Linear Dual-polarized

Cross-polarization level -30 dB at maximum scan range and -20 dB ICPR, Isolation port level Better than -25 dB at scan range, Power per panel (peak 75 W Power per T/R module (peak) 1.25 W/stick, Active reflection coefficient:<0.3 in all scan range.

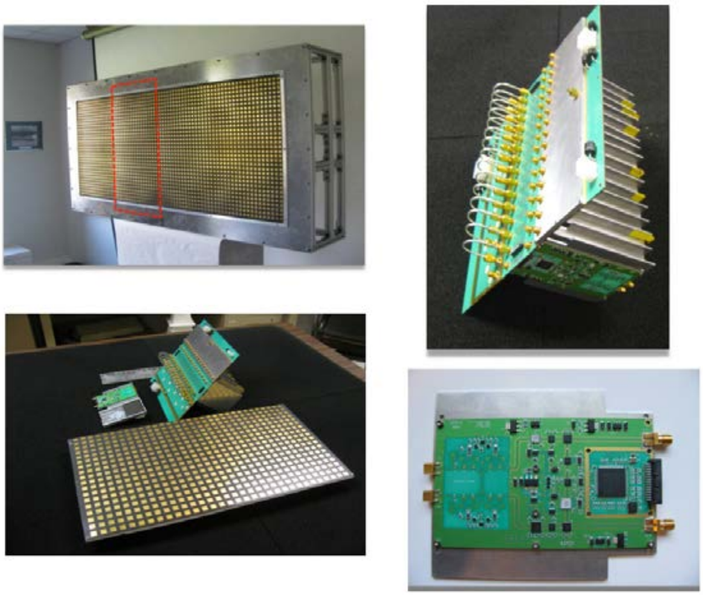


Figure 50: UMASS Prototype of 1D E-scan Phase tilt Phased Array

RAYTHEON 2D Electronic Scanning Full Digital Array Prototype : Full 2D (azimuth and elevation) electronic scanning, Electronic beam scanning range: +/- 15 ° (in elevation plane), +/- 45° (in azimuth plane), Mechanical tilt antenna face in elevation: -10 ° to 90° (zenithal), Elevation beamwidth: 1° to 2°, Azimuth beamwidth: 1° to 2°, Dual polarization at reception : HH and VV, Volume exploration renewal period: 1s to 200s (depending on operating mode), Duty cycle: > 20 %,, Pulse duration: 0.5 μs to 40 μs,, Pulse repetition interval : 400 μs to 1000μs,, Range resolution : 40 meters.

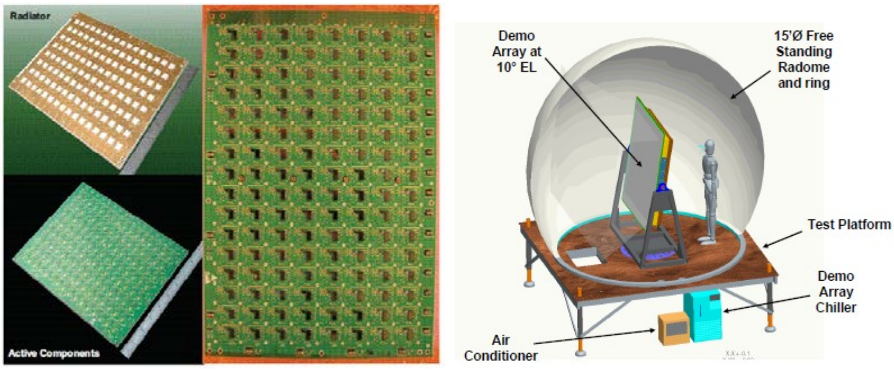


Figure 51: Raytheon Panel CCA Assembly Overview

The Raytheon electronically scanned radar structure is based on a building block 128 transmit/receive channel panel array that is nominally 20cm x 26cm x 0.5cm thick. As in many COTS products, the panel array leverages high volume commercial manufacturing techniques.

5.2.2.3 US NextGEN S-band Weather / Surveillance Multifunction Radar for Airport

- Partners : LOCKHEED (US), MIT Lincoln Lab (US)
- Funding : FAA (NextGEN, MPAR project)
- Run-time : From 2011 to 2017 (Derisking program with demonstrator , 215 M$)
- Principal goal : Development of Multifunction S-band Weather/Surveillance Radar for Airport
- Topics and achievements in the scope of the project :

  A Multifunction Phased Array Radar (MPAR) system has been proposed as the next generation solution for the joint air surveillance and weather needs (full system implementation will result in the deployment of approximately 350 radars). To effectively compete with current mechanically scanned solutions, the MPAR system must achieve equaling or bettering current performance metrics. Cost remains a major consideration in the feasibility of implementing the MPAR approach. Limitations of the current surveillance/weather network have been identified: update interval (less than four seconds desired), coverage (contiguous coverage desired of territories, borders and surrounding waters at 3000 ft and higher above ground level, extending 600 nmi beyond the boundaries.), low-level radar coverage and sensitivity.

  The MPAR concept is based on Multifunction Phased Array Antenna. This permits multiple functions to be carried out with the same radar. Thus the basic concept underlying the Multifunction Phased Array Radar (MPAR) initiative is to use a single radar type to carry out the multiple functions of aircraft surveillance and weather.

  The radar performs simultaneous functions: Rapid Update Weather Scan, Weather Scan, High Fidelity 3D Volume Weather Scan; but also: High Fidelity Horizon, Aircraft Track While Scan, Non Cooperative Target Recognition. Each of these modes has a scan update interval set by the minimum revisit time. In the future, it is expected that adaptive scan strategies will reduce these timelines even further.

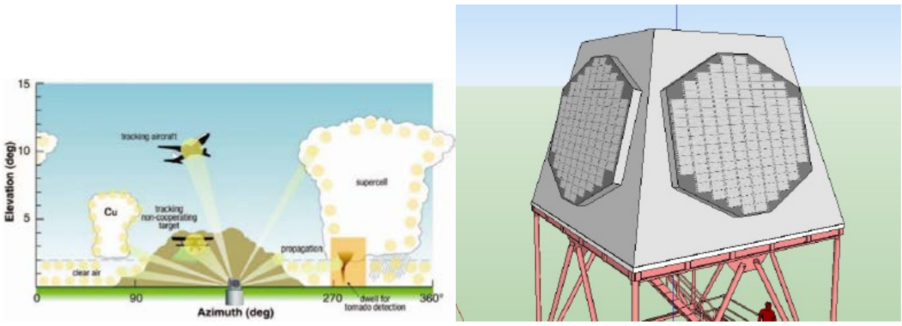


Figure 52: MPAR Multiple functions by beam-steering & electronic scanning

A NextGEN Plan covers the period through 2017, which can be thought of as the "Risk-Reduction Period." It is assumed that a full-scale development decision will be made in the 2017 timeframe based on the results of this effort, and additional R&D will be conducted leading up to a deployment decision. This Risk Reduction Phase will be funded by 15 M$ each year from 2011 to 2017.

A Terminal MPAR, called T-MPAR is also envisaged for airport. System Architecture is based on overlapped subarray beamformers: Number of subarrays/face: 24, Maximum # concurrent beams/face: 24

The T/R modules are integrated into an array panel, which consists of the radiating elements, the overlapped subarray beamformer, and DC and RF distribution networks. Following figure shows the dual polarized stacked patch antenna. The patch radiator is fed with a balanced feed to provide a low cross polarization response, which is required for accurate dual polarized weather radar measurements. The beamformer is fabricated on multiple stripline layers, which are integrated with the printed circuit antenna elements and the RF and DC distribution networks to form the array panel. Following figure shows the assembled array panel under test in the MIT LL near field test chamber.

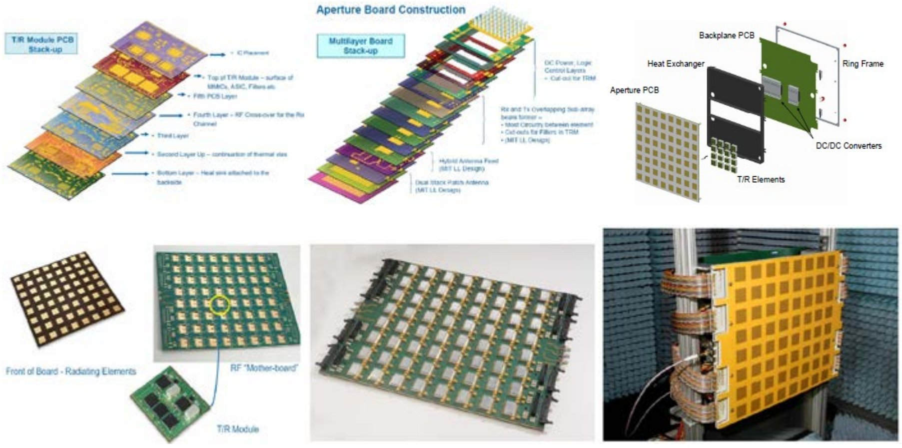


Figure 53: MIT LL Prototype of S-band Tile for MPAR under test

Another prototype is funded by CERDEC (US Army) and ARO (Army Research Office). This project in S-band (3.1-3.5 GHz) is called DAR (Digital Array Radar) and used 25 W T/R modules (35 W per element has been demonstrated with limited cooling on RF GaN antenna panel) with Dual Polar antenna. This project is now funded by MPAR R&D Plan.

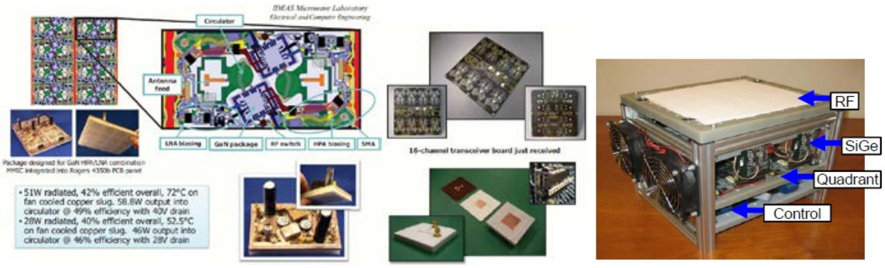


Figure 54: DAR Tile Development at Purdue University

A DAR Polarimetric testbed is under study at Purdue University, with Aperture-coupled, stacked-patch antenna used for case study and tests:

- Designed for broadside cross-polar and port-to-port isolation (>-35 dB)
- Lightweight, panelised and wide bandwidth (3 to 3.6 GHz)
- Rogers 4350b feed with Rogers 5880LZ top patch substrate

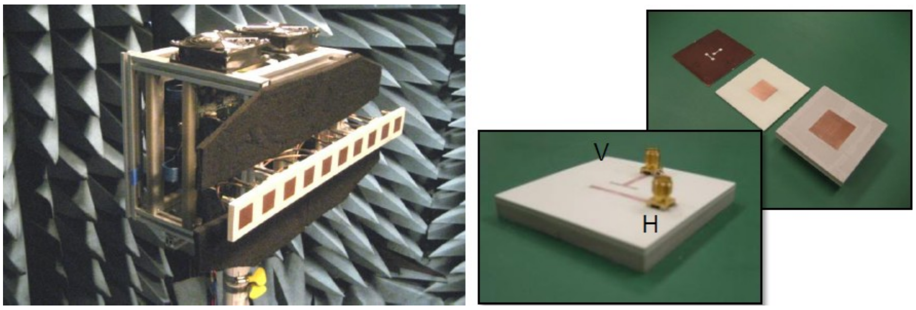


Figure 55: DAR with Polarization Testbed

An S-band Polarimetric Antenna is also under study at Oklahoma University with: Dual-polarized patched antenna at 2.705 GHz, 10 Watt GaN HPA in S-band, 3 by 3 by 4 inches and 14 oz weight, 12 Watt total power consumption and 2 watt in receive mode, Flexible MCU control and TR control interface, Azimuthally commutating scan, Scan invariant beam, Orthogonal polarization.

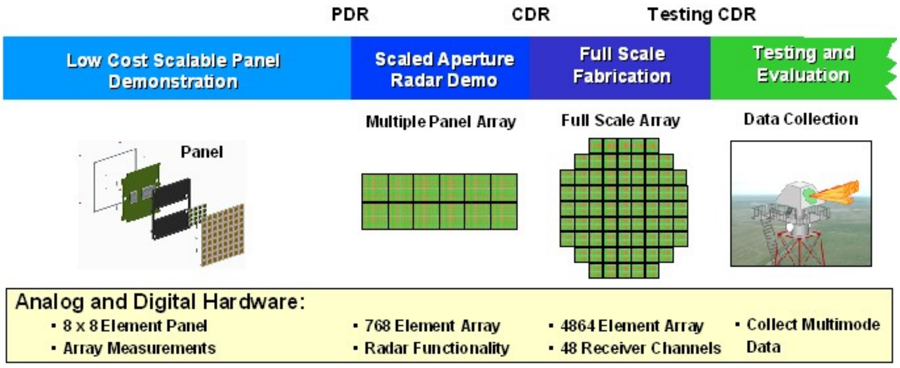


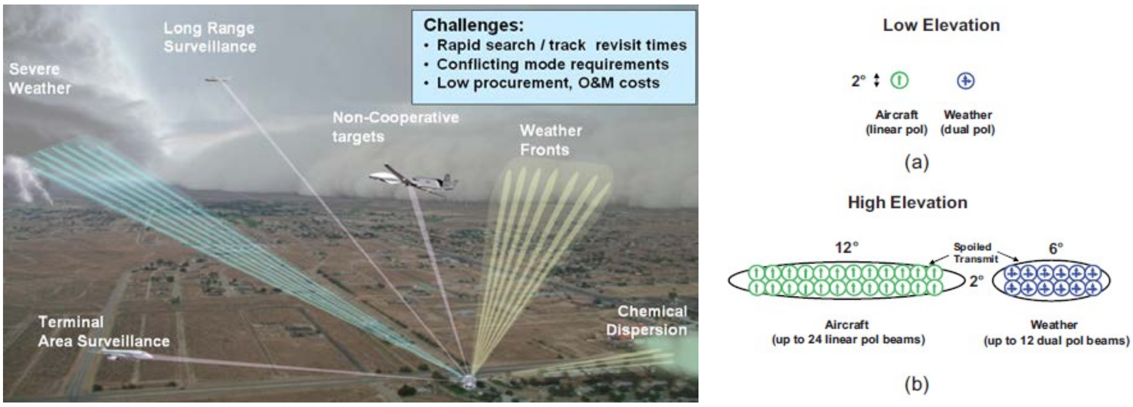
Figure 56: System architecture from prototype to full scale product

Operating frequency:	> 20 MHz band located with in 2.7-2.9 GHz
Array size:	~35(azimuth) × 25 (elevation) dual-polarized elements
Cylindrical dimension:	~1 m radius × 2 m height
Beamforming sector:	90° (135° implementation)
Beamwidth:	< 4° AZ × 4° EL
Element spacing:	<0.7 λ (AZ,EL)
Scanning range (+/-)	22.5° AZ (commuting scan) and 30° EL
Peak transmit power	~ 10 KW (HP demo), ~1 KW (LP demo)

-Dual-polarized patched antenna
@ 2.705 GHz
-10 Watt GaN HPA @ S-band
-3 by 3 by 4 inches and 14 oz weight
-~ 12 watt total power consumption and 2 watt
In receive mode
-Flexible MCU control and TR control interface
< $300 each module for productions

Figure 57: (at left) Cylindrical S-band Testbed with Polarization capability at Oklahoma University, (at right) Dual-Polarized Patched S-band Antenna for Cylindrical Testbed

Final Full Scale MPAR Array will be made of 4864 elements with 48 Receiver Channels.



Challenges:
- Rapid search / track revisit times
- Conflicting mode requirements
- Low procurement, O&M costs

Figure 58: Beam-steering with Pencil beams or Beams cluster linear (in green) or dual polarization (in blue)

5.2.2.4 US, Japanese, Russian & French Wind & Wake-Vortex LiDAR

- Partners : LOCKHEED CT (US)
- Funding : NASA (NextGEN)
- Run-time : Product
- Principal goal : New 1.6 micron (non-fibered) 3D Scanner LiDAR (Windtracer)

- Partners : MITSUBISHI (Japan)
- Funding : JAXA, ENRI (CARATS)
- Run-time : use for trials since 2008
- Principal goal : 1.5 micron fibered 3D scanner LiDAR

- Partners : LASER SYSTEMS (Russia)
- Funding : Russian Federation
- Run-time : in production since 2011

- Principal goal : 1.5 micron LiDAR Profiler

- Partners : LEOSPHERE (France)
- Funding : R&D Selffunding (development funded by Greenmarket)
- Run-time : Product since 2011
- Principal goal : 1.5 micron fibered 3D scanner LiDAR (Windcube 200S)

- Partners : FIBERTEK (US)
- Funding : NASA, SBIR (funded by NASA for NextGEN, and funded by SBIR program)
- Run-time : Demonstration in development since 2010
- Principal goal : 1.5 micron fibered 3D scanner LiDAR

- Topics and achievements in the scope of the project :

  The 1.5 µm fiber laser technology is a new promising candidate for wind monitoring LiDARs on airports. Based on reliable telecom components, this innovative technology provides a wide flexibility on LiDAR parameters allowing various applications such as wind vertical profiling, long-range wind shear and turbulence measurements, or fast wake-vortex monitoring.

  Developed and produced by USA Coherent Technologies, WindTracer® Doppler light detection and ranging (LiDAR) system is used for airport applications, wind resource assessment and meteorological research. WindTracer LiDAR is one of the first Lidars dedicated to operational use like tracking hazardous winds. The system provides advanced warning of wind shear, allowing air traffic control personnel to give precise, timely direction to pilots during takeoff and landing.

  The system is used by the Federal Aviation Administration (FAA) to conduct wake vortex detection and tracking for consideration of future flight rule changes.

  In Japan, Mitsubishi has developed a LiDAR, operated by ENRI & JAXA for airport studies. More recently, Russian company “LiDAR Systems” has presented a LiDAR Profiler for airport wind-shears.

Figure 59: (from left to right) US Lockheed 1.6 & 2 micron Lidars, Japanese Mitsubishi 1.5 micron LiDAR

Figure 60: Russian 1.5 micron LiDAR from “LiDAR Systems”

Available 3D scanner technologies are available in US with Windtracer LiDAR (very expensive technology), in Russia (very low power technology) and in Japan (with limited export restriction). The only European source of 1.5 micron fibered 3D scanner LiDAR is the technology proposed by the SME LEOSPHERE in collaboration with the French Aerospace Agency ONERA. This technology is based on a 1.5 µm pulsed LiDAR using an all fiber laser source and has been developed and allows to measure accurately the wind field. This technology has been successfully tested in SESAR P12.2.2 for wind & wake-vortex monitoring in cleair air. This product needs R&D Funding support for development for higher laser source.

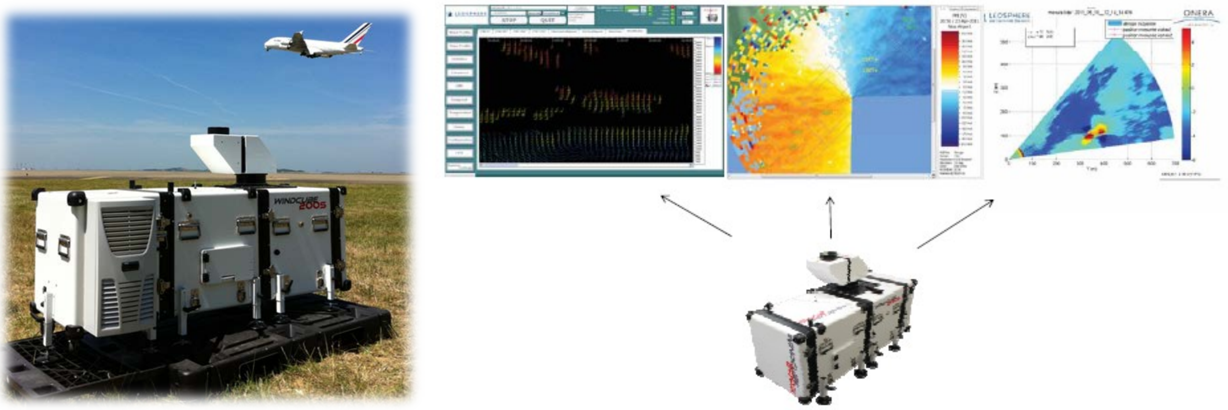


Figure 61: 3D LiDAR Scanner in 1.5 micron fibered technology, WINDCUBE-200S from LEOSPHERE

The most widespread implementation of a coherent LiDAR transmitter is a high energy (milliJoules) and low repetition rate (multi Hz) solid-state laser. The higher energy is desirable to reach further range and relax requirements on the receiver. However, the low repetition rate is not attractive due to possible fluctuations of the laser and the atmospheric conditions from pulse to pulse, yielding inaccurate measurements. Additionally, the lower repetition rate reduces the overall measurement time for a LiDAR scan. In contrast, a higher repetition rate enables faster time-resolved measurements, and provides capability for averaging the measurements to smooth out speckle and other distortions. The solid-state laser technology cannot provide repetition rates higher than ~few kHz due to thermal problems, whereas fiber-optic based coherent LiDARs can provide up to GHz repetition rates, but with lower energy levels. Additional benefits of fiber-optic technology arises from the size weight and power improvements, flexible installability of subsystems, robustness and maturity of component technology, availability of ultra-stable local oscillator lasers, and powerful pulse formatting capabilities for multi-function LiDAR operation. These characteristics make fiber-optic LiDARs ideal tools for airport and airborne applications.

US company FIBERTEK is developing a 1.55 micron LiDAR in fiber technology, with good compromise between spatial resolution and velocity resolution (pulse width as ~800 ns, 25 kHz repetition rate or ~0.13 MHz at 1.55 µm wavelength). They use ultra-low noise laser sources with ~kHz level linewidth, and -140 dBc/Hz amplitude noise (40 averages are enough to yield greater than 1.5 km range at 100 µJ pulse energy). The transmitter is based on a fiber-optic master oscillator-power amplifier (MOPA) architecture where the master oscillator is a ultra-low noise semiconductor distributed feedback (DFB) laser. This work was funded by NASA Langley Research Center through SBIR program NNX10CB26C.

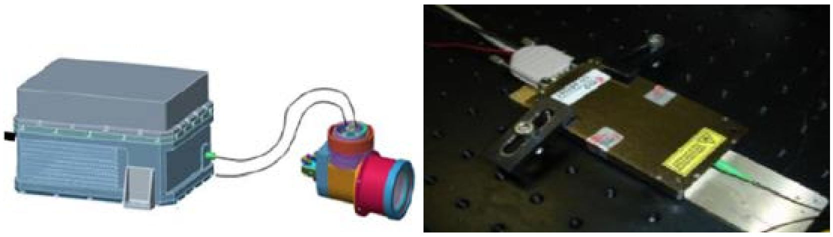
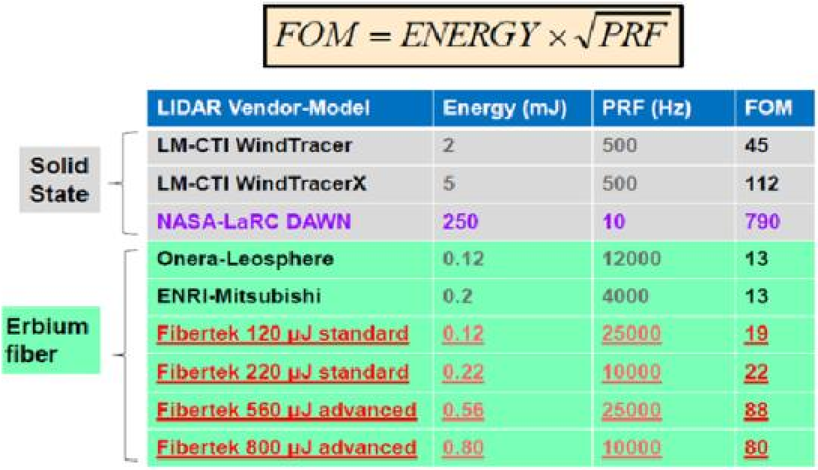


Figure 62: (at left) US FIBERTEK Coherent 1.55 micron LiDAR system, (at right) Master Oscillator

In the following table is provided Figure of Merit (FOM) to compare LiDAR performances :



$$FOM = ENERGY \times \sqrt{PRF}$$

	LIDAR Vendor-Model	Energy (mJ)	PRF (Hz)	FOM
Solid State	LM-CTI WindTracer	2	500	45
	LM-CTI WindTracerX	5	500	112
	NASA-LaRC DAWN	250	10	790
Erbium fiber	Onera-Leosphere	0.12	12000	13
	ENRI-Mitsubishi	0.2	4000	13
	Fibertek 120 µJ standard	0.12	25000	19
	Fibertek 220 µJ standard	0.22	10000	22
	Fibertek 560 µJ advanced	0.56	25000	88
	Fibertek 800 µJ advanced	0.80	10000	80

Figure 63: Figure of Merit to Compare Lockheed, Mitsubishi, Leosphere and Fibertek LiDAR

5.2.2.5 Airborne LiDAR sensors by Thales

- Partners : THALES (Europe)
- Funding : Self-funding
- Run-time : Until 1997
- Principal goal : Development of Airborne LiDAR
- Topics and achievements in the scope of the project :

Thales has started an airborne, forward-looking LiDAR system for air speed measurements 50 to 150 meters in front of an aircraft in all operating circumstances. Such a LiDAR is envisioned to support several aircraft flight control functions including Wake Encounter Prevention System / Control, Gust Load Alleviation and Turbulence Active Control. Those aircraft flight control functions, enabled by a short range forward-looking LiDAR, will positively affect aircraft operational capabilities and costs as well as safety.

A global aircraft model reproducing the behaviour of the aircraft (including flight controls, autopilot or human pilot models) and of the turbulence events (including gusts, wind, and wake generated by other aircraft) will allow adjustment of main LiDAR characteristics (parametric model) in order to perform sensitivity assessments of the functions benefits versus these characteristics.

In addition to the aircraft and the turbulence models, a LiDAR simulation model is needed in order to:

  - Assess the feasibility of these functions
  - Improve the specification of a LIiDAR system suitable for several flight control functions

Such forward looking LiDAR application has already been flight tested in the frame of the FP5 AWIATOR project but without connection to an aircraft's flight control system. The approach envisaged addresses a more systematic approach, trying in a first step to define the overall system requirements for the different applications.

5.2.2.6 Airborne UV Doppler LiDAR sensor by EADS / Airbus

- Partners : EADS Innovation Works and Airbus
- Funding : FP5 AWIATOR program
- Run-time : Until 2007
- Principal goal : Development of UV direct detection Airborne LiDAR and flight testing thereof
- Topics and achievements in the scope of the project

An UV direct detection LIDAR was developed, integrated and flight tested, being able to measure at 4 direction 50m ahead of the aircraft (measuring the full 3D air flow vector) at 60 Hz. The achieved standard deviation was in the order of 1-1.5 m/s, even at high altitude of FL 390. The data have been recorded and evaluated off-line. Even though the real time capability is still missing, the principle feasibility of a forward looking UV LiDAR was proven [Schmitt, N., 2007], [Jenaro-Rabadan, 2010].

The flight tests of the AWIATOR system have been successful, however major steps are still needed to prove the system concept, especially a) develop a real time data analysis and b) connect the real time data with the flight control to demonstrate feasibility off the general concept.

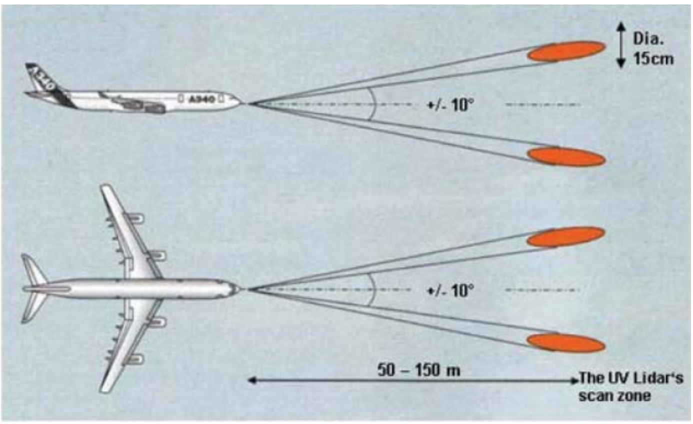


Figure 64: The measurement geometry for the AIWATOR UV LiDAR flight tests. Four measurement directions were updated with 60 Hz in order to detect the full 3D wind speed vector 50-150m in front of the aircraft, detecting turbulences from any direction, at m/s accuracy

Figure 65: The EADS UV LiDAR developed within the AWIATOR project (left) and the integration in an A340 aircraft during Airbus flight tests (right); the LiDAR is included in the fairing beneath the cockpit

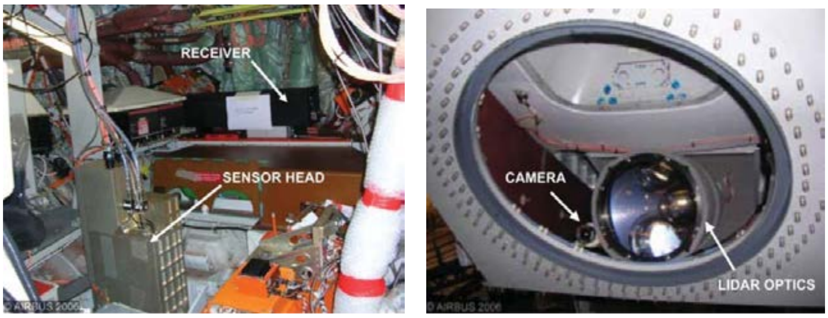


Figure 66: LiDAR integrated in the A340 test aircraft avionics bay (left) and fairing (right)

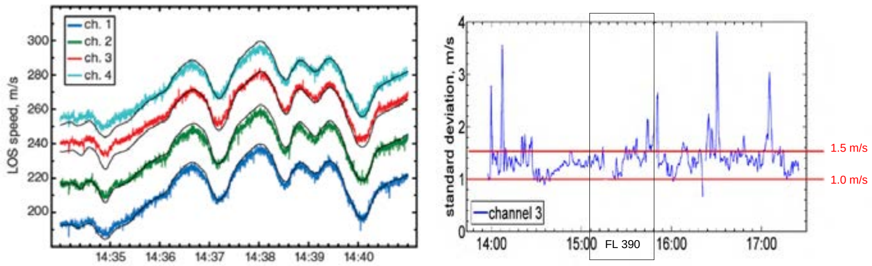


Figure 67: Flight test results of the EADS/Airbus AWIATOR UV LiDAR: Left: Sequence of high speed dynamics. The narrow black lines represent standard aircraft reference air data, the coloured lines represent the unfiltered UV LiDAR air speed data, measured in 4 directions, which are shifted by 20 m/s in this graph for better visibility. Right: Standard deviations achieved versus flight time. The high outliers may be caused real turbulence.

5.2.2.7 US NextGEN ADS-B Downlink of MET Data for Airport application

- Partners : US industries (ITT, Rockwell Collins, …)
- Funding : FAA (NextGEN)
- Run-time : Work Group launched since 2010 (RTCA SC-206 SG-1 Subgroup)
- Principal goal : ADS-B Downlink of MET Data (especially Wind/EDR Data for Wake-Vortex Hazards)
- Topics and achievements in the scope of the project :

  The Automatic Dependent Surveillance – Broadcast (ADS-B) system has been designed to provide highly accurate current aircraft position data. Currently, wind data are limited by the accuracy and age of meteorological data along planned aircraft routes. These limitations create operational inefficiencies that degrade the benefits achievable through implementation of new concepts envisioned by the European SESAR and the US NextGen program. In 2009, leaders within the FAA and the aviation industry stepped forward to request that RTCA Special Committee 186 (SC-186) start to develop consensus standards and lay the groundwork for international agreement on the use of ADS-B as a vehicle for broadcasting a limited set of meteorological data. A US Working Group RTCA SC-206 SG-1 Subgroup for Wake, ATM, & MET has recently (in 2011) provided an Operational Services and Environmental Definition (OSED) of "Aircraft Derived Meteorological Data via ADS-B Data Link for Wake Vortex, Air Traffic Management, and Weather Applications". The OSED, written by RTCA working group, describes the technical concepts of broadcasting Meteorological (MET) and Air-Reference Vector (ARV) data within next generation ADS-B as well as a range of applications, among them wake vortex dependent separation procedures. The insertion of wind and turbulence data into the ADS-B message is foreseen and the development of the respective data format and standards has been initiated.

Global Architecture of MET Data Downlink by ADS-B is given in the following figure:

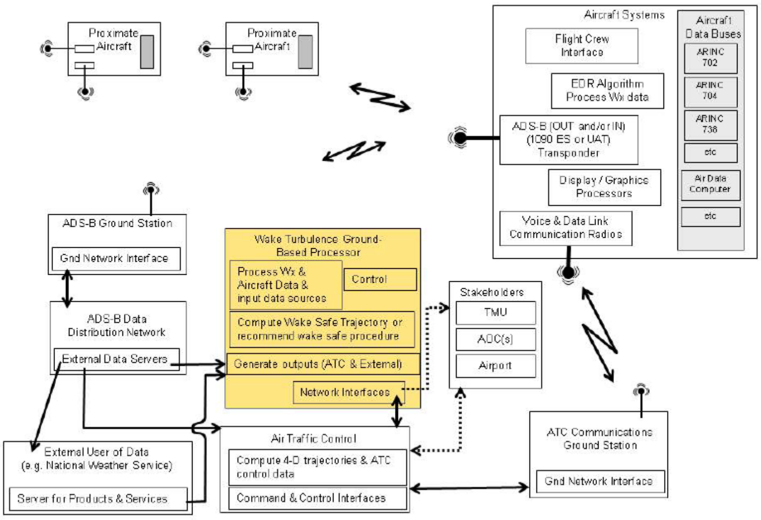


Figure 68: RTCA SC-206 SG-1 Subgroup for Wake, ATM, & MET on ADS-B Downlink Architecture

5.2.3 Research Needs

The following European research needs have been identified for sensors:

5.2.3.1 Wake-Vortex Monitoring Radar / LiDAR Simulators Study

Radar and LiDAR simulators should be developed, by coupling the 3D output of Large Eddy Simulations (LES) of ambient atmosphere (parameterised by Humidity, stratification and ambient air turbulence) with Electromagnetic model taking into account that scattering characteristics of each sensor are different: the LiDAR detects the movement of particles (aerosols) due to the wind and the Radar detects the intensity of the refractive index structure function Cn2 calculated with the pressure, temperature and humidity gradients outputs from the LES simulation. These simulators should be dedicated to assess capability of each sensor to detect wake-vortex and to retrieve Wind/EDR in different weather conditions and analyze their complementarities. These models should be validated and calibrated by sensors trials on airports.

LES simulation of idealized turbulent humid atmosphere, i.e. turbulence in a fully periodic domain with uniform or linear mean profiles, for different EDR levels and humidity levels should be developed and a modification of the existing LES code should be foreseen for introduction of the Lagrangian part with raindrops. The raindrops should be introduced using a classical raindrop size distribution linked to the rainfall rate. The outputs of these LES simulations should offer a unique possibility to make a coherent simulation of Radar and LiDAR.

- Wake-Vortex RCS (Radar Cross Section), Reflectivity and Doppler Radar signature in clear-air and in rain

  Radar simulator should be developed to be able to finely couple atmosphere models (LES) with electromagnetic models. This simulator should be calibrated with real Radar data, and should be exploited to size future Radar sensors and to assess their performances in all weather conditions. Calibration of ground Radar sensor/simulator should be achieved during trials on airport by comparison with In-situ data provided by an experimental aircraft with airborne equipment like wind & EDR probes.

- Wake-Vortex LiDAR signature in humid weather conditions

  Coherent Doppler LiDAR simulator should take into account Laser beam propagation through a clear atmosphere with typical molecular and aerosol concentration models. Phase-screen numerical simulations, assuming a homogeneous and isotropic turbulence with a known refractive index constant, should consider the scintillation effect, which degrades the system performance.

  For LiDAR simulator, LES code should contain raindrops in the turbulent humid atmosphere for different EDR levels and different drop size distributions. It could be expected that the raindrops will be responsible for the main effects in the LiDAR in the presence of rain and the effect of the aerosols will be dominant in the absence of rain. Various hypotheses will however to be checked in a preliminary phase before the simulations, such as, for example, the variation of the concentration of aerosols with rainrate.

5.2.3.2 High Power Low-Cost 3D scanning Radar / LiDAR Technology study

Range and probability of wake-vortex detection could be improved by power emitters/sources increase of respective X-band Radar and 1.5 micron Lidar. These high-power sensors technologies should be developed at low cost for civil application. These sensors should be able to monitor in 3D based on agile scanning technology.

- Electronic scanning X-band Radar Antenna based on Tile Technology

  Electronic scanning radar antennas are very complex system in which Transmit / Receive module (HPA/LNA/Multifunction Chip) are set on a regular grid. These elements shall typically lie in a small cell about 1.8 cm x 1.8 cm for X-band operation and shall be connected together for electrical, RF, logic command … Nowadays, in order to manage this issue, the used architectures are like brick architecture:

the distribution, clustering of modules and packaging are perpendicular to the front face (radiating panel), which leads to “thick” equipment. So, the brick architectures RADAR based are heavy, thick and needs many connectors and interconnects. It increases the number of elements in the antenna, handling, test … So, the antenna is not low cost and does not fit with the ATC market expectation.

A phased array antenna based on a compact tile architecture is the only way to reach the desired compactness. In this architecture, the set of modules are parallel to the front face, so the depth (so the weight) are less than in the former architecture as the cost: Interconnection remains however the main challenge to handle. As a matter of fact, the move from a standard “Brick” architecture to a “Tile” one brings new challenges to antenna designers: Tile architecture means that we will have to stack electrical “functions” that will have to be vertically connected, while in a brick configuration we only have to consider planar interconnects.

- High Power 1.5 micron laser source for pulsed LiDAR in Fibered technology

  Wind Lidars with fiber lasers benefit from telecom technology flexibility and availability in Europe. However, because of non linear effects, their laser power is not high enough to measure wind and turbulences in the full required volume at the requested rate for airport applications. Based on progress in complex fiber technology in European labs, high peak powers have been recently obtained, with 1kW peak power. R&D Funding is needed to adapt this laser technology to a wind LiDAR and make it compact enough for a first outdoor demonstration.

  Laser source study should be achieved based on definition of laser requirements, compact rugged laser source architecture design with increased performance compared to commercially available technology, Laser demonstrator development using the best technology, which includes the laser construction and performance validation. Outdoor demonstration is also needed: the high power LiDAR should be tested outdoor to validate range, resolution and integration time.

5.2.3.3 Advanced Sensors Processing studies

These new functions (wake-vortex detection, circulation retrieval, EDR assessment) should be defined for new emerging Radar and Lidar sensors. These processing should be adapted for individual sensors or for collaborative suite of sensors. Upgrade of processing of existing sensors could be envisaged in an intermediate step.

- Doppler Radar Processing for Wake-Vortex Detection, Circulation Retrieval and Wind/EDR assessment

  A combination of single-Doppler Radar algorithms, multiple Doppler Radar algorithms, and directly measurement of the Doppler velocity should be explored and compared. A combination should benefit from the high resolution and fast update of a dedicated airport radar system and the high accuracy of the multiple Doppler algorithms using additional radar measurements from other operational weather radars and the weather channel of ATC PSR radars.

  In addition to Wake-Vortex Detection, Circulation Retrieval and Doppler velocity assessment, radar signal processing should retrieve the width of the Doppler spectrum. This parameter is a measure for the turbulence in the exploration volume. Spectral width is also affected by wind shear, signal-to-noise ratio, or antenna rotation speed. But, as it has been shown by comparison with EDR measurements from aircraft, the observed spectral width can be used to estimate EDR on the scale of a radar measurement volume.

- Multi-Doppler Radar/LiDAR Processing for wind/EDR retrieval

  Complementarily design of a multiple-Doppler 3-D wind and EDR field retrieval system for Radar/LiDAR should be studied. Doppler radar and LiDAR only can access the radial wind component (normally termed as Doppler velocity or line-of-sight velocity) of the 3-dimensional wind vector field, provided that there is sufficient atmospheric scatter. This is for example, for a radar or LiDAR looking along the aircraft glide path only the wind component (head- or tail-wind) along the glide path. However, for forecasts of the propagation of wake vortices, the crosswind and vertical wind component is of major interest. Under certain assumptions it is possible to retrieve these missing components from the Doppler measurements of a radar or LiDAR. Certain single-Doppler algorithms do exist already, like the Uniform Wind Technique or techniques using 3- or 4-D variational approaches. Their performance is best in weather situations with low wind shear. Further, the spatial resolution is low, since a number of measurement volumes in azimuth and range have to be integrated. The accuracy of the estimated wind vector field and the spatial resolution is not sufficient for requirements of wake-vortex hazard mitigation. Alternatively, the radial velocities from a number of spatial distributed radar or LiDAR systems can be combined to observe the same area from different directions. In this situation, termed as dual- or multiple-Doppler analysis, the horizontal wind vector field could be estimated directly with sufficient high accuracy. In combination with a 3- or 4-D variational approach the vertical motion could be estimated. The spatial resolution could be as high as the individual measurement volumes. Instead of active radar systems, bistatic Doppler receivers can be used in combination with one single active radar.

- Collaborative/Coordinated Radar/LiDAR Sensors 3D Scanning Strategies

  Based on new agility capabilities of new generation Radar/LiDAR Sensors, new Radar/LiDAR Scanning strategies in coordinated functioning should be studied. These scanning strategies should be dependent of weather conditions and observed weather hazards, and could be envisaged for each sensor independently or in a collaborative way to improve Wind/EDR Retrieval accuracy.

  This approach will include Shared awareness (definition of data exchanges between both sensors to have a global weather picture) and Collaborative Decision & Management (Rules and Procedures to assign resources between both sensors according to sensors capabilities, Definition of Collaborative scanning strategies of LiDAR/Radar Sensors).

- Upgrade of Primary Surveillance Radar Weather Channel

  Study of Weather channel upgrade of European ATC PSR radar should be done including new functions; single-Doppler wind retrieval based on Uniform Wind Technique, EDR assessment based on High Resolution Doppler assessment of Spectrum Width and clouds tracking based on Radar Image processing.

5.2.3.4 New standard for Met data down-link by Mode S and ADS-B

Development of ADS-B datalink is an opportunity to define each aircraft as a potential source of relevant MET information (wind, EDR,…) for terminal approach and initial take-off. Technological challenges should addressed to consider limited bandwidth in respect with requested high tempo of data downlink for safety nets.

- Study of new ADS-B Data-Link standard for Met Data Down-link at high tempo

  For ADS-B Downlink of MET data study, analysis of data to be transmitted and corresponding update rates should be conducted. A mobile VHF ADS-B telemetry link for the flight trials should be designed, followed by an experimental setup including wind and EDR onboard measurement equipment to test the downlink of weather data. A research aircraft should be equipped with standard pitot static probes comparable to that of a commercial aircraft as well as with high precision air data probes usable to determine airborne EDR. The output of the high precision system should serve as airborne reference for comparison with measurements from ground based LiDAR and Radar.

  Extensive testing with Mode-S data has shown that wind and temperature observations from individual aircraft are subject to systematic and random errors that may be overcome by periodic calibration and validation on-ground. All relevant data from the trial campaign instruments should be then gathered and subjected to a rigorous evaluation, validation and calibration.

5.2.3.5 Airborne Forward-Looking LiDAR

Airborne UV Doppler lidars are emerging sensors that should be developed based on technological bricks and validated by flight testing, especially for their fully integration in flight control.

- Airborne LiDAR Model study

  A global aircraft model, including the LiDAR model, has to be used to define the requirements and characteristics of the forward looking LiDAR, for the different envisaged applications, such as Wake Encounter Prevention System / Control, Gust Load Alleviation and Turbulence Active Control. Following this phase of requirement definition, a technological assessment has to be performed, in order to evaluate the ability of the current and foreseen technologies to fulfill the requirements.

  This technology analysis has to deal with the different sub assemblies of the forward looking LiDAR: laser source, optical signal processing, detectors, electrical signal processing. This analysis should be conducted both for the IR and the UV wavelength.

  This technological analysis should take into account the functional performances of the LiDAR sub-assemblies, as well as their ability to stand the environment associated with the function to be performed. Aircraft installation is also a parameter to be considered. Not only existing technologies should be investigated, but also technologies under laboratory or industrial development. For example, the backscatter lidar (Hirschberger et al. 2012), an airborne sensor with a still low technology readiness level but the advantage to measure velocities perpendicular to the line of sight of the laser should also be considered.

  Finally, both the requirement analysis and the technological analysis will define the main choices for the development of a short range forward looking LiDAR that will positively affect aircraft operational capabilities and costs as well as safety.

  Further analysis is needed in order to quantify the benefits of a forward looking LIDAR. The challenges of such a study are a) the quantification of the benefits themselves and b) the correlation of different benefits into an overall estimation, e.g. analysing not only wake vortex and turbulence auto-control benefits, but also additional value with respect to air data measurement, passenger safety, maintenance, etc.

- Developing technology bricks for on-board UV Doppler LiDARs

  The UV LiDAR technology at the moment seems to be the most promising for measuring air flow and disturbances (wake vortices, clear air turbulences, shear wind, gusts) in front of the aircraft, as this is the only known technology being independent from aerosol presence, thus being a reliable measuring method at all flight altitudes, geographical regions and environmental conditions. Aerosol based technologies are mostly limited to a maximum distance of some meters at larger altitudes. Although the basic proof of concept on-board UV LiDAR sensors is already been made, before planning a new airborne LiDAR flight test with flight-control integrated architecture, a number of LiDAR technology bricks need to be developed, targeting to

  - a real time LIDAR data processing system, capable computing true air speed values from LIDAR physical inputs to feed a flight control in real time
  - technologies for conformal integration of LIDARs into aircraft structures
  - Highly efficient and miniaturized optical subsystems like scanners, lasers, optics, adapted to the need of forward looking wake vortex and turbulence measurement requirements.

  Optical technologies have dramatically improved (e.g. for high power fibre lasers, new optical materials for windows, fast scanning systems) in recent years. This is also the case for fast parallel data processing systems and LiDAR algorithms adapted to those processing architectures. As a future LiDAR demonstrator needs a much higher degree of integration and miniaturization in order to perform long-term measurements, and definitely need to provide data in real-time for an operational technology proof in real atmospheric disturbance environment and flight control interaction, those bricks need to be developed to be available for a full system flight test.

Due to the required duration of such investigations, the research on the major technology bricks should be started as soon as possible.

- Flight testing of on-board UV Doppler LiDAR fully integrated with flight control

  On-board LiDAR feeding into flight control demonstrate the most promising technology to counteract to atmospheric disturbances like wake vortices, turbulences, shear wind, because of three reasons: a) pilot-in-the-loop concepts would require a very large detection range, very difficult if ever achievable b) the long range data might be of no relevance when the aircraft really encounters the relevant space c) new technologies should be use to decrease, not to increase pilot work load. Thus auto piloting functions need to be advanced rather than indicating more information for the pilot he needs to react on.

  Beside all simulation, the final proof can only be performed by a flight test with a forward looking LiDAR system directly connected to flight control. The following topics need to be investigated

  - Integration of an on-board LiDAR system according to technology bricks available
  - Integration of flight control strategies to use LiDAR data for atmospheric disturbance alleviation and/or auto control
  - Data fusion of LiDAR data and other sensor data to achieve best adapted performance
  - Evaluation of disturbance counteraction potential and remaining influence by flight testing
  - Concepts for future aircraft performance and air traffic operation

5.3 Weather Prediction and Monitoring

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5.3.1 Overview

Wake vortex behaviour strongly depends on the prevailing meteorological conditions. Therefore, most wake vortex concepts and prediction systems (see §3) depend on current meteorological observations and forecasts of conditions for the near future (10 min to next hour) and typically along an aircraft's glide or takeoff path or also along the flight path in cruise. Even tools for risk analysis (see sections 5.5 and 6.2) require appropriate representations of the weather conditions including both the typical weather in a climatological sense and unusual, potentially critical, weather situations.

5.3.2 State-of-the-art

Due to the variability of the meteorological conditions deterministic wake vortex prediction may not represent the variability of the consequential wake vortex behaviour. Probabilistic wake vortex prediction aims to consider all related uncertainties by producing envelopes for wake vortex trajectories and circulation with defined probabilities. For many applications the most important mechanism is the advection of wake vortices out of a flight and runway corridor. Unfortunately, major uncertainties are related to the prediction of crosswind and its fluctuation which are most relevant for lateral vortex transport.

Methods for probabilistic weather prediction appear to have a strong potential to improve probabilistic wake vortex prediction and thus to improve the performance of wake vortex advisory systems. Ensemble weather prediction methods may improve the prediction of average quantities and, additionally, characterize the related forecast uncertainties. However, for short prediction horizons, ensemble prediction may not be the best choice. In contrast, probabilistic nowcasting methods (based on observations) are less time consuming and well suited for a short prediction horizon. Both approaches are faced with interesting developments, yet they have to be adjusted to the requirements of a specific application.

In SESAR WP11.2 "Meteorological Services" the EUMETNET Consortium consisting of several national meteorological services and other partners are preparing the development of systems that shall provide weather data tailored to the needs of Air Traffic Management. The information shall be integrated into a weather database containing meteorological measurement data and prediction data as part of a System Wide Information Management (SWIM). Promising approaches aim at establishing local-area short-range weather prediction models (around airports) employing ensemble prediction techniques and assimilation of weather data at airports. On the other hand, there is an initiative to install common European-wide, high-resolution ensemble prediction systems such that high-quality ensemble prediction data may become available even en route in the future. In relation to this new terminal weather systems are being installed at airports (Evans 1995, Lau 2000). For example, the LLWAS/ITWS (Low Level Wind Shear Alert System/Integrated Terminal Weather System) will be installed at Frankfurt and Munich Airports by the German Weather Service (DWD) and several LIDARs and RADARs will be established at Nice Airport by Meteo France.

In the following the requirements of wake vortex models with respect to their meteorological inputs are discussed. Then a survey on recent developments of weather prediction and monitoring is given. Promising methods are introduced and their potential for wake vortex systems is discussed.

5.3.2.1 Requirements

The meteorological input parameters required by wake vortex prediction models are crosswind, headwind/tailwind, turbulent kinetic energy (TKE), eddy dissipation rate (EDR), and (virtual) potential temperature. Vertical profiles of these variables are needed in the height range where the wake vortices develop, i.e. from the generation height of the vortices down to their lowest descent height.

Ideally, the vertical resolution of the meteorological parameters close to the ground is on the order of 10 m and at higher altitudes not coarser than 50 m. For different applications the temporal prediction horizon may vary from 2 min (warning time needed by airborne wake encounter prevention systems to avoid wake vortices ahead of an aircraft), 6 min (time after which aircraft separation during approach should not be readjusted), 20 min (time to plan sequences of approaching aircraft), 1 hour (time for more comprehensive planning of sequences of approaching aircraft) and up to 6 hours (planning horizon that may already affect aircraft prior to take off).

Most wake vortex encounters occur at flight altitudes below 100 m, because wake vortices cannot further descend below the flight corridor but tend to rebound as a consequence of interaction with the ground. Moreover, the possibilities of a pilot to counteract the imposed moments and forces are restricted due to a low height of the aircraft above ground. Therefore, highest accuracy of the meteorological quantities is needed within a distance of about 1 NM from the touchdown zone or take off position, respectively.

Lateral wake vortex transport driven by crosswind plays a prominent role:

- It is the most important mechanism for many wake vortex advisory systems (in ground proximity, it is the primary mechanism that may clear a flight corridor from wake vortices).
- It is easy to model (crosswind advection can be directly translated into wake vortex transport distances, if the wake vortex residence times during the descent along the crosswind profiles are modelled correctly and if effects of vortex deformation, turbulence, wind shear, and ground proximity can be neglected).
- It introduces the largest uncertainties within the predicted wake vortex properties (lateral transport, vertical transport, and circulation decay). These uncertainties are related to crosswind fluctuations (gusts, turbulence) and spatiotemporal variations of crosswind.
- The knowledge of the remaining meteorological parameters is also important, if highly accurate predictions of wake vortex behaviour are required. EDR is the most important parameter for characterizing wake vortex decay.
- During cruise vortex lifetime and vortex descent are mainly limited by thermal stratification because turbulence typically is very weak.

The uncertainties related to meteorological input parameters contribute significantly to the uncertainties of predicted wake vortex behaviour. Other sources of uncertainty are initial conditions, reference data (typically LiDAR measurements that are closest to the *true* wake vortex behaviour), and the intrinsic variability of wake vortex data. As a consequence, probabilistic predictions of wake vortex behaviour are required. Instead of a deterministic average behaviour, probabilistic predictions yield upper and lower bounds of wake vortex behaviour, ideally with assigned probabilities.

Anticipating that probabilistic weather prediction methods may yield a larger spread for less predictable situations and smaller spread for well predictable situations, wake vortex prediction methods have been developed that utilize spread information for adjusting the probabilistic predictions (Holzäpfel 2010). The ultimate goal of the combination of probabilistic weather and wake vortex prediction methods is to achieve, on average, more compact probabilistic wake vortex predictions resulting in reduced uncertainty allowances. However, initial attempts to exploit ensemble weather prediction have produced little benefit, for reasons that will become clear below.

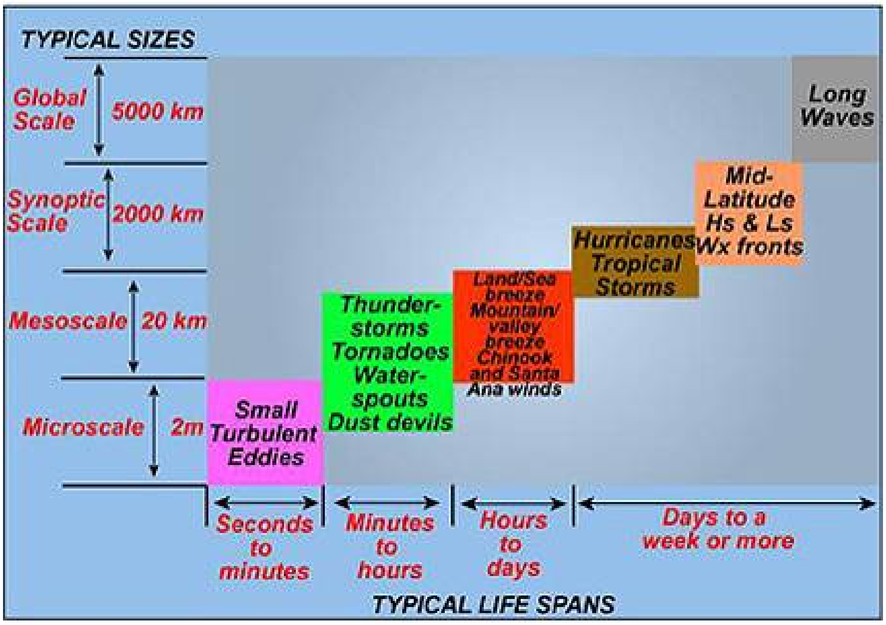

Figure 69: Time and space scales of atmospheric motion (from The Remote Sensing Tutorial, NASA).

5.3.2.2 Features and Opportunities of Weather Prediction Methods

Because of a non-linearity of the underlying transport equations, weather is a chaotic phenomenon. Slightly varying initial conditions may lead to drastically varying outcomes. The predictability of weather phenomena scales with their characteristic length and time scales (see Figure 69). In particular, wind and turbulence scenarios depend on phenomena characterized by a wide range of characteristic length and time scales. This is one reason why the predictability of these parameters may largely depend on the prevailing weather situation.

Basically two approaches for short-term weather prediction are available: nowcasting methods and numerical weather prediction models. Nowcasting is the extrapolation of observed values in space and time. The extrapolation may be based on persistence, Lagrangian approaches, or simple physical or statistical models. Basically, vertical extrapolation is much more restricted than horizontal extrapolation; for example, inversions decouple layers at different altitudes. Also, errors of the underlying measurements are typically smaller than the extrapolation errors. A comprehensive survey on available measurement instrumentation is provided in §5.2.

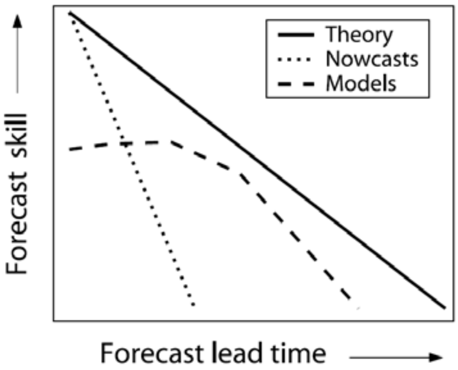

Figure 70: Forecast skill of nowcasting and numerical weather prediction models (from Kober after Lin et al. 2005).

The forecast skill of nowcasting rapidly decreases with forecast lead time. At some forecast lead time numerical weather prediction becomes superior to nowcasting (see Figure 70). The crossover time for prediction skill of these two methods depends largely on the encountered weather conditions and phenomenon of interest. For precipitation forecasts, the crossover time tends to be on the order of 3 to 6 hours (Kober 2010), whereas for wake vortex prediction the crossover time may be around one hour (Frech & Holzäpfel 2008). For convective precipitation forecasts, it has been demonstrated that a smart blending of nowcasting and numerical weather prediction can improve forecast quality (Kober 2010). The blending may be based on weighting functions that depend on the prediction skill of a particular method. This appears to be a promising approach also for wake vortex prediction purposes.

A complete description of the required weather parameters should be stated in terms of appropriate probability density distributions, such as average values and standard deviations. For numerical weather prediction this may be achieved either by basing uncertainty estimates on subgrid scale models used in deterministic numerical weather prediction or by ensemble prediction methods.

For the relatively short prediction horizons required for many wake vortex systems, it is possible that deterministic numerical weather predictions, including assimilation of observations taken in the airport environment, might well capture the average state of the atmosphere. In this case, the subgrid scale variability of weather parameters will make the dominant contribution to the overall uncertainty. Currently, the turbulence parameterization of the COSMO model is being augmented (Raschendorfer 2010). Improved EDR forecasts will consider the effects of horizontal shear, mountain blocking, and convection. The developed turbulence scheme accounts for scale separation of kinetic energy of circulation and turbulence. Further, the EDR output will be calibrated by regression of crucial parameters against EDR measurements.

The above single deterministic approach may be termed *microscale* approach in contrast to the *mesoscale* approach implemented by ensemble prediction methods that are based on a finite number of deterministic integrations. Different classes of ensemble prediction methods have been developed (see Figure 71). The most expensive and powerful approach employs several weather prediction models, combined with perturbed initial and boundary conditions. If properly configured and calibrated (which is not trivial), this approach may likely deliver reasonable spread for short lead times and maintain good prediction skill also for longer lead times. However, such an approach appears way too costly for wake vortex applications at this time. On the other hand, there is an initiative to install common European-wide, high-resolution ensemble prediction systems such that high-quality ensemble prediction data may become available for airport environments in the future.

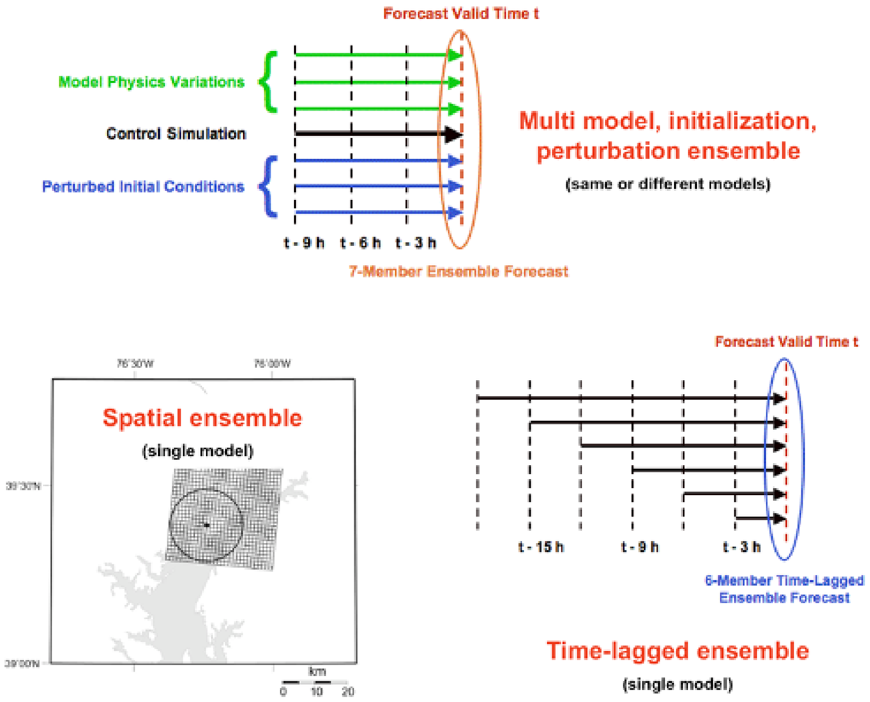

Figure 71: Sketch illustrating different ensemble prediction methods (M. Steiner 2010).

A less expensive approach is the *time-lagged ensemble* forecast that employs a number of overlapping predictions achieved by the same model initialized at different times in the recent past (Lu et al. 2007). For wake vortex applications the most recent members of a time-lagged ensemble may exhibit superior wind prediction skill, whereas turbulence predictions require certain spin-up times. However, experience shows that for short lead times the ensemble spread does not cover the observations in as many cases as desirable.

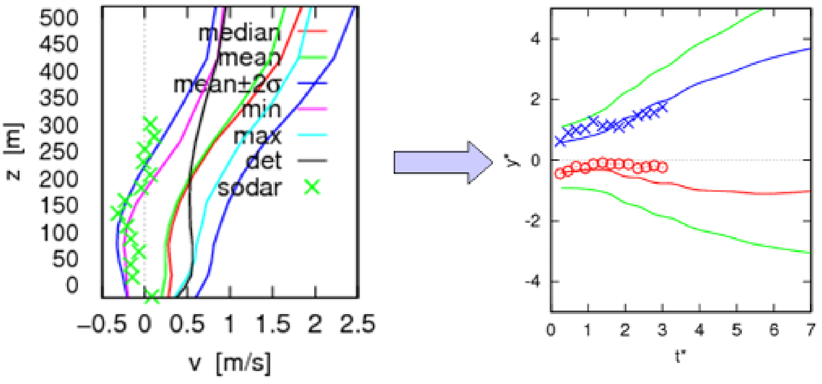

Figure 72: Use of time-lagged ensemble spread for probabilistic wake vortex prediction.

An example of the use of time-lagged ensemble prediction as input for probabilistic wake vortex prediction is shown in Figure 72. The vertical profiles of crosswind (Figure 72, left) have been predicted by the COSMO-FRA weather prediction model (Dengler et al. 2010) employing a time-lagged ensemble with six members and an hourly update rate. The model assimilates local measurement data from SYNOP, TEMP, AMDAR and precipitation Radar. From the six ensemble members averages and the ensemble spread (mean ±2σ) are calculated and are used for the probabilistic predictions of crosswind transport of the wake vortices (Figure 72, right: symbols: LiDAR measurements, red and blue lines: deterministic predictions, green lines probabilistic envelopes, Holzäpfel 2006).

A third approach is the *spatial ensemble* that may be derived from output data of a single model run or, alternatively, from a synthesis of spatial measurements (e.g. radar or LiDAR) with a suite of other observations. The evaluation of neighbouring grid points or measurement data may increase the spread of predictions and, depending on the weather situation, include information of an air mass that is about to be transported to the actual location where predictions are needed.

The described ensemble prediction methods can also be combined, as described above for precipitation prediction. For example, a combination of the time-lagged ensemble and a spatial ensemble may constitute an economical approach for wake vortex prediction purposes.

Experience and analytical considerations suggest that even for a perfect ensemble (one in which all sources of forecast error are sampled correctly) there need not be a high correlation between ensemble spread and prediction skill. The correlation between spread and skill should be larger for meteorological quantities featuring large day-to-day variability of the spread.

Certainly, all types of numerical weather prediction methods may benefit from improved boundary layer physics, parameterizations, and initial conditions. Moreover, weather prediction products can be enhanced by careful calibration which, however, requires sustained predictions and observations over long times.

In conclusion, it is noted that whenever measurement instrumentation may cover the air volumes of interest, short-term predictions based on nowcasting should be preferable. Added value may be achieved from spatial ensembles based on spatial measurements or spatially distributed instrumentation possibly enhanced by 4D data analysis. Utilization of numerical weather prediction becomes necessary, if the air volumes of interest cannot be covered by instrumentation alone. For remote areas and short lead times, the use of available high frequency data using appropriate assimilation schemes will likely increase the forecast skill. Time-lagged ensembles, especially with adjusted data assimilation schemes and possibly combined with spatial ensembles, may economically yield improved prediction skill. Alternatively, uncertainties may be retrieved from models of the subgrid scale variability based on deterministic predictions. Blending of nowcasting and numerical weather prediction has the potential to bridge the gap between the two methods and to improve the overall prediction quality.

5.3.3 Research Needs

5.3.3.1 Sensors

- A generation of new meteorological sensors has emerged (see §5.2). For each of these sensors the spatial and temporal resolutions as well as the weather dependent availability are different. Various sensors have been benchmarked in a three-month measurement campaign in SESAR WP12.2.2. It has to be elaborated which sensors are best suited and how the selected sensors can be combined optimally to provide a consistent weather data base for wake vortex predictions.
- The accuracy of meteorological data measured by standard instrumentation of aircraft should be estimated. The provision of the required parameters with the required resolution transmitted via ADS-B (Automatic Dependent Surveillance – Broadcast) and/or AMDAR (Aircraft Meteorological Data Relay) should be advanced.

5.3.3.2 Numerical Weather Prediction

- Ensemble prediction methods should be employed to improve the prediction skill of average quantities and to quantify the predictability of specific weather situations in terms of the spread of these quantities.
- An economical approach for numerical weather prediction appears the combination of time-lagged ensembles and spatial ensembles enhanced by data assimilation schemes.
- All types of numerical weather prediction may benefit from improved boundary layer physics, parameterizations, and initial conditions.
- Any weather prediction products can be enhanced by careful calibration.

5.3.3.3 Combined Weather Monitoring and Prediction Systems

- Algorithms to deduce robust eddy dissipation rate estimates from various measurement sources and forecast models should be developed.
- Added value from the measurement data can be extracted by the assembly of spatial ensembles. This approach could be enhanced by methods of 4D data analysis.
- Because many applications rely on short-term weather prediction enhanced nowcasting methods employing more sophisticated physical and/or statistical methods should be developed.
- Methods for blending of nowcasting and numerical weather prediction in time may bridge the temporal gap between the methods. Blending of nowcasting and numerical weather prediction in space may improve the prediction skill along the flight path.
- Numerical weather prediction models should assimilate available local measurements in order to improve their forecast skill. It should be investigated which measurements are best suited to improve the prediction skill of the respective required parameters (wind, temperature, turbulence).
- The accuracies achieved by the various measurements sensors (in-situ, remote, and airborne e.g. AMDAR/ACARS), by nowcasting methods, and by weather prediction models should be determined and compared. The respective accuracies (i) should guide the selection of the weather monitoring and prediction methods, (ii) are important inputs for probabilistic wake vortex prediction, and (iii) are critical for the feasibility and success of the different operational concepts.
- Methods for the determination of weather data along the intended flight path of an aircraft are needed for airborne wake vortex prediction. These methods may employ meteorological measurements of the own aircraft and of neighbouring aircraft (provided by ADS-B) and/or may use uplinked ground based weather data. The fusion of weather data from different sources may improve the overall performance of the system.
- For the activities in SESAR WP11.2 “Meteorological Services” and for the new terminal weather systems that are installed at different airports it should be ensured that the developed systems will provide all the parameters needed for wake vortex systems with the required accuracy as well as the required temporal and spatial resolution.

5.4 Wake Alleviation

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5.4.1 Overview

The driving question with regard to wake alleviation concerns the source of the wake, the generating aircraft: is it possible to design an aircraft such that the vortex wakes are less harmful?

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 circulation strength Γ_0 follows from:

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

with W, b, AR and C_L the weight, wing span, wing aspect ratio and lift coefficient respectively of the aircraft. U and ρ 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 π/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 τ^* ($=t/t_0$). 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=bs, the vortex spacing and w_0 the initial sink speed. In terms of aircraft parameters t_0 can be written as:

$$t_0 = \frac{2\pi\rho U (bs)^3}{W} = \frac{4\pi ARbs^3}{C_L U}$$

The larger the value of t_0, the slower the vortex decays. The two formulae above indicate that for aircraft of different size, but at similar weight and landing speed, Γ_0 is proportional to 1/b, and t_0 to b^3. Therefore, an aircraft with a larger aspect ratio will have a weaker vortex which persists longer. 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 τ^* scaling (too much scatter in the ‘in flight’ data sets to discriminate between aircraft of different sizes).

Theoretically, there would 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. The fact that no large variations have been observed between flying aircraft might also indicate that a "low vortex design" would not be very obvious.

During their evolution, the vortex cores grow in size due to diffusion and develop 3-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 Γ and the vortex spacing b_0 are essentially constant. Only in the later stages, when the two vortices interact, Γ will decrease and b may vary. To express the "danger" of a vortex, e.g. described as an induced rolling moment for a follower aircraft, the following various quantities could be used:

- $\Gamma_{5\text{-}15}$, the averaged circulation between 5 and 15 m distance to the vortex core, from LiDAR measurements for real aircraft applications, and between b/12 and b/4 for aircraft models,
- E_{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 $V_{t,max}$ at the core radius r_c.

For quiescent air, the vortex field generated behind an aircraft is then generally split in four regions (Figure 73):

- 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 $0.5 < x^* = x/b < 10\text{-}15$, 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 ~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.

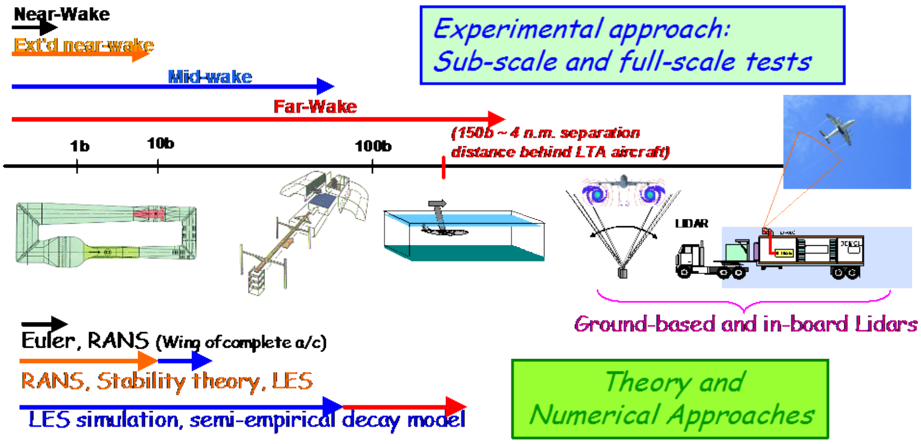


Figure 73: Four regions of the wake flow field as well as their dedicated tools for investigations

Measurement techniques have advanced significantly, as a result of the program mentioned above. For investigations of high-lift wing configurations at landing conditions - without any effect of temperature stratification or installation (known as "end-effect") - the validation domain could reasonably be identified as ~150b and ~100b for large towing tanks (HSVA, INSEAN) and the B20 catapult facility, respectively; ground effects usually alter the wake development behind these limits. The combination of wind tunnel, towing tank or catapult tests is well suited for wake vortex identification in the near- to mid-/far-wake field, knowing that appropriate instrumentation has been adapted or developed in such facilities in order to fully track wake vortices.

Full scale wake characterisation was conducted using LiDAR technology (see §5.2.1.1). In the AWIATOR trials, excellent agreement between the considered on-ground LiDAR tools (short range continuous mode and medium range pulsed mode) was obtained, allowing records of the circulation over about 200 spans behind a four-engine type aircraft. However, measurements indicated a large effect of weather conditions (turbulence, stratification and shear) on wake vortex decay. As a result, further investigations had been pursued, using a pulsed LiDAR mounted in a chase aircraft tracking the wake generated by another aircraft. This technology was validated, too.

Last, but not least, the computer simulations of the development and decay of vortices, even including some effects (turbulence, stratification, near the ground) have advanced significantly and allowed a detailed description of the details of vortex development (see §5.1). It is now possible to perform 3D RANS computations on a complete high-lift wing configuration down to 0.5 - 1 spans for both sub- and flight-scaled

Reynolds numbers. Vortex methods 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 LES techniques. Recent results have pointed out the possibility to build up a numerical chain, based from DLR & ONERA tools, to compute the wake flow field up to about 60 wing spans, avoiding the issues of initial conditions needed for standard LES simulations. Therefore, the stability of vortex systems can be investigated with linear stability theory. This allowed a parametric investigation in search for the highest levels of amplification for several multiple-vortex systems.

Thus, nowadays, a complete methodology including theory, CFD, sub-scale tests and full-scale flight tests, had been validated for the wake characterisation of a baseline high-lift wing aircraft configuration in the framework of the AWIATOR project. The tools are available to see if and how wake vortices can be reduced by design. However, is this chain complete and are important links missing?

Strategies for Wake Vortex Alleviation

Knowing that it is impossible to inhibit the generation of the aircraft wake vortices, the question is: “How can we alleviate, destroy wake vortices, or at least minimise their intensity”?

Two main strategies can be pursued for wake vortex alleviation (Figure 74):

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) (Figure 74b). The total circulation will not be affected, but a weaker rolling moment is expected for the following aircraft. This can be obtained by add-on wing devices such as winglet, flaplet, cylinders, fences, spoilers … (cf. Figure 76).

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 (Figure 74c). This can be reached either by a passive concept leading to span wise wing loading modification (via arrangement of flap or spoiler deflections) or by active devices such as blowing, oscillating flaps or ailerons…

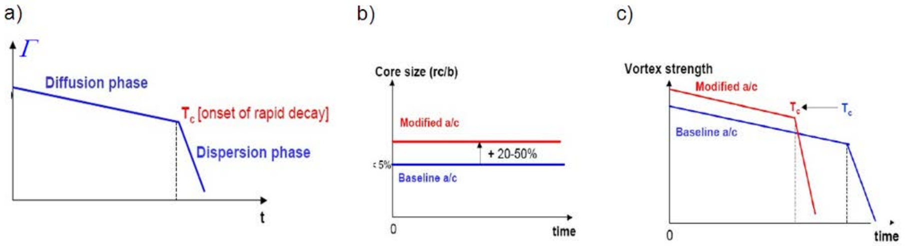


Figure 74: Sketches of evolution of vortex characteristics vs. time: a) "usual" circulation strength, b) alleviation will result from a more diffuse vortex (larger core), c) alleviation will result in an earlier decay.

Passive systems exploit the natural evolution of the instability modes with the highest growth rates, while active systems rely on hastening selected modes of instabilities by “forcing” the vortices. Vortices are characterised by a high degree of unsteadiness; several experimental tests allowed identifying the presence of both short-wave (wavelength $\lambda \sim O(r_c)$) and long-wave ($\lambda \sim O(b_0)$) instabilities.

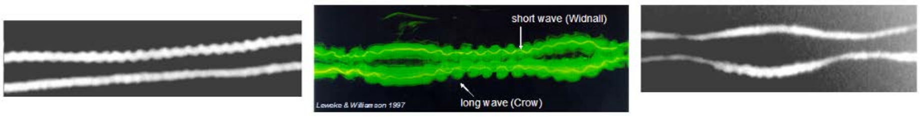


Figure 75: Illustration of evidenced of short-wave and long-wave instabilities.

The former instability (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 roll-up and evolution process of the wake vortices. The “classical” Crow instability ($\lambda \sim 8b_0$, and growth rate ~ 0.8 $\Gamma_0/(2\ \pi\ b_0^2)$) supports the destruction 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.

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 the horizontal tail plane, 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 Ω-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.

An alternative approach independent from specific aircraft designs and configurations is the installation of suitable obstacles following the runway tails that enhance vortex decay during the phase of flight where most encounters occur (see §5.1.2.5).

5.4.2 State-of-the-Art

In the last decade or so, a great number of European projects have addressed this question like Eurowake, C-Wake, AWIATOR or more recently FAR-Wake. 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 wind tunnel, water tank, towing tank or catapult facilities up to full-scale flight trials (each requiring the development of appropriate instrumentation).

As a general comment, research so far has not been very successful in reducing the wake vortex strength behind an aircraft. As vortex formation is essentially related to lift generation, a weaker vortex can only result from design features that affect the decay characteristics far downstream.

In what follows, the main findings will be summarized, although the list being of course not exhaustive. Emphasises will be put on:

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

5.4.2.1 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 (Figure 76) acted in the near- and 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.

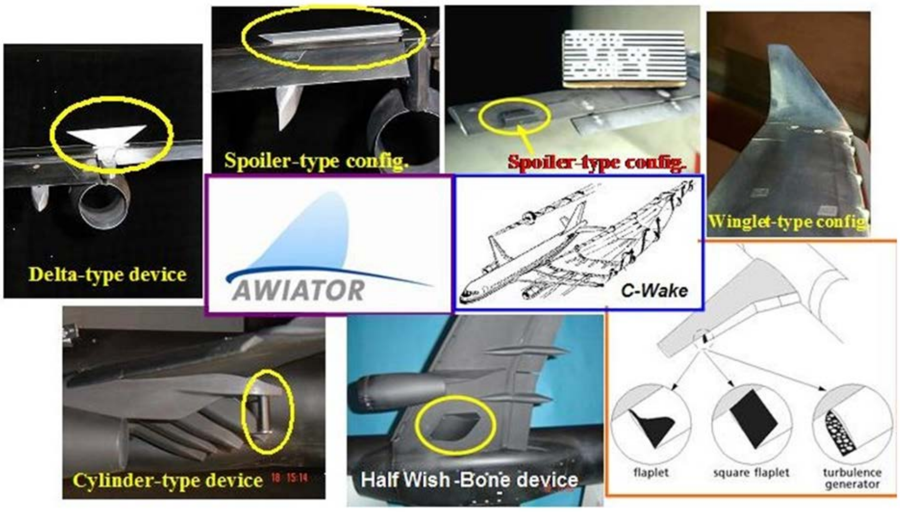


Figure 76: Illustration of wing add-on devices investigated in different EC projects.

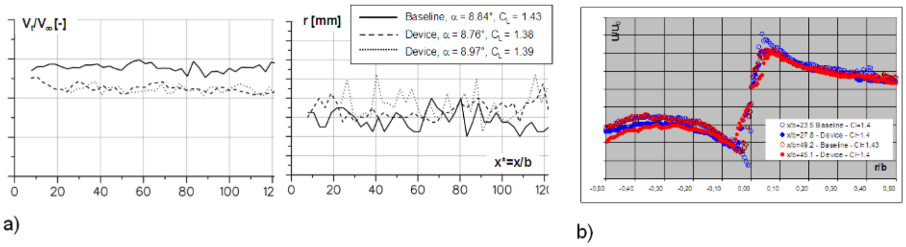


Figure 77: Characterisation of wing add-on device (delta-type plate): a) peak vortex velocity and core radius (HSVA towing tank, PIV meas.); b) tangential velocity profiles (B20 Catapult, LiDAR meas.).

A few devices do modify the vortex core structure: increase of core size and reduction of peak velocity. Towing tank and catapult tests led to the same conclusions for the inclined delta plate (Figure 77).

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.

5.4.2.2 Modification of span wise wing loading distribution

The basic idea is to enhance instabilities by creating a 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 or spoiler 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 (Figure 78, left) that merge very quickly, within a couple of spans behind the model. The aim was to promote a strong inboard vortex, either co-rotating or counter-rotating relative to the combined outer flap / wing tip vortex (Figure 78, middle and right, respectively).

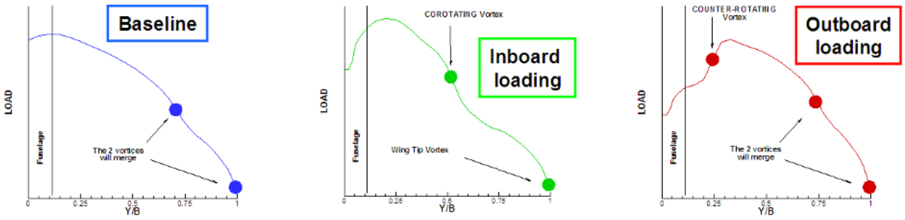


Figure 78: Possible modifications of wing span load distribution.

A real potential of span wise 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 (Figure 79).

Inboard loading (co-rotating 4-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 persists over a longer life-time than those for the outboard loading case (Figure 80).

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. A most promising 4-vortex configuration was selected and rather recently tested in a large towing-tank facility in Potsdam, Germany. These experiments showed a strong interaction between main and counter-rotating secondary vortices at around 30 wing spans downstream, with a substantial decay of circulation strength and an increase in core radius, even if the resulting 2-vortex system had a larger lateral spacing and decayed slower than a conventional 2-vortex configuration with the same lift.

For a double pair of counter-rotating vortices and depending on their relative size and position, it has been shown through LES simulations and in tests on generic models that so called Ω-loops can be generated. They significantly enhance the dissipation of the vortex (Figure 81).

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 Ω-loops (or other instabilities) need a certain time to develop (effectively $\tau^* \sim O(1)$).

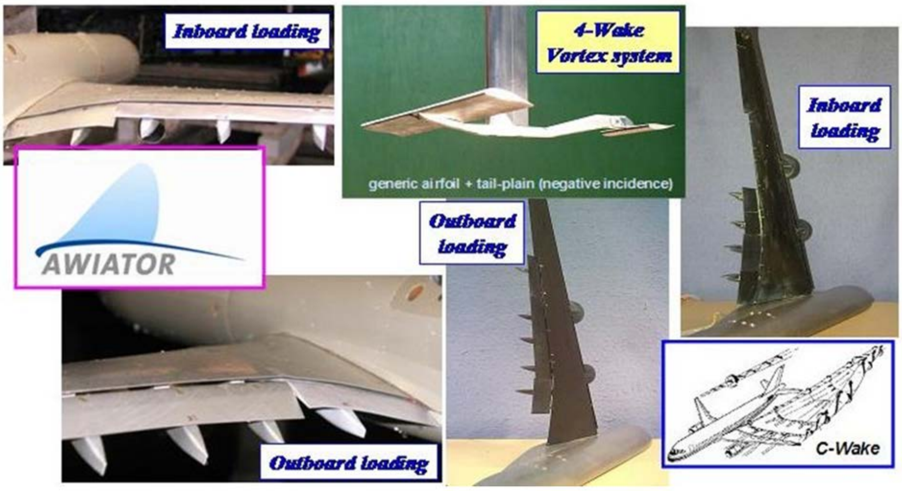


Figure 79: Illustration of differential flap setting concepts for 2- and 3-flaps high lift systems, and generic airfoil.

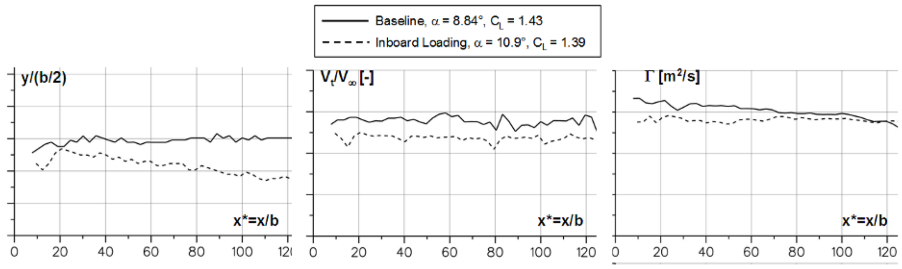


Figure 80: PIV Towing tank results for inboard loading case on vortex spacing, peak velocity & circulation.

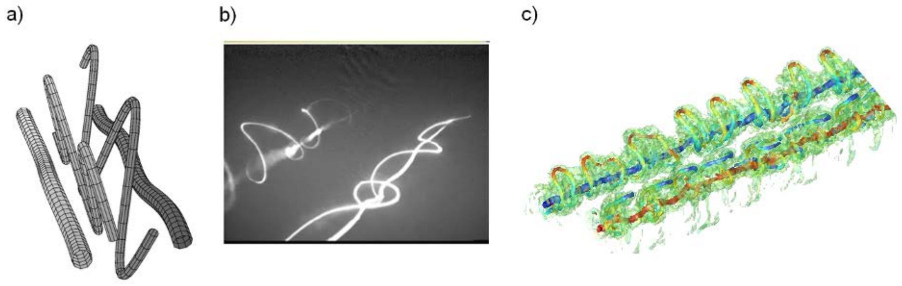


Figure 81: Long wave perturbation in the wake of a 4-vortex system: a) linear stability theory; b) experiments; c) iso-contours of vorticity at τ^*=0.48 for LES.

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 may pay 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.

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

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 was almost negligible from recent catapult tests.

Combination of blowing with modified span loading configurations could be considered.

Applicability of active wake control to a real aircraft has to be envisaged.

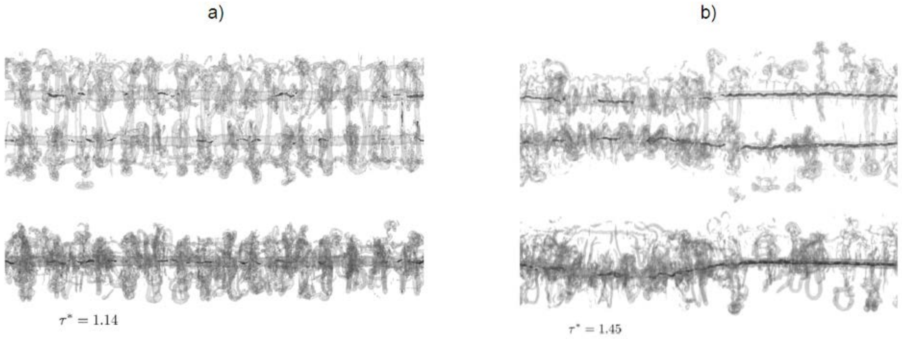


Figure 82: Iso-vorticity surfaces from 3D LES simulations of the baseline configuration a) without oscillating ailerons at τ^* = 1.14; b): baseline configuration with oscillating ailerons at τ^* = 1.45.

5.4.3 Research Needs

Numerous EC projects, partially devoted to Wake Vortex Alleviation had been launched in the preceding FP5 / FP6 calls, e.g.: Eurowake, C-Wake, AWIATOR, and FAR-Wake. FAR-Wake ended in May 2008. An International Workshop on "Fundamental Issues Related to Aircraft Trailing Wakes" was organised by the FAR-Wake coordinator at IRPHE Marseille, France (27-29 May 2008). One of the objectives was to sum up and try to define a follow-up of the wake vortex activities.

As the main conclusion for all research performed in the afore-mentioned EC projects related to Wake Vortex Alleviation, the most promising results have been obtained for the following concepts:

- 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?);
- outboard spoilers: significantly more diffused vortex observed but the underlying causes not clear: favours inboard loading?, turbulence?, specific multiple vortex interactions?;
- 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.

But, that future research should be pursued to carefully understand the mechanisms and check the efficiency of such concepts and devices in order to reach sufficiently high TRLs.

Unfortunately, there are no more EC research projects, national activities as well as collaborative research programs on Wake Vortex Alleviation on this topic nowadays for several reasons, one of them being the safely reduced minimum aircraft separation rules for the A380 aircraft with the summer 2008's ICAO recommendation letter.

Nevertheless, the concept which appears to have the biggest potential is related to the dynamics of four-vortex systems, characteristic of aircraft wakes in take-off/landing configurations. It was demonstrated that medium- and long wavelength instabilities can be used to enhance the global wake decay. LES of various 4-vortex systems showed that significant enhanced vortex decay can already be obtained for a lower-than-optimal, but much more practical, circulation strength ratio. Interesting results were notably recorded in FAR-Wake from linear stability theory and numerical simulations for the optimum forcing of counter-rotating 4-vortex wakes with respect to the long-wavelength Crow modes of the resulting final vortex pair (Figure 83).

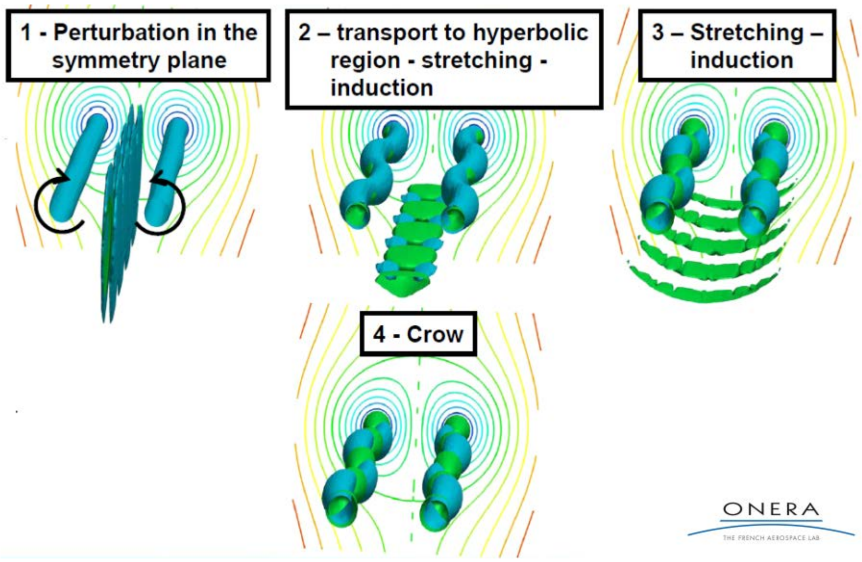


Figure 83: Optimal perturbation in dipolar vortices; iso-vorticity.

The optimum forcing location was found to be close to the wake symmetry plane, which has implications for a possible practical exploitation to be investigated further. This point would at first need to be validated using the developed methodology, first sub-scale tests coupled with numerical simulations including non-linearity and turbulence effects. This would allow performing a realistic evaluation of first interest and then feasibility of such an optimal perturbation concept.

5.5 Encounter Mechanisms and Simulation

Main contributing authors:
Robert Luckner, David Bieniek – TU Berlin
Tobias Bauer, Dietrich Fischenberg, Carsten Schwarz, Dennis Vechtel - Institut für Flugsystemtechnik, DLR Braunschweig

5.5.1 Overview

Figure 84 shows how the complex physical process of the wake vortex encounter (WVE) mechanism - from vortex generation to encounter hazard - is modelled by linking several sub-models. The overall process model is suited to determine the conditions for which modified separation minima are safe and can be applied to risk assessments that are needed to revise wake turbulence separation standards as well as for evaluation of new operational ATC concepts. Parts of this overall model can be used for other applications, such as real-time flight simulations to investigate WVE physics or for the development of vortex detection, warning and avoidance (DWA) systems for onboard and on-ground applications.

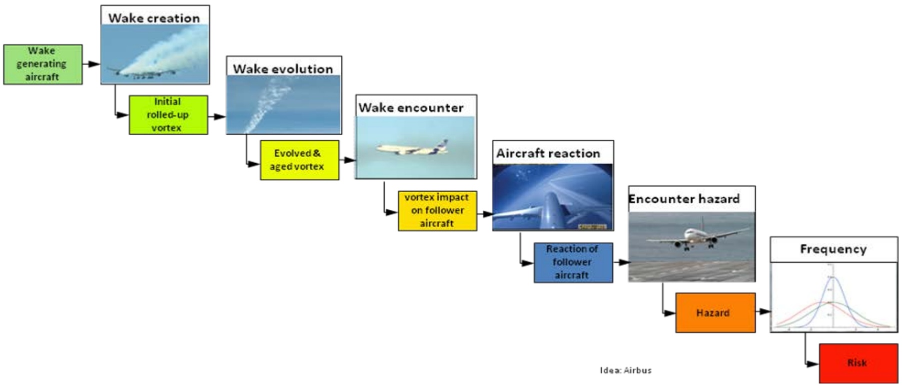


Figure 84: Modelling wake vortex encounter physics from vortex generation to encounter risk.

For the sub-process “aircraft reaction”, well-established and validated models exist. They are used in aircraft development by aircraft manufacturers and for pilot training by airlines. For all other sub-processes models exist as well. However, they still need to be validated and accepted before they can be used in safety cases for new air traffic regulations.

The sub-processes that describe the dynamic process from wake evolution, via wake encounter and aircraft reaction to encounter hazard have been addressed in a WN3E Specific Workshop, see (Luckner and Amelsberg 2010). They comprise:

- Wake vortex models that describe the vortex-induced velocity field
- Aerodynamic interaction models,
- Models of pilot control behaviour, and
- Models for severity assessment.

Figure 85 illustrates the application of WVE simulations in real-time and in fast-time (Monte Carlo) flight simulations. Real-time simulations are used, for example, to record pilot control inputs during an encounter and their severity assessment. The recorded data are used to develop models that can replace the pilot in fast-time simulations.

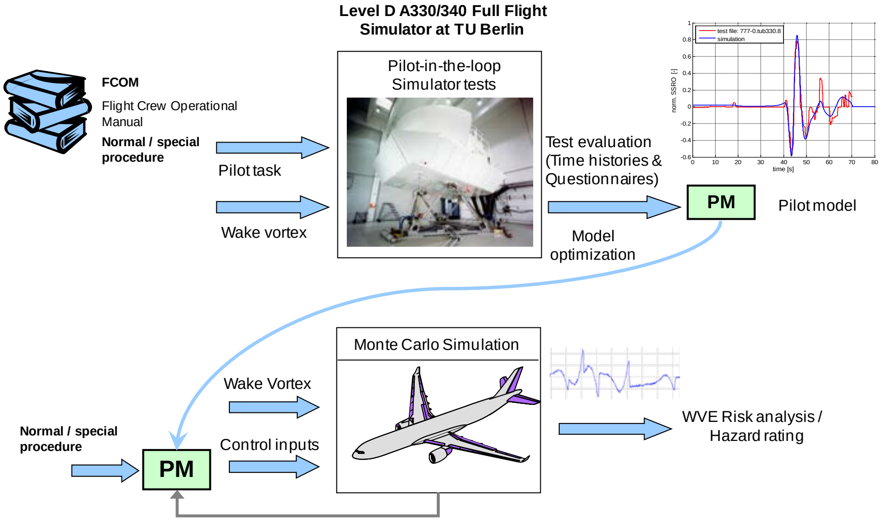


Figure 85: Application of WVE simulations in real-time and in fast-time flight simulations.

5.5.2 State-of-the-art

5.5.2.1 WVE Flight Simulations and Flight Simulators

A wake vortex encounter (WVE) package has been developed in the European S-WAKE project. It consists of two main modules: the Wake Vortex Model (WVM) and the Aerodynamic Interaction Model (AIM). The WVM computes the vortex-induced velocities and the AIM computes the aerodynamic delta forces and moments resulting from the interaction between flow field and aircraft; see Figure 86. Details can be found in (de Bruin 2003). Since then, the implementation has been improved to adequately represent the distributed 3-D flow field in the kinematical equations of the basic simulation, see Luckner et al. 2004.

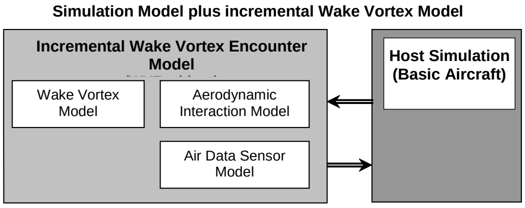


Figure 86: Incremental WVE Model as add-on to any basic aircraft simulation

Various flight simulators (see Figure 87) have been equipped in 2001 with the WVE software package to investigate aircraft and pilot reactions in WVEs and to answer the question: Which level of vortex-induced disturbances is unacceptable?

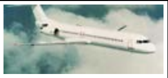
Aircraft / ICAO Category		Simulator type	Location
Airbus 330-300 **HEAVY**		Certified Training Simulator (FAA level D) Motion system, visual system, side sticks, Fly-by-Wire flight control, Autopilot, additional research facility	TU Berlin
Fokker 100 **MEDIUM**		Research Flight Simulator of NLR Motion system, visual system, control column, mech. Flight Control System	NLR, Amsterdam
VFW614-ATD **MEDIUM**		Develoment Flight Simulator THOR of Airbus Visual system, generic cockpit, side sticks, programmable displays, Fly-by-Wire flight control, no motion	Airbus, Hamburg
Cessna Citation **SMALL**		Research Flight Simulator of NLR Motion system, visual system, control column, mech. flight control	NLR, Amsterdam
Dornier **Do 228-200** **SMALL**		Certified Training Simulator (JAR level B) Motion system, visual system, control column, mech. flight control	Simtec GmbH, Braunschweig

Figure 87: Flight simulators used in the S-WAKE project, from (Luckner et al. 2004).

Recent Developments

Since then, TU Berlin developed an enhanced WVE software package for its VFW614-ATD research flight simulator SEPHIR that is capable to simulate straight, wavy vortices and ring vortices as well as vortices that move with wind and in ground effect. In cooperation with UCL and DLR, complex WVMs have been generated. UCL's LES models are being integrated directly into the VFW614-ATD flight simulator. Vortex-induced forces and moments that DLR calculated offline with their LES models have been integrated into an Airbus A330 flight simulator.

Airbus has developed an A320 wake vortex encounter simulation on its THOR development simulator that was used in the EC projects I-WAKE (see Rouwhorst et al. 2008) and FlySafe for development of vortex detection, warning and avoidance systems and in CREDOS to investigate WVEs during departures. TU Berlin investigated the impact of the flight simulator's motion system on pilot response during a WVE in a certified Airbus A330-300 flight simulator; see (Fucke and Luckner 2007).

DLR conducted a simulator campaign in an A330 flight simulator to analyse the impact of vortex curvature on the encounter hazard (Vechtel 2010, Vechtel 2012). One major issue of this campaign was the interaction between pilot and aircraft for controller augmented aircraft and the capability of modern flight control systems to cope with the wake vortex disturbances. The flow-fields of the wavy vortices were generated by Large-Eddy-Simulations prior to the very simulation campaign. The vortex-induced forces and moments were pre-computed for different predefined tracks through the vortex flow-field using an aerodynamic interaction model (strip method). The force and moment time histories were then applied to the simulation depending on a specific playback height. More details are given below in the section on "Vortex models for fast-time simulations".

In-flight simulations have been conducted by DLR with the research aircraft VFW614-ATTAS. Recorded vortex-induced forces and moments were mimicked by the experimental system using flight control deflections. In this way it was possible to investigate the influence of vortex deformation on the encounter hazard under real flight conditions (Vechtel 2012).

In the US, NASA Ames and Langley Research Centers investigated WVEs in flight simulators in the 1970s and 1980s; see (Hastings and Keyser 1988, Sammonds and Stinnett 1976, Stewart 1998). In the 1990s, the FAA equipped a Boeing 737 flight training simulator with WVE simulation; see (Dillard et al. 1999). Although this package is available on some training flight simulators, it is not used for routine pilot training. Currently FAA AFS is conducting WVE simulations on a certified 737-800 (new generation) and a certified Airbus A330-200 full flight training simulator to develop a wake hazard severity matrix as well as standards for determining acceptability of wake vortex encounters from a pilot's perspective. The tests are embedded in simulator training or in experiments in order to avoid learning effects; see (Greenhaw 2010).

5.5.2.2 Wake Vortex Models

This section describes the state-of-the-art in simplified wake vortex models that are needed for wake vortex encounter (WVE) risk assessment. The more sophisticated vortex behaviour models that are discussed in §5.1 are not suited for such applications.

Simplified wake vortex models are used in fast-time simulations and in real-time flight simulations to model aspects of the vortex physics that are relevant for WVE risk. Such models exist and they have been applied to compute:

- Encounter probability: To determine the encounter probability, the minimum distance between the trajectory of a follower and the vortex pair of the leading aircraft has to be computed. This is achieved by simulating the flight trajectories of two aircraft (vortex generator and follower) as well as the evolution of the vortex pair that the leading aircraft generates. If the distance between follower and one of the vortices falls below a certain limit, this is counted as an encounter and transferred to an encounter severity assessment for further analysis.
- Encounter severity: If an encounter is discovered, the influence of the vortex-induced flow field on the encountering aircraft has to be simulated, taking the encounter geometry and initial conditions into account. The evaluation of the resulting aircraft reaction leads to the encounter severity.

The *encounter probability computation* requires a *wake vortex evolution model* that computes vortex transport and vortex strength taking the decay into account, whereas the *encounter severity computation* requires the 3D vortex-induced velocity field around the encountering aircraft.

Various wake vortex evolution models (WVM) exist that compute this temporal-spatial distribution with different levels of fidelity. The highest fidelity is achieved with Large Eddy Simulation (LES) models (see §5.1) that cover the vortex and its complex flow structure nearly over the whole life-time. LES models are not suited for fast-time and real-time simulations as they require extremely high computational performance. However, pre-computed LES flow field data can be used for both simulations. In any case, LES data can be used to validate simplified models that are better suited for real-time and fast-time simulations.

The encounter severity computation requires a flow field model that computes vortex-induced velocities at the position of the encountering aircraft (three velocity components as function of space and time). Its temporal evolution depends on characteristics of the generating aircraft and on atmospheric conditions. Flow field models that are currently applied assume a stationary 2D flow field and define it either by a parameterized analytical model (circulation, vortex separation, core radius, straight or disturbed (curved or wavy) vortex axes and an analytical velocity distribution model) or by a numerical model.

Existing tools that compute encounter probabilities are WakeScene (DLR/Airbus), WAKE-4D (UCL), WIDAT™/ASAT (ATSI/FAA), WAVIR (NLR). Refer to §6.2 for more details.

Recent Developments

Improved WVMs for real-time and for fast-time flight simulations have been developed in Europe by UCL and DLR recently. They have been integrated into simulation tools to simulate the vortex evolution behind an airplane in space and time:

- The Deterministic and Probabilistic wake Vortex Model (DVM/PVM), see §5.1, was integrated into UCL’s tool WAKE4D; see §6.1.
- The Deterministic and Probabilistic 2-Phase Model (D2P/P2P), see §5.1, was integrated into DLR’s tool WakeScene; see §6.1.

Vortex modelling for real-time simulations

University of Sheffield has developed an approach to use high quality vortex data in real-time flight simulation, see (Allerton and Spence 2010). The vortex data is generated by LES methods, compressed and reorganised for real-time access. The aim is to capture evolving short and long wave instabilities (e.g. Crow instabilities). The LES methods require high resolution meshes to reproduce vortex decay (spatial and temporal). One wavy wake vortex segment was calculated in 3-D boxes and linked to a vortex trajectory. Each segment contains a vortex state dependent on the time behind the wake generating aircraft.

Figure 88: Wake vortex visualisation in the visual system of a flight simulator; from (Spence et al. 2005).

Vortex models for fast-time simulations

Boeing has conducted a 737-300 autopilot offline simulator campaign to determine the role of vortex strength versus distortion on encountering aircraft upsets (Loucel and Crouch 2005). Encounters in three different vortex states were investigated: straight vortices (analytical solution for velocities), wavy vortices (numerical integration for velocities) and ring vortices (numerical integration for velocities). All vortex states were modelled by vortex filaments frozen in space and time to be fast-time capable. Results show a significant reduction in maximum bank angle upset experienced by an encountering airplane, due to vortex distortion and break-up. Findings are that a large number of fast-time simulations are required to assess potential upset severity and the potential upset may be linked to vortex characteristics using simple measures.

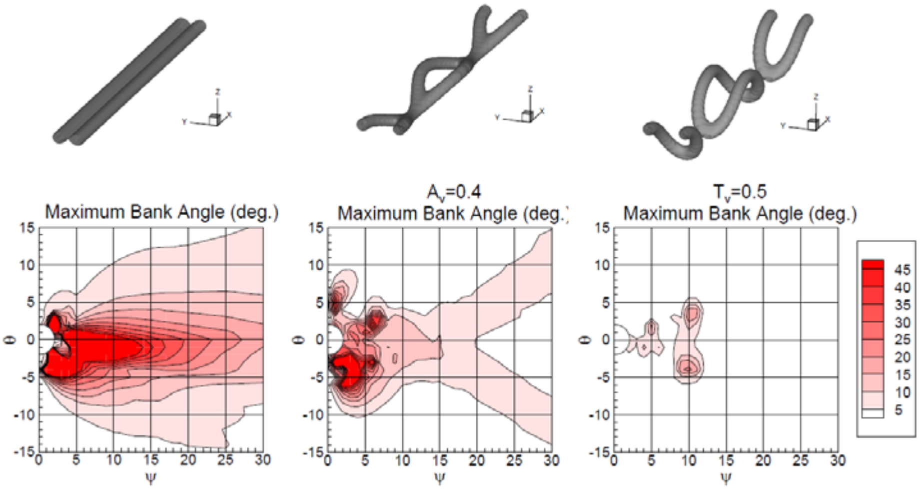


Figure 89: Reduction of maximum bank angles in WVEs with different, distorted vortices (Loucel and Crouch 2005).

Airbus has implemented three vortex models into the Airbus VESA (see §6.2) tool:

- simple straight vortices of infinite length are used to investigate the influence of vortex parameters (strength, position, intercept angles, etc.) on encounter severity;
- simulated parameterized wavy and ring vortices, useful for investigating influence of vortex waviness and break-up into vortex rings on encounter severity;

- curved, segmented vortices, increasing realism of vortex representation along a flight path without undue computational effort (developed by UCL within CREDOS).

The approaches are in general applicable to all flight phases and have been successfully applied for specific investigations (e.g. S-WAKE, CREDOS). The maturity of the models is assumed to be good and adequate for the application, especially for the out-of-ground (OGE) case. A combination of the different models into a single one, i.e. curved vortices plus waviness, is not envisaged (Kauertz 2009, Kauertz 2010, Kauertz et al. 2012).

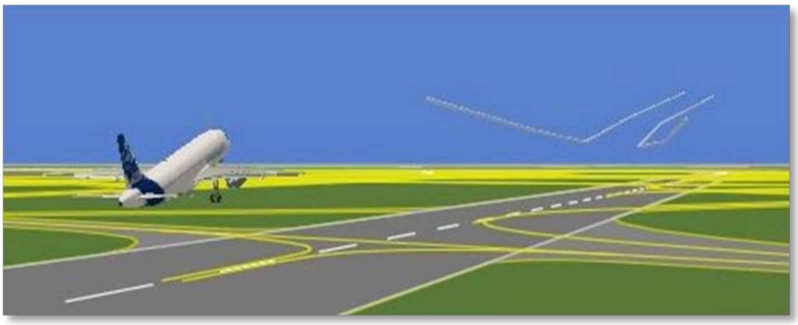


Figure 90: Vortex encounter simulation during departure with curved vortices; source: Airbus.

DLR has developed the WakeScene (Wake Vortex Scenarios Simulation) Package (including Deterministic and Probabilistic 2-Phase Model, D2P/P2P) that allows assessing the encounter probabilities and the related vortex strengths behind different wake vortex generating aircraft for arrivals and departures. WakeScene is described in §6.2.

Currently DLR develops a wake model for real-time and fast-time simulations as a compromise between the simplicity of analytical vortex models and the flow field accuracy of LES. The simulation model applies the BIOT-SAVART law to arbitrarily shaped vortices. The vortex geometry and decay is adapted to LES results for different atmospheric conditions. With this model encounter simulations can be performed with realistically shaped vortices covering the whole decay process (from initially straight vortices via wavy vortices to vortex rings) without the necessity of extensive data management like with LES flow fields.

5.5.2.3 Aerodynamic Interaction Models

Several aerodynamic interaction models (AIM), which model the aerodynamic forces and moments that are induced by the wake vortex flow field, exist for use in offline simulations for e.g. hazard assessment as well as in real-time flight simulations for upset training. Well established and easy to use are Δ-AIM-models, which can be simply added to the basic aerodynamic model without any need to change the basic aero model structure.

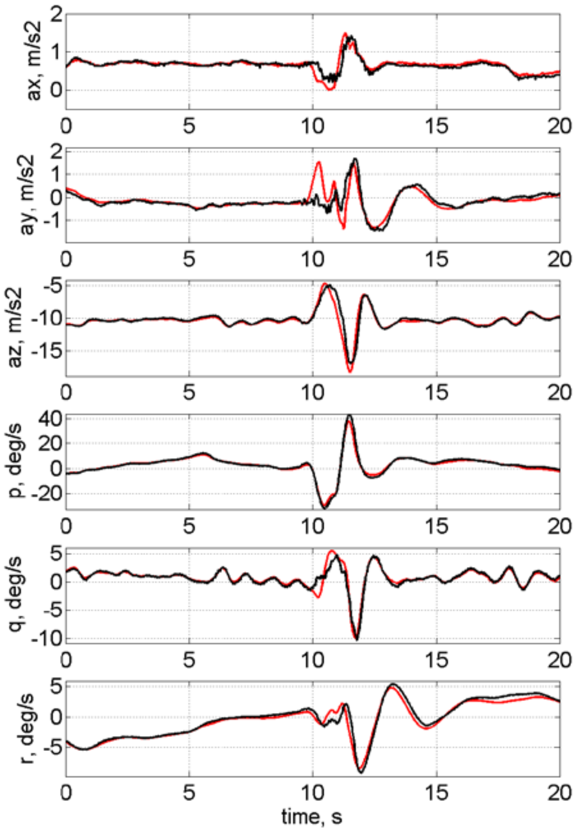


Figure 91: State-of-the-art simulation quality with SM-AIM for lateral wake encounter with a rectangular wing aircraft (Do128); model output (—); flight test data (—), from (Fischenberg 2010)

Two established Δ-AIM-models are the LSM, a lifting surface method, and the SM, a strip method. Both methods were validated in former EU-projects, in a quasi static manner using wind tunnel tests (WAVENC, 1999), and also with flight test data in (S-WAKE, 2000-2002); see (Fischenberg 2002, Reinke and Fischenberg 2002). In S-WAKE, a validation procedure using wake encounter flight test data was derived (Reinke and Fischenberg 2002) including sensor calibration, wake identification and basic model identification. The simulation quality of both the LSM and the SM were compared to the test data and the model quality could be assessed. The data were gathered by the Dornier Do 128 aircraft flying into the wake of the medium size VFW-614 ATTAS.

For the Do128 aircraft with its rectangular wing plan form, it was shown that both the SM and the LSM are capable to reproduce the most important vertical and roll degrees-of-freedom in high quality. The pitching motion is represented also with sufficient quality. However, the simulated yawing motion showed discrepancies to the flight test data. Overall, there were no significant quality differences between the LSM and the SM method. A conclusion was that the much simpler SM can be recommended to be used in WVE simulations. However, validation for aircraft with swept wing, for flight at higher Mach numbers (compressible aerodynamics) and for flow with separation is still needed.

Recent Developments

Some effort to further improve the SM model quality was undertaken in the DLR project “Wetter & Fliegen” 2008-2011 using the Do128 flight test data of the S-WAKE project. A simple model extension for drag effects was derived, keeping the idea that the strip model should have an incremental structure independent from the basic aerodynamic model. Additionally, the model was extended for fuselage effects. A further model improvement in the yaw and in the longitudinal axis was achieved, and the model quality in other axes (roll, lateral and vertical) could be enhanced. Despite those improvements, the fidelity of the AIM, especially regarding the induced side force and yawing moment, should be enhanced further.

In order to validate the strip method as an aerodynamic interaction model for swept wings, in the project “Wetter & Fliegen” DLR recorded more than 60 wake encounters with the swept wing aircraft Falcon 20 behind its VFW-614 ATTAS in 2010, both aircraft in approach configuration and about 200 wake encounters in cruise with the Falcon 20 in 2011. Final analysis of this data is still pending, and so is the AIM validation work.

Also in an effort to validate the aerodynamic interaction models, Airbus has compared AIM model results with wake encounter flight tests in approach configuration for two leader and two generator aircraft. Results of this effort have not been published.

5.5.2.4 Pilot Behaviour Models

Systematic research in modelling the control behaviour of a human pilot controlling an aircraft began in the 1950s. The objective of the models was "*to summarize behavioural data, to provide a basis for rationalization and understanding of pilot control actions, and, most important of all, to be used in conjunction with vehicle dynamics in forming predictions or in explaining behaviour of pilot-vehicle systems*" (McRuer and Jex 1967).

The models of pilot control behaviour can be classified into two main categories:

- *Behavioural models* that describe the intentional pilot action during (compensatory) tracking tasks.
- *Biomechanical models* that simulate involuntary control inputs that are caused by the pilot acting as a passive biodynamic element within the pilot-aircraft system.

Biomechanical models have been successfully applied to describe phenomena such as "roll ratcheting". However, behavioural pilot models are better suited to describe pilot control behaviour when they compensate vortex induced disturbances or recover from vortex encounters. A brief overview on existing behavioural pilot models is given below.

The analytical theory of manual control of vehicles that has been developed in the 1950ties and 60ties has emerged as a useful engineering tool for the explanation of test results and prediction of new phenomena. It became part of handling quality criteria and was used for aircraft and flight control law design. An essential feature of this theory is the use of quasi-linear analytical models for the human pilot wherein the models' form and parameters are adapted to the task variables involved in the particular pilot-vehicle situation (McRuer and Krendel 1959).

An important class of situations for which pilot vehicle models are useful are closed-loop *compensatory tracking* tasks, in which the pilot acts on the displayed error between a desired command input and the comparable vehicle output motion to produce a control action. A fundamental finding of McRuer and Krendel was that human pilots adapt their behaviour in such a way that dynamic deficiencies of the controlled aircraft are compensated, essentially leading to similar open-loop behaviour of the pilot-aircraft system near the crossover frequency[2], see (McRuer and Jex 1967). Based on this finding, they proposed the simple four parameter *Crossover model*. It is the most commonly used pilot model. Further research expanded the model from a single axis to the multi-axis control case and resulted in more complex models such as:

- *Precision model*: An extension to the Crossover model considering a representation of the human neuromuscular system.
- *Structural pilot model*: An explicit description of the human signal processing including sub-models for the human central nervous and neuromuscular system. In comparison to other models it focuses on the human processing of proprioceptive feedbacks in addition to visual or vestibular cues.
- *Descriptive model*: A detailed model of the human operator information processing. It includes several sub-models for the dynamics of visual and vestibular channels.

Those quasi-linear pilot models were also expanded from a single-axis to the multi-axis control case. Furthermore, several other approaches exist, e.g. models that are based on optimal control theory, such as the Optimal Control Model (OCM), and models using alternative concepts such as Fuzzy Logic or Artificial Neural Networks.

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[2] The crossover frequency is the frequency for which the open-loop describing function of the pilot aircraft system passes the 0 dB line and it determines the bandwidth of the system.

Pilot models for recovery from WVEs belong to a *disturbance suppression* task where the pilots have to maintain the current flight condition while the aircraft is exposed to disturbances. This task is related to *tracking* tasks, in which a pilot follows a target command. Developing pilot models for either task can build on the available vast experience. This is especially true for pilot models for recovery from wake vortex encounters.

However, a WVE is a single unexpected event, in which the aircraft's flight condition can be severely disturbed. Pilots are typically surprised and their reaction is not necessarily optimal. This is in contrast to disturbances from atmospheric turbulence that typically last for a while so that pilots can adapt their control behaviour.

The target applications for WVE pilot models are risk assessments that can discriminate safe, tolerable or unacceptable encounters. As the results shall be used to ensure the safety of regulatory changes (e.g. minimum wake separations) or modified ATC procedures (e.g. approaches to closely-spaced parallel runways) the validation requirements are stringent.

For WVE risk assessment pilot models are needed that simulate pilot control commands during a WVE. They have to be validated with results from WVE in flight tests or simulator tests. Figure 92 illustrates the procedure that is used for pilot model optimisation.

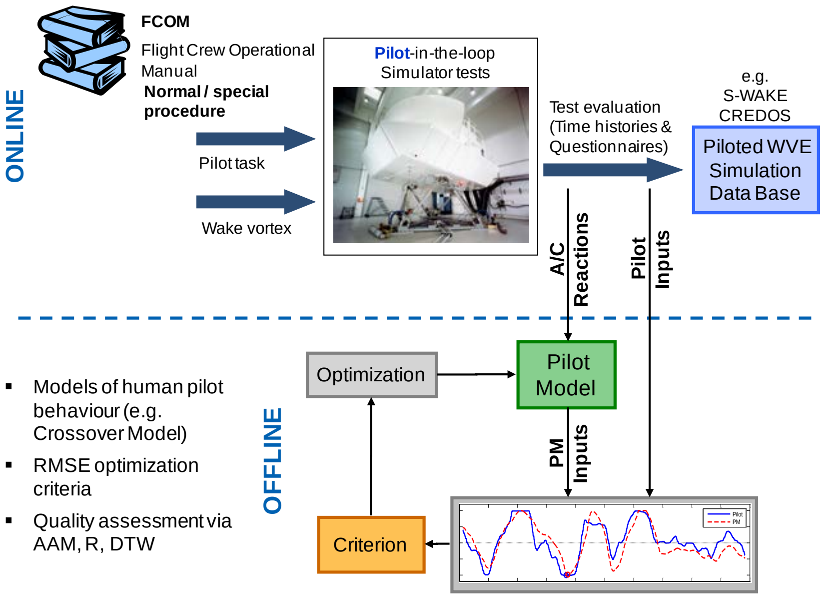

Figure 92: Measurement of pilot response in real-time flight simulations and optimisation of pilot models in offline computations, from (Bieniek and Luckner 2010).

Pilot models have been developed in the EC funded projects S-WAKE and CREDOS by Airbus, DLR and TU Berlin starting in 2001. The first models were *crossover models* that addressed roll control. Pilot model parameters are adapted by means of numerical optimization in the time domain to achieve a match between simulated and recorded control commands. Applicability of the models is limited to the flight phase and aircraft type for which the model parameters have been validated. For the VFW614-ATD a roll control behaviour pilot model has been successfully used in the Airbus VESA fast-time simulation tool (Höhne et al. 2004).

TU Berlin operates a suite of pilot models in support of wake vortex safety assessment. This suite includes pilot models that generate aircraft trajectories, pilot models that control the aircraft during a vortex encounter and models for pilot's judgement of wake encounter severity. The models are developed for safety analyses that are based on fast-time Monte Carlo Simulations to simulate wake vortex encounter under varying conditions.

Recent Developments

Recent research on WVE pilot models was performed at TU Berlin (TUB). The structure and the scope of models have been extended as described below.

- Pilot model for take-off, departure and wake vortex recovery

  TUB has developed a deterministic pilot model for WVE simulation during departure in the European project CREDOS (Crosswind-Reduced Separations for Departure Operations), (Amelsberg et al. 2009). The model controls the aircraft throughout the complete departure that includes the following flight phases: take-off run, rotation, tracking of SID flight path and vortex encounter. For each flight phase a specific sub-model has been developed based on recorded data from piloted Airbus A320 and A330 flight simulator tests with commercial airline pilots.

  The sub-model for vortex upset recovery consists of two artificial *static feed-forward neural networks* that simulate pilot side-stick commands in roll and pitch during the WVE. Flight director commands, angular rates and angular accelerations in both axes are inputs to the pilot model. The neural networks were trained for the time interval in which the encounter occurred, using the recorded pilot side-stick commands as reference.

  To validate the model, identical encounter scenarios as used during the piloted tests were simulated with the pilot model controlling the aircraft. The results show a very good agreement between pilot and pilot model control behaviour, especially in the roll axis, see Figure 93. Additionally, the largest vortex induced aircraft upsets (peaks) have been used as validation criteria. In most of the cases, pilot model outputs lie within the standard deviation of results with human pilot simulator tests.

  The pilot model was successfully integrated into Airbus's VESA tool to perform Monte Carlo simulations for risk assessment within the CREDOS project. The model for generation of departure trajectories has been implemented into WakeScene.

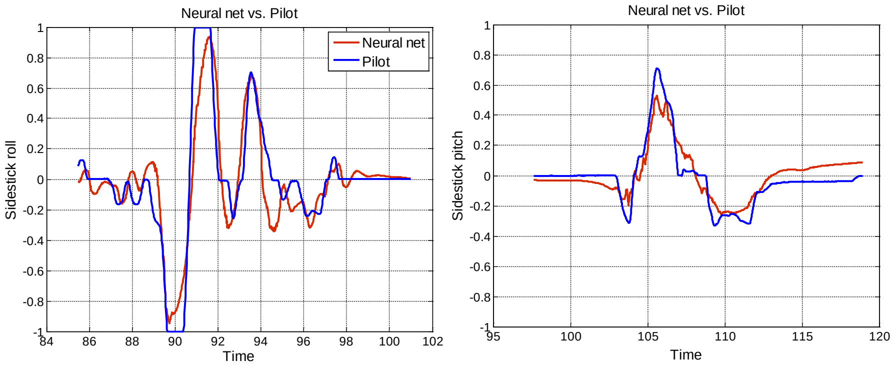

Figure 93: Comparison of a Neural Network pilot model with pilot response in a WVE a) side-stick roll and b) side-stick pitch commands (Amelsberg et al. 2009).

- Probabilistic pilot model approach for WVE simulations

  Statistical variations in pilot behaviour have been addressed. Recorded pilot control inputs from flight simulator tests show a significant scatter in pilot behaviour for identical encounter scenarios. Pilot control commands during the vortex encounter affect the magnitude of resulting aircraft upsets. These upsets contribute to the pilot's perception of the hazard and are used as metrics in current severity assessment models. To account for the variation in pilot control behaviour probabilistic pilot models are needed.

  TUB has proposed a methodology to set up a probabilistic pilot roll control model based on the crossover model. For two of the four model parameters statistical distributions (rather than fixed values) are identified from piloted simulator tests. The other two parameters are kept constant to account for correlations between model parameters. Only data from special "fixed" encounter simulations is used, where identical vortex encounters are repeated multiple times. This eliminates effects of varying encounter conditions on the pilot behaviour.

The methodology was applied on available data from piloted A330 and A320 vortex encounter simulations (e.g. S-WAKE, CREDOS). Static tests with recorded aircraft upsets indicate how the probabilistic pilot model responses scatter around the deterministic model. Dynamic fast-time simulations with the probabilistic pilot model have to be carried out to evaluate the effect on the scatter of aircraft upsets.

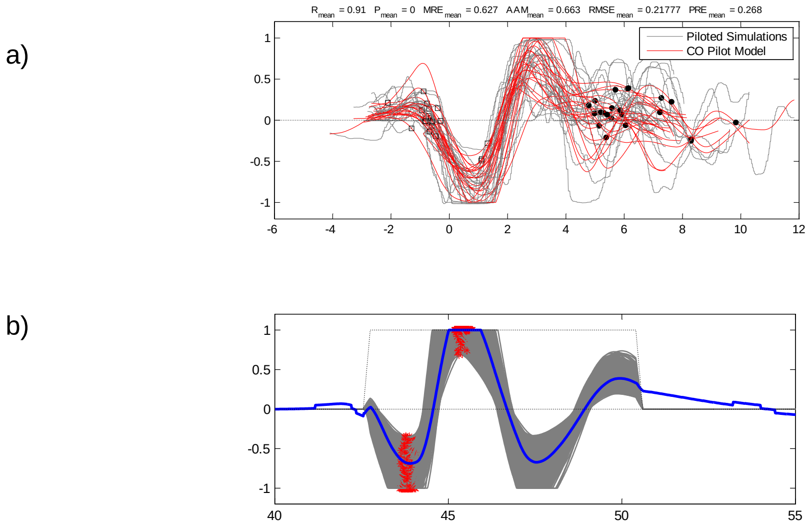

Figure 94: a) Scatter between human pilots (grey) and a deterministic pilot model (red) in multiple WVEs; b) scatter of a probabilistic pilot model (peak values red, mean deterministic model blue), from (Bieniek and Luckner 2010).

- Application of Modified Optimal Control Model (MOCM) for WVEs

The applicability of a Modified Optimal Control Model for pilot control behaviour has been investigated; see (Schönfeld et al. 2007). This approach is based upon the assumption that well-trained and motivated human controllers behave optimally in a certain sense that is subject to their inherent psycho-physical limitations. The model can be applied to model multi-axis and multi-loop tasks and it also allows considering fractional attention of the pilot.

To evaluate the applicability of the model for vortex encounter simulation, piloted tests (no licensed pilots) with a simplified aircraft model and a representative vortex disturbance were performed. At first the human operators had to correct upsets from atmospheric turbulence before being confronted with the vortex disturbance. The pilot model was also tuned using the turbulence tracking task, and was then applied to compensate vortex induced upsets.

Results showed a correspondence to the piloted experiments for the first couple seconds of the encounter. As the operator was trained to flight in turbulent conditions he was surprised by the WVE but adjusted his behaviour after a certain time delay leading to differences between recorded inputs and model results.

5.5.2.5 Severity Assessment Methods

Models that assess the severity of a WVE are based on severity criteria (hazard criteria) that relate pilots' hazard assessment to objective, measurable flight data. Development of severity criteria for WVEs started in the 1970s. The first criteria were *single-parameter* criteria addressing the roll axis. An often cited result is the dependence between the maximum bank angle excursion that was acceptable for pilots during a WVE in landing approach and the encounter altitude; see Figure 95.

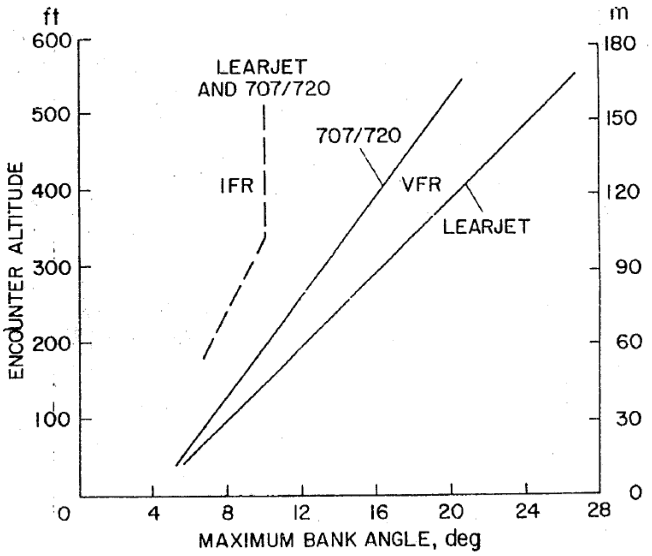

Figure 95: NASA Bank angle boundary; from (Sammonds et al. 1976).

But also other parameters that represent aircraft reaction in the roll axis were investigated as hazard metrics: roll acceleration, the so called *Roll Control Ratio* (RCR), as well as combinations of bank angle, roll rate and roll acceleration. The RCR relates vortex-induced roll moment to the maximum roll moment that the pilot is able to command (roll control power).

Those criteria address the roll axis only and may not be sufficient to fully describe the overall hazard. So, more complex criteria with multiple metrics from the longitudinal and the lateral motion were investigated. In Europe, research on severity criteria was performed by Airbus, NLR and TU Berlin in the S-WAKE project. Various criteria were developed and optimized using results from flight simulator tests (Airbus A330, Dornier 228, Cessna Citation, Fokker 100, VFW614-ATD); see (De Bruin 2003, Luckner et al. 2004).

A simple approach that covers the complete aircraft reaction by using only one metric is DLR's Simplified Hazard Area Prediction method (SHAPe), see (Schwarz and Hahn 2006). The boundary between acceptable and unacceptable encounters is defined by a (conservative) RCR limit that was determined in offline WVE simulations and pilot-in-the-loop flight simulator as well as in flight tests. It was found that pilots rated all WVEs below this boundary as acceptable and all relevant aircraft upset parameters stayed within their typical operational envelope (Schwarz and Hahn 2007). As the required aircraft data for this severity assessment is not necessarily readily available for all aircraft of interest, there is a need to obtain this input data. With the Simplified Hazard Area Prediction Method (SHAPe), the required aircraft data is provided for a given maximum takeoff weight (MTOW) as the only input parameter required (Hahn et al. 2004, Schwarz 2011). Hence the SHAPe method can be universally applied for a safety assessment of wake vortex separation minima and wake vortex advisory systems for improved air traffic management.

However, still there exists no severity criterion (and no boundary that separates acceptable and unacceptable WVEs) that has been agreed upon by all stakeholders to be used in risk assessments. A recent literature survey by DLR has shown widely varying assumptions for acceptable values of certain aircraft states (report to be published).

Recent Developments

Current research on hazard metrics and on models for severity assessment is performed by DLR, FAA, NLR and TU Berlin.

- Characterizing wake vortex encounters for hazard analysis

  The FAA runs the project *"Characterizing wake vortex encounters for hazard analysis"* for purposes of the Safety Management System (SMS). An overview on the status is given in (Greenhaw 2005). The objectives are: (i) to develop a wake hazard severity matrix that conforms to SMS severity and likelihood practices; (ii) develop standards for determining acceptability of wake vortex encounters (distinguish safe and unsafe encounters) from a pilot’s perspective; (iii) to develop metric(s) to evaluate WVEs in terms of hazard severity and acceptability. Those standards should be harmonised with current SMS guidance, procedures, and practice. FAA proposes a wake vortex risk matrix for the final approach phase (revision 4, not final) that has been derived from the general risk matrix that relates safety effects and probabilities and is also used in aircraft certification. FAA uses “observable effects” to assess all possible situations that may affect crew’s workload, expose passengers to injuries or death, or may cause damage to or loss of equipment and property, or damage the environment. This leads to a multi-parameter approach. However, currently no established WVE tolerance criteria exist. The need for such criteria consistently arises as an issue, e.g. for Re-Categorisation, introduction of new large aircraft, introduction of new operations and procedures as well as for WVE census. Such safety criteria are essential to: Safety Management System requirements, absolute safety cases to support changes and for the implementation of NextGen initiatives.

WVE data collection is ongoing in Boeing 737-800 and Airbus 330-200 Full Flight Simulators of FAA at Oklahoma City with current and qualified pilots. Wake scenarios are embedded in simulations for other testing purposes in order to have unexpected, surprising encounters and to minimize learning effects (surprise encounters). The objective is to generate a data base for development of a Hazard Severity Matrix. This FAA project is expected to last for 2 years.

- Multi-parameter wake encounter severity criterion

  Reinke proposed a severity criterion that addresses multi-parameters of a wake encounter by using severity metrics including: aircraft attitudes, pilot control commands, aerodynamic parameters (angle-of-attack, angle-of-sideslip, airspeed), flight path deviations, and accelerations, see (Reinke 2006).

- Wake vortex severity criteria developed by NLR

  Fokker developed the C-criterion, which takes changes of energy (energy rate) and induced moments into account, as a severity measure for atmospheric disturbances; see (van der Geest 2010). It is an algorithm that addresses aircraft performance and handling, and it is an extension of the accepted F-factor (TSO-C117a 1996). The criterion that was developed for windshear prediction in the 1970s is also suited to define the severity of a wake vortex encounter.

  NLR has investigated the *equivalent roll rate* (ERR) in an attempt to find a single metric for wake vortex hazard, see (van der Geest 2012). ERR performed favourable compared with other single metrics. Due to its simple and integrated concept ERR is seen as a possible candidate for applications in the WV domain, but still further research into the viability of the criterion is required.

- Wake vortex severity assessment for realistically deformed vortex geometries

  DLR currently investigates the effect of vortex deformation (wavy vortices and vortex rings) on wake vortex encounters. This study is based on offline and pilot-in-the-loop simulations as well as flight tests. The analysis of the simulation results revealed that wavy vortices typically result in shorter encounter duration. Nevertheless aircraft response is similar compared to encounters with straight vortices, as are the pilot ratings. The simulator campaign also revealed an increased risk of pilot-induced oscillations (PIOs) with manually flown encounters of distorted vortices. With the evaluation of the small amount of encounters simulated, no final conclusions can be drawn, but Figure 96 indicates that the encounter acceptance threshold concerning the maximum roll-control-ratio (RCR) may be significantly lower for wavy vortices than for straight vortices (Vechtel 2010, Vechtel 2012).

  DLR also performed in-flight simulations with the DLR research aircraft ATTAS to investigate the influence of vortex deformation on the encounter hazard under real flight conditions (Vechtel 2011). Those flight tests were conducted using wake vortex flow fields generated with large-eddy simulations. Different vortex ages and vortex shapes, respectively, were analysed, namely wavy vortices before and vortex rings after the linking of both vortices. In principal the in-flight simulations show the same tendency as the simulator studies (Vechtel 2010). PIO did not occur during encounters simulated during the flight tests with ATTAS, which features a conventional flight control system. As the aircraft simulated in the simulator study possesses a modern controller augmented flight control system, this might indicate that the risk of PIO increases for aircraft with controller augmented flight control systems due to possible interference between pilot and flight control system. The ATTAS in-flight simulations are the first real flight tests using an in-flight encounter simulation with highly realistic (LES) wake vortices for hazard assessment.

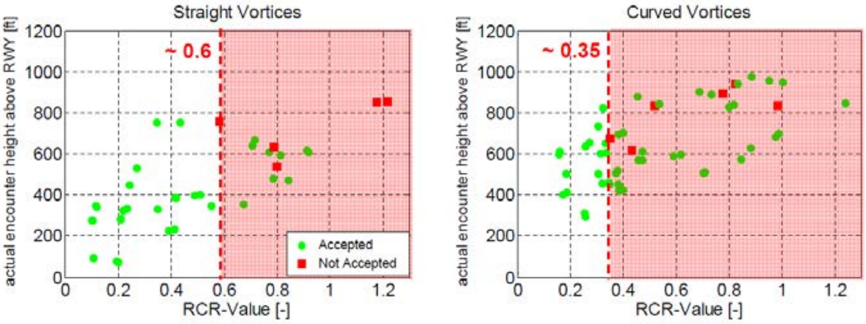

Figure 96: Encounter acceptance with straight and wavy (curved in DLR's terminology[3]) vortices of identical circulation (A330 simulator) with preliminary RCR thresholds (Vechtel 2010).

- Wake vortex severity criteria for departure

TU Berlin developed a multi-parameter severity criterion for assessment of WVEs during departure; see (Amelsberg 2009). The work was performed in the CREDOS project. The criterion consists of four two-parameter sub-criteria, each addresses certain safety relevant metrics: aircraft pitch and roll attitude, vertical and lateral cabin accelerations, attitude control and air flow parameters (angle-off-attack and angle-of-sideslip). The sub-criteria are plotted in two-dimensional diagrams. For each metrics pair, two limits that confine the envelopes for normal operations and unacceptable aircraft upsets were derived from several sources: flight manuals, reference data for passenger comfort, results from the European S-WAKE project and published papers. The overall severity criterion is a combination of all sub-criteria. All criteria parameters can be determined quantitatively.

The hazard ratings for simulated WVEs, which were computed with the criterion, were compared and verified with the hazard ratings of the pilots. The reference data were recorded during piloted tests in a certified Airbus A330 full flight simulator with current and qualified airline pilots and in an A320 development flight simulator.

The criterion was implemented into VESA and it was used to analyse the influence of parameter variations (e.g. crosswind velocity) on encounter risk, i.e. the probability of having an encounter that exceeds a certain level and may be hazardous.

5.5.3 Research Needs

5.5.3.1 Wake Vortex Models

In the last 5 years, significant and visible progress in fidelity of wake vortex models for WVE simulations has been achieved and the steep gradient of the learning curve has been left. The number of considered parameters has increased significantly and it becomes necessary to distinguish between primary and secondary aspects. The models, which capture many real-life features, can be used in real-time WVE

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[3] Note: Here, the term *curved* is used for vortices that are generated by an aircraft that is flying curved trajectories. The term *wavy* is used when the axes of an aging vortex pair deform. In (Vechtel 2010) *curved* is used for vortex deformation due to aging, as the terminology is not standardized.

simulations in flight simulators or in fast-time WVE simulations either for parameter sensitivity studies or to compute statistics of vortex characteristics. The improvements address the following aspects:

- curved aircraft trajectories and curved vortex axis,
- wavy vortex pairs and ring vortices,
- impact of atmospheric conditions on vortex decay,
- impact of atmospheric conditions on vortex transport,
- vortex behaviour in ground effect,
- efficient code for fast-time computations.

Future research should be focussed on the following topics:

- Fidelity of models and simulations

  Is the achieved fidelity sufficient or is further research required? Models of high complexity could be used to identify more simple models that are good enough for the purpose. Uncertainties still exist regarding the size of the vortex core radius (which may have a large influence on instantaneous angles, forces and moments even if the integral values for the encounter are not much affected) and its evolution in time. For operational use of the models, as envisaged in SESAR and NextGen, the main problem is to correctly measure and predict input data for the models (e.g. turbulence, temperatures and wind velocities at multiple locations in space).

- Validity of models and of input data including their statistical characteristics

  As a full validation is impossible, confidence has to be built that models and simulations are correct. How can this be achieved? Simple vortex models should be - and have been - validated by comparison with LES results and flight test data. Ultimate validation should focus on flight test results. In cooperation with the regulators, a validation plan should be developed that defines the validation requirements, and determines data that are available and data that needs to be generated. This may become a repetitive activity. Such a process is described in (Greenhaw et al. 2005).

  During an encounter the interaction of the vortex flow field and the aircraft surfaces will modify the vortex flow field. It should be investigated how strong these effects are; whether they must be considered or whether they can be neglected in encounter simulations.

- Requirements for wake vortex models that shall be used in Re-Cat Phase II and III
  - Do current models cover all aspects? What else should be included?
  - Is it necessary to consider WVEs with a wake system (pair) or is it sufficient to model only a single vortex?
  - Is it necessary to consider WV models with perturbed vortices?

5.5.3.2 Aerodynamic Interaction Models

Two methods for aerodynamic interaction models (AIM) are used in WVE simulations: the lifting surface method (LSM) and the strip method (SM). Although considerable verification and validation work has been performed model quality should be assessed and improved in the following areas:

- Validation of an Aerodynamic Interaction Model (AIM) for swept wing

  In S-WAKE, the AIM was validated for a rectangular wing configuration only. The first validation of an AIM for a swept wing aircraft was performed by DLR with data from Airbus flight tests in 2006-2008. The wakes of HEAVY aircraft (A380, A340, and B747) were encountered by MEDIUM aircraft (A318 and A320) in cruise and in approach configuration. AIM validation using the S-WAKE validation method was done for the SM and also for an AIM panel method developed by SAAB. However, these flight test data for swept wing aircraft are not publically available and the results are not published.

Therefore, there is a need to gather more encounter flight test data for swept wing configurations for AIM validation and for further model improvements. Additionally, methods need to be derived to determine necessary parameters for the AIM such as lift and downwash gradients depending on aircraft configuration. A limited amount of wake encounter flight test data with a swept wing follower aircraft is available at DLR, both for landing approach and cruise. Final analysis of this data is still pending, and so is the AIM validation; however a more extensive data base would be desirable. Additionally, methods need to be derived to determine necessary parameters for the AIM such as lift and downwash gradients depending on aircraft configuration. Also, WVE data for different aircraft configurations, such as T tails, should be recorded and used for validation.

- Improvement of yawing response simulation quality

  Parameter identification has shown that the AIM quality is high for all forces and moments with the exception of the yawing moment, see (Fischenberg 2010). As those deficiencies affect dynamic aircraft response in the other axes the AIMs still need further improvement in the yawing axis.

- Local stall effects

  Current AIMs have only rudimentary representations of stall effects (linear lift curve, limited lift coefficient if maximum angle of attack is exceeded). Is this sufficient in all cases, for example when slowly flying aircraft encounter high vertical wind velocities or when the authority of the control surfaces, in particular the ailerons, may be negatively affected?

- Effects of vortex flow field on flow sensors

  The high local velocities affect the angle of attack and velocity sensors of the aircraft, additionally the barometric height measurement is perturbed if the vortex core with its changes in static pressure is encountered. The effects on the flight control system need to be investigated (e.g. alpha floor function or angle-of-attack protection might be inadvertently triggered; the aerodynamic state assumed by the avionic systems may not represent the actual state).

- Effects of the encountering aircraft on the vortex flow field

  All AIMs neglect the effect that the encountering aircraft has an impact on the vortex flow field. Vortices distort and deform. How large is the impact?

- Generic AIM for fast-time simulations

  The current Δ-approach for the AIM has proven to achieve a certain level of accuracy (for a straight wing) when a 6DoF simulation of the basic aircraft is available. For safety assessment purposes (such as in re-categorization efforts) it is necessary to model arbitrary aircraft, at least a few dozen of the most common types. Hence it must be investigated how the necessary basic aeromechanical models can be obtained for that approach. As it is cannot be expected that aircraft manufacturers release proprietary data into the public domain, it must be investigated whether it is possible and viable to use handbook methods or methods that use publicly accessible geometric data to compute the required model data or if other solutions can be found that guarantee the confidentiality of the manufacturers’ data.

5.5.3.3 Models of pilot control behaviour

Up to now, most WVE risk assessments are performed without pilot models using parameters like maximum takeoff weight of the vortex generator aircraft, vortex strength (circulation) or induced rolling moment. But those parameters do not cover essential aspects of the complete encounter mechanism, as shown in Figure 84.

It is obvious that an accurate relative (as well as a quantitative absolute) WVE risk assessment, i.e. from WV creation to encounter hazard (as shown in Figure 84), requires a representation of the pilot. The pilot model needs to be “conservative” and it should be as simple as possible. However, to investigate the achievable fidelity of pilot models, it may be necessary to develop more complex models for comparison.

In summary it can be stated: research in modelling pilot control behaviour during WVEs can build on more than 60 years of expertise in pilot behaviour modelling. Recent research improved the knowledge on pilot behaviour in WVEs significantly:

- Pilot models that address all flight phases,
- Alternative approaches for WVE pilot models have been investigated with the objective to improve model fidelity,
- Techniques for assessing variations in pilot control behaviour,
- Knowledge about the variation (scatter) in pilot response to a WVE,
- Methods to consider probabilistic pilot behaviour during WVEs,
- Validation requirements and validation techniques.

Future research should be focussed on the following topics:

- Fidelity of pilot models
  - What is the necessary level of model fidelity?
  - Is the fidelity of available pilot control behaviour models sufficient for WVE risk assessments?
  - Is a probabilistic pilot model necessary for risk assessment or are deterministic models sufficient?
  - How well does the pilot control behaviour in flight simulator tests reflect the pilot reactions in real life WVEs? What about the missing surprise effect and the training effect when simulated WVEs are repeated?
- Validity of models and of input data including their statistical characteristics

  Still, there is a gap between the pilot models that have been developed by research and a validated pilot model that can be used for risk assessments of new regulations. As a full validation is impossible, confidence has to be built that models and simulations are correct. The development process for pilot models has to be transparent and the validation process (in particular the validation criteria) have to be acceptable for authorities. How can this be achieved? As for the vortex models, a validation plan should be developed in cooperation with the regulators that defines the validation requirements, and determines data that are available and data that needs to be generated, see (Greenhaw et al. 2005).
- Pilot models for Re-Cat Phase II and III

  The pilot model affects aircraft response in a WVE. As aircraft response relates to encounter severity, pilot models have a direct impact on the encounter severity. Therefore, a validation of pilot behaviour models is essential.

  Future research activities should define criteria for pilot model validation that are agreed by all stakeholders beforehand. A possible way ahead is the risk analysis process of FAA’s Flight Systems Laboratory. It is used to produce safety studies related to flight procedure design and is described in (Greenhaw et al. 2005). This process requires defining and agreeing on validation requirements as well as on reference data for models that are used in risk assessments. The process needs to be a joint activity of model developers and authorities.

  Authorities (FAA) have raised the following questions regarding the use of pilot models for ReCat Phase II and III:

  - Why should pilot response models be included in the analysis for Phase II or Phase III?
  - Should pilot or auto-pilot response be included in the analysis of wake encounters? If so, how complex does it have to be?

- How is the reference pilot behaviour defined and which deviations from this behaviour should be considered?
- What kind of pilot response model should be included and how?
- Is the performance of current pilot models satisfying for WVE risk assessment?

A comparison of pilot behaviour in a flight simulator WVE with his behaviour in an identical WVE in an aircraft (artificially generated in bootstrap mode, e.g. DLR's VFW614-ATTAS) is recommended as a potential option for pilot model validation.

5.5.3.4 Severity Assessment

Recent research on hazard metrics and on boundaries between acceptable and unacceptable WVEs has expanded single-parameter criteria to multi-parameter criteria that take into account aircraft reaction, passenger comfort and pilot control effort. The on-going research at FAA, TU Berlin, NLR and DLR addresses the following areas:

- improvements of criteria quality,
- the definition of hazard boundaries that are accepted by all stakeholders,
- validation of results in order to “clear” them for being usable in risk assessments.

The choice of the suitable models for risk assessment is an important question for the Joint EUROCONTROL/FAA Wake *Turbulence* Re-Categorization Effort. The need for accepted and validated severity criteria was expressed by the authorities (EUROCONTROL, FAA) at multiple occasions including the WN3E specific workshop on Re-Categorization.

- Severity assessment models for Re-Cat Phase II and III

  The definition of hazard boundaries requires establishing an agreement of all stakeholders on the definition of suitable metrics and on the limits for acceptable or unacceptable WVEs. The validation process should follow the risk analysis process of FAA’s Flight Systems Laboratory (Greenhaw et al. 2005). Questions that have to be answered are:

  - How can validation and credibility of models be achieved?
  - Which metrics should be considered as a measure of safety? Are simple metrics such as wake induced rolling moment, roll control ratio sufficient to define the safety level for risk assessments? Do we need dynamic simulations or is a stationary evaluation of the flow field sufficient?
  - What is the safety level of worst-case WVEs under current ICAO separation rules (safe baseline)? This knowledge is important for quantitative safety assessments.
  - Are subjective pilot severity ratings from flight simulator studies valid (e.g. because of missing reality of motion system or training effects after multiple encounters) to be used for the validation of severity criteria?
  - Does the type of flight control system (classical flight control with direct linkage between pilot control devices and control surfaces, or electronic flight control systems) have an impact on the encounter effects?

5.5.3.5 Wake Vortex Encounters in Flight Simulation and in Flight Simulators

Flight simulation of WVEs studies should be used for systematic parameter variations and sensitivity analyses to study the impact of variations in core radius, tangential velocity profile, vortex strength, and vortex topology on encounter severity. This will in return define the accuracy with which the vortex flow fields must be represented in measurements and simulations.

To develop models for pilot severity assessments, a significant number of vortex encounters have to be recorded and rated by pilots. Manual analysis of in-flight WVEs recorded during routine airline operations is extremely costly. WVEs in flight tests have the disadvantage that the pilots are prepared for an encounter. An alternative are certified full-flight simulators with WVE capabilities, in which unexpected encounters during routine pilot training can be performed. Simulated aircraft reactions should be validated against flight test results and the impact of flight simulator limitations on pilot ratings should be investigated.

With the greatest realism, the hazard of wake encounters can be evaluated under real flight conditions only. Flight tests, in which a pilot intentionally flies into a vortex, lack the surprise of an encounter that occurs in airline operations. In-flight simulations are an alternative. They allow investigating reproducible encounters that can be arbitrarily defined. It is recommended to use in-flight simulations for hazard assessment of wake encounters.

5.6 Capacity Analysis Methods and Metrics

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5.6.1 Overview

The assessment of expected capacity benefits of the operational scenarios (CONOPS) presented in Sections 3.1 to 3.5 has become an important part of wake vortex operational research. The results can serve as a figure of merit for the concept under study and are an input of the cost-benefit analysis.

Some years ago in 2005, the “European Wake Vortex Mitigation Benefits Study” (Galpin et al. 2005), also known as the Euroben study, investigated the impact of three concepts (ATC-Wake, CREDOS and TBS) on the capacity of a generic ATM system. This high level study indicated possible capacity gains but the significance of the results was limited to its context and assumptions.

Final figures can only be obtained through a more detailed analysis taking into account specific (site dependent) details, when all boundary conditions (uncertainties in weather and wake prediction, system complexity, operational aspects, proof of safety, …) are properly dealt with. Such assessments were conducted in the scope of projects described in the previous sections taking into account site and concept dependent details.

An important item in this investigation is the clear differentiation of tactical capacity gain (as a function of mainly weather and other factors), which allows to mitigate ad-hoc delays and hence environmental impact, and strategic capacity gain (as a function of revised separation applicable in all weather conditions or at least close to 100% of the time), which enables to increase the scheduled airport capacity. Some concepts explicitly do not aim for a capacity increase but try to recover lost capacity in unfavourable visibility (e.g. SOIA) or strong headwind conditions (e.g. TBS).

Various methodologies have been used in order to assess the capacity benefit of the specific concepts, such as analytical approaches, fast-time simulation and real-time simulation including human-in-the-loop approaches. So the results should also be regarded in the context of methodology used.

In order to avoid repetitive descriptions of the available concepts the results of capacity assessments have been included in the previous sections 3.1 to 3.5 together with the descriptions of the concepts. In this section, a definition of the capacity term will be given as well as a description of currently used capacity assessment methods.

5.6.2 State-of-the-art

5.6.2.1 Definition of Capacity

The term capacity in the context of an airport or airspace describes the capability of the facility to provide service within some period when there is continuous demand, e.g. the number of aircraft landings and/or departures per hour. A distinction has to be made between the maximum theoretical capacity of an airport and its practical capacity which is always smaller. Scheduled airport capacity is associated with the practical capacity due to the trade-off between maximum throughput and the acceptable level of delay.

Another aspect of capacity investigation is the division into strategic and tactical capacity gains. Strategic capacity is equal to the scheduled capacity of an airport and it is assumed that it is available for nearly 100% of operational time. Tactical capacity is available only when specific operating conditions are met (e.g. when crosswind conditions are favourable) and can be used to reduce delays or accommodate additional unscheduled flights.

It should be considered that capacity is characterised by the number of arrivals and departures on a runway. This should be kept in mind during the design of a concept and during the capacity assessment process.

5.6.2.2 Capacity Analysis Methods

In order to assess the capacity impact of a new operational concept, different methods can be applied that imply modelling the system under investigation, running simulations and designing metrics to evaluate the impact. These models, simulations and metrics vary in the level of detail and complexity. The following methods are usually used to perform capacity analyses, with increasing level of detail:

- Analytical models which can be applied to different airports and are used for high level analyses.
- Process or event driven simulations that make use of synthetic traffic scenarios and emulate basic functions.
- Fast-time simulations that take into account realistic traffic scenarios, ATC procedures and the airport and airspace layout.
- Real-time simulations that take place in the complete operational context including realistic aircraft behaviour and the entire ATM system with its interactions; human factors are also assessed via human-in-the-loop simulations involving air traffic controllers and (pseudo) pilots.

Examples for the use of these methods have already been given in the previous sections 3.1 to 3.5 where various methods have been used for capacity benefit assessments.

5.6.3 Research Needs

Based on the overview of the capacity benefit assessments presented above as well as on the discussions lead during the specific workshops, the following recommendation for further work in the area of capacity analysis can be given:

5.6.3.1 Influencing factors of capacity analysis

Factors influencing results of capacity analyses are manifold and should be taken into account when assessing a concept and creating benchmarks. Among those factors are:

- Influence of uncertainty (e.g. in weather prediction for wind/weather based concepts)
- Stability of forecast and the persistence of operational modes
- Airport design and procedures
- Traffic mix
- Impact on safety and the risk assessment
- Selected metrics to quantify capacity (e.g. influence of metrics related to payload/passengers)

As a consequence, methods to account for these influencing factors need to be refined (e.g. for the time when changes from the re-categorisation effort become effective). Various studies have shown that capacity benefit is above all airport specific; in order to produce comparable results and to transfer findings from one airport to another, a holistic methodology is recommended for future studies.

5.6.3.2 Finding the right capacity metric

The right capacity metric is still under discussion – aspects of this discussion are:

- Relation of capacity metric to the aircraft type (payload/passenger)
- Weighting between arrivals and departures

5.6.3.3 Capacity gains of new and evolving concepts and systems

The capacity benefits for wake mitigation developed e.g. in SESAR WP6.8.1 and WP12.2.2 need to be assessed consecutively for each implementation phase. In order to provide realistic estimations, the methods should be refined and real-world conditions should be taken into account. It should also be considered that there has to be a trade-off or a sound balance between capacity increase (referring to scheduled capacity) and the tolerated increase of delay occurring when the conditions of a concept cannot be satisfied. It should be considered to transfer some of the capacity gain into delay reduction.

The impact of future traffic growth but also other changes envisioned in the future air traffic system (advanced landing aids, continuous decent procedures, 4-D business trajectory etc) need to be considered during capacity assessments of any evolving wake mitigation concept.

For most of the concepts developed today, one of the central questions remains: What capacity increase is needed to adopt the concept or to justify the implementation of the concept by the stakeholders? Therefore, the communication between developers, authorities and operational stakeholders is one of the important challenges for the next years to find a common answer.

6. Safety

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It is important to close the gap between end-users and equipment manufacturers and the regulatory authorities in defining a consistent set of safety requirements and safety assessment procedures that are acceptable for the authorities to serve as a baseline for the operational approval of actual new systems or procedures. To achieve this, three separate tasks are identified:

- Creation of a common understanding on the applicable rules, regulations, and associated safety requirements, for *operators, service providers, manufacturers, end-users (e.g. pilots and air traffic controllers).* This task deals with the fundamental issue of what is acceptable for *regulatory authorities* to serve as baseline for the operational approval of new wake vortex advisory systems or procedures.
- Promotion of information exchange and communication between partners, participants and stakeholders on requirements, development, definition, validation of:

  1) wake vortex encounter severity criteria and 2) safety assessment methods
- Promotion of European WV incident monitoring and analysis by 1) establishing and maintaining a link to existing wake turbulence incident reporting activities, 2) implementing Wake Vortex reporting and analysis at Frankfurt airport, and 3) trigger WV incident monitoring and analysis at other airports.

This Section therefore deals with three sub-tasks, which are described and explained in the following.

- *Applicable wake vortex regulations and safety requirements*. ICAO Annex 14, by referring to the ICAO PANS-ATM (Doc 4444), mentions wake vortex standards. The PANS-ATM provides guidance on the standards for wake vortex separation minima, and is used by CAAs and ANSPs to define operational procedures and AIP defining separations at national level. ICAO Doc 9426 gives a very high-level set of (prescriptive) requirements for the introduction of wake vortex advisory systems, whereas ESARR4 provides the basic ATM safety requirements for an (analytical) approach to derive - using guidance material and safety assessment methods - specific safety requirements for the humans, procedures, and subsystems involved. Detailed Acceptable Means of Compliance (AMC) for new ATM concepts and systems for wake vortex avoidance (as are being developed in SESAR) are not yet available. In addition to the ESARR 4 Risk Assessment and Mitigation, applicable to the EUROCONTROL Member States and for which AMC are existing and used, the EU Members States must comply with a set of EC safety regulations, including EC 2096/2005 with respect to which ANSPs are certified.
- *Wake vortex safety assessment*. Several simulation models that support the assessment of the actual wake vortex risk level of flight procedures have been identified. The simulation models that support wake vortex safety assessment 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 comparison and validation of sub-models used within different methods is likely to reveal several differences at sub-model level. Therefore, it is important to compare the available models and investigate to what extent the employed sub-models have been validated. This would provide an indication which simplifications would be allowable, and where the models would be sensitive to the modelling structure and parameters. This will give an indication of the level of differences between models and will help to identify required accuracies of sub-models to equalize differences to an acceptable level.
- *Wake vortex incident and accident monitoring and analysis*. Within Europe, so far only in the U.K., a well-structured incident reporting and analysis scheme has been applied to adapt wake turbulence separations according to objective local safety needs. These well-known current best practices can be used as a starting point for wake incident reporting at the various interested European airports. The CREDOS project provides recommendations for a Wake Vortex Safety Management System for Air Navigation Service Providers with respect to safety policy; safety achievement; safety assurance; and

safety promotion. This includes details for wake vortex safety data collection, data processing and statistical treatment of data to be processed and used as part of a Safety Management System.

6.1 Regulation and Safety Requirements

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6.1.1 Overview

It is important to close the gap between end-users and equipment manufacturers and the regulatory authorities in defining a consistent set of safety requirements and safety assessment procedures that are acceptable for the authorities to serve as a baseline for the approval of new wake vortex systems and/or procedures. This deals with the fundamental issue of what is acceptable for regulatory authorities to serve as baseline for their operational approval. This chapter therefore 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 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 main organisations involved in regulation and their responsibilities. Subsequently the actual regulatory framework (standards and recommended practices) 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.

6.1.2 Current status

6.1.2.1 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 organised, globally, and on a European and national scale as well, with particular emphasis on Air Navigation Service provision.

On a global scale, the regulatory framework has been established by ICAO. Within Europe EUROCONTROL (comprising today 38 states) previously 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). This responsibility has been shifted by the EC by end of 2012 to EASA (EC Regulation 1108/2009, 2009). The aviation regulatory framework therefore clearly has it roots in international rulemaking. However, the main regulatory functions so far are still the responsibility of the 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.

6.1.2.2 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 endeavour 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. In general, the ICAO regulatory framework is considered as a set of 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 cannot 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.

6.1.2.3 EUROCONTROL

In 1998 EUROCONTROL established a Safety Regulation Commission (SRC), which main objective is to harmonise ATM 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 European Commission (EC) legislation. The concern with EUROCONTROL's 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 differences exist in the implementation of ESARRs among the Member States of EUROCONTROL.

6.1.2.4 Wake turbulence separation minima

Annex 14 – Aerodromes – is the only regulatory standard document that mentions the issue of wake turbulence separation minima, as part of a recommendation concerning the minimum distance between two parallel runways, by referring to the so-called called ICAO 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 it is referred to the PANS-ATM itself. 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 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 its actual max. take-off weight it would be categorized as “medium” weight aircraft. It is expected that the FAA will increase the upper limit of their 'Large' category, so that the Boeing 757 is no longer in the Heavy category. 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 (> 162000 kg), medium (between 162000 and 40000 kg), small (between 40000 kg and 17000 kg) and light (< 17000 kg). Further, in addition to the Boeing 757, which is in the UK Medium category for departures and in the UK Upper Medium category for arrivals, 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.

6.1.2.5 Requirements for wake vortex advisory systems

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 basis. 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 to 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.

6.1.2.6 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 a 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.

6.1.2.7 Practical approach towards approval of wake vortex advisory systems

If we would now focus on the introduction of 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, which provides 1) guidance material for States in the development of their national services, 2) a basis for harmonization of planning activities on a regional scale (as included in regional air navigation plans) (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 wind-shear detection and guidance systems (see e.g. FAA TSO-C117 and FAA 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 the ESARR4. Moreover guidance material for the application of ESARR4 is available and safety assessment methods (e.g. EUROCONTROL SAM) have been defined to conduct the safety analysis. Nevertheless application of ESARR4 is not without difficulty.

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, on 21 October 2009, the European Parliament and the European Council adopted two regulations to improve the performance and safety of the European aviation system – the first strengthens the Single European Sky legislation, while the second extends the tasks of EASA to the safety of aerodromes, air traffic management and air navigation services (Regulation (EC) 1108/2009). Both regulations were adopted following a first-reading agreement with the European Parliament in March 2009. The Regulation (EC) 1108/2009 has transferred the regulatory competences in the mentioned domains to EASA. This implies that an approval or certification of wake vortex advisory systems within Europe will fall under the authority of EASA, against the safety requirements that are (to be) adopted by EASA. It is as yet not clear how such framework will 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. In the context of wake turbulence regulations it is furthermore important to mention that there are several ongoing and future technological and operational developments, in which regulatory authorities (including EC, ICAO, EASA, FAA) are either participating or providing guidance as member of a steering group. Noteworthy are the SESAR Programme, EC project CREDOS, EUROCONTROL activities on Time Based Separation, Airbus A380 Wake Vortex Steering Group (which prepares new separation criteria for take-off and landing behind the Airbus A380 with representatives from EASA, FAA, EUROCONTROL, and Airbus), the FAA/EUROCONTROL Re-categorization effort, the Boeing B747-8 Wake Vortex Steering Group (which prepares guidance for separations behind the new Boeing B747-8), and the ICAO Wake Vortex Study Group. It is therefore reasonable to assume that emerging results will be embedded in future wake turbulence regulations.

6.1.2.8 Future developments

A new structure for operational and implementing rules has been developed as part of the work on the 1st extension of the EASA remit. It is planned to accommodate into this structure the future implementing rules for ATM and aerodromes as part of the 2nd EASA remit extension to be completed by 2013. Three ATM working groups have been set up by EASA in support of this 2nd extension:

- ATM.001 for development of rules on Requirements for Air Navigation Service Providers
- ATM.003 for development of rules on Air Traffic Controller licensing.
- ATM.004 for development of rules on competent authorities

These working groups will e.g. deal with the transposition of and cross reference to the Single European Sky (SES) regulations (including the ESARRs) and the ICAO SARPS. As the objective is to develop Implementing Rules (IRs) and, as appropriate, the necessary Acceptable Means of Compliance (AMC), Certification Specifications (CS) and Guidance Material (GM), the resulting regulatory material will encompass the safety regulatory requirements and related implementation material for ATM concept and systems, including the wake vortex advisory systems such as are being developed as part of SESAR.

As mentioned before, the ICAO A380 Wake Vortex Steering Group which - with representatives of EASA, FAA, Airbus and EUROCONTROL - has prepared new separation criteria for take-off and landing behind the Airbus A380. This aircraft, with a maximum take-off mass in the order of 560 000 kg, is the largest passenger aircraft that has ever entered into revenue service. According to ICAO standards, the aircraft is in the HEAVY wake turbulence category and the Procedures for Air Navigation Services — Air Traffic Management (PANS-ATM, Doc 4444) apply. However, as vortices generated by the A380-800 are stronger than for other aircraft in the HEAVY wake turbulence category, the Steering Group has developed guidance recommending States to implement an increase in relation to the wake turbulence separation minima published in the PANS-ATM. Further research efforts to revise this ICAO guidance further are still ongoing, and this is expected to eventually result in an update of the ICAO PANS-ATM.

Following a request from ICAO, an update of the existing wake turbulence categories has been initiated. It is colloquially called “Recategorisation” (see §3.5). The existing categories are felt to be out of date and do not take the latest aircraft types into account. This project is driven by EUROCONTROL and FAA. Other stakeholders like aircraft manufacturers (e.g. Airbus, Boeing) or airspace users are not directly involved. The project aims to look into:

- Characteristics other than weight which could be used to determine wake vortex separations;

- Sub-divisions of the current Medium and Heavy categories will be investigated;
- Dynamic pair-wise spacing based on actual aircraft weight is a long term objective of this project.

This effort is expected to lead to amendments of all ICAO reports that use wake turbulence categories.

It is noted that the Quality Assurance Manual for Flight Procedure Design (ICAO Doc 9906-AN/472), Volume 1, contains specific guidance regarding the safety assessment of the Time Based Separation concept as is currently being developed by EUROCONTROL. This guidance is based on the EUROCONTROL preliminary safety case approach, in which five safety (sub)arguments are distinguished for which safety evidence will need to be gathered: intrinsic safety, design completeness, design correctness, design robustness, and mitigation of internal failures. The latter is usually supported by a Functional Hazard Assessment (FHA) and a Preliminary System Safety Assessment (PSSA).

The recently started SESAR Development Phase contains four projects that specifically deal with wake turbulence related activities:

- WP6.8.1 (Flexible and dynamic use of wake vortex separations, see §3.4.1)
- WP9.11 (Aircraft Systems for Wake Encounter Alleviation, see §4.2.2.1)
- WP9.30 (Weather Hazards / Wake Vortex Sensor, see §4.2.2.1)
- WP12.2.2 (Runway Wake Vortex Detection, Prediction and decision support tools, see §4.1.2).

It is expected that these projects will deliver (proposed) safety requirements using a similar approach as recommended for Time Based Separation (and contained in the new document ICAO Doc 9906-AN/472), Volume 1). However, the ultimate responsibility for approval and certification in Europe will be with EASA.

6.1.3 Research Needs

Emphasis is now being placed on establishing wake vortex encounter safety arguments that will satisfy the concerns of all stakeholders, with particular emphasis on the concerns of pilots and pilot associations given that they are in the ‘front line’ of WVEs and their consequences, and also airline operators, controllers, controller associations, ANSPs, airport operators, and safety regulators. Additional research might be needed to investigate how such WVE safety arguments can be used in certification processes.

Even though requirement c) from ICAO Doc 9426 (see §6.1.2.7) states that a wake vortex advisory system should be ground based, with no additional avionics required, efforts are underway (e.g. in the SESAR projects 9.11 and 9.30) to develop airborne wake vortex systems. Industry will remain cautious towards progressing from R&D towards actual implementation of new ground and aircraft wake vortex advisory systems as long as it is unclear if and how such system’s new capabilities will be taken into account in future separation standards and how such advisory systems will have to be certified. Additional research might be needed to investigate how the certification process for such systems in detail should look like, and how the safety benefits of such systems could be incorporated in the related regulatory framework.

A big hurdle towards the development of ground and airborne systems aiming at reducing wake turbulence separation requirements while assuring today’s safety level is the unavailability of detailed Acceptable Means of Compliance (AMC) and detailed requirements from regulators regarding the development of the associated safety case. While there have been recent example wake turbulence safety assessments (e.g. A380, WIDAO), which for the first time since the introduction of ICAO wake turbulence separations allowed defining new separation requirements, so far these initiatives mainly take into account the characteristics of the wake vortex but not specifically the capabilities of the follower aircraft. The EASA WATUS (Safety Case for Wake Turbulence Separation of Large Aircraft) project, which is being performed by NLR, provides an attempt to take the capabilities of the follower aircraft into account. However, WATUS is still ongoing and the first results are currently not expected to be made available to the public before the end of 2011. Additional research might be needed to investigate how to progress from the individual safety case examples towards harmonized requirements for the safety case.

6.2 Safety Assessment

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6.2.1 Overview

All efforts addressing the safety of flight operations with regard to wake vortex encounter (e.g. wake warning systems) or aiming at increasing the capacity of the air transport system by adjusting wake turbulence separations (e.g. new separation schemes) ultimately aim at reducing the risk of severe wake encounters or must assure that the level of risk is not increased. It is the task of dedicated safety assessments to validate that this risk is either reduced or kept at current levels. Those risk-based safety assessments that consider the possibility of unintentional wake encounter must determine the probability (i.e. frequency) of wake vortex encounters and their associated severity level. Severity assessments concern the determination of the severity of a specified wake vortex encounter. Within such assessments severity criteria correlate objective, measurable quantities with severity descriptions of more general nature and stakeholder-wide understanding. Safety assessments may differ in depth. The most detailed assessments include models of air traffic, weather, wake vortex transport and decay as well as dynamic wake encounter simulations to determine frequency and severity of wake encounters on a statistical basis. Experience shows that a common definition of applicable severity criteria is especially difficult to achieve. This difficulty is due to the fact that many different stakeholders are directly concerned (basically answering the question: “which wake encounter is acceptable?”) but that they have different perspectives, experiences and requirements. While an airline might already be concerned about the number of encounters affecting passenger comfort, a regulator is more likely to be concerned only about encounters leading to incidents.

6.2.2 Current status

6.2.2.1 Absolute safety assessments

Application of ESARR4 is often based on specification of the required safety target of the system in an absolute sense. Such safety target can (but not necessarily 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 $1.55*10^{-8}$ 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):

- 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 auto-land 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, wind and weather prediction, and human interaction.

Therefore it is clear that 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.

6.2.2.2 Relative safety assessments

A possible outcome of mentioned research might be that an absolute estimation of the actual risk cannot 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.

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.

6.2.2.3 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 of wake vortex advisory systems it is therefore prudent to conduct further research to specify a suitable introduction phase for such systems.

6.2.2.4 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.

At present, twelve simulation models that support the assessment of the actual (wake vortex) risk level of flight procedures have been identified:

- WAVIR, developed by NLR-ATSI.
- WakeScene, developed by DLR
- VESA, developed by Airbus
- Airbus A380 wake turbulence minima assessment by Airbus
- Wake Encounter Pilot Model, developed by the TU Berlin (see §4.5)
- RECAT safety assessment method, developed by FAA – EUROCONTROL (see §2.5)
- Wake Vortex Encounter Risk model, developed by DNV
- Wake Vortex Scenario Screening Tool, developed by EUROCONTROL
- Wake Encounter Risk Indicator Simulation package, developed by M3S and UCL
- ASAT, developed by the FAA Flight Procedure Standards Branch
- Probabilistic wake vortex hazard model, developed by the George Mason University
- Recat Step I method, developed by Airbus

These models differ in scope and complexity. Some of the models are actually sub models of others or sub models of a common, larger process.

WAVIR

WAVIR (Wake Vortex Induced Risk) is a stand-alone risk assessment method, based on a modular approach. Risk assessment process employed by WAVIR (Speijker, 2007; Speijker et al., 2004) is depicted in the figure below.

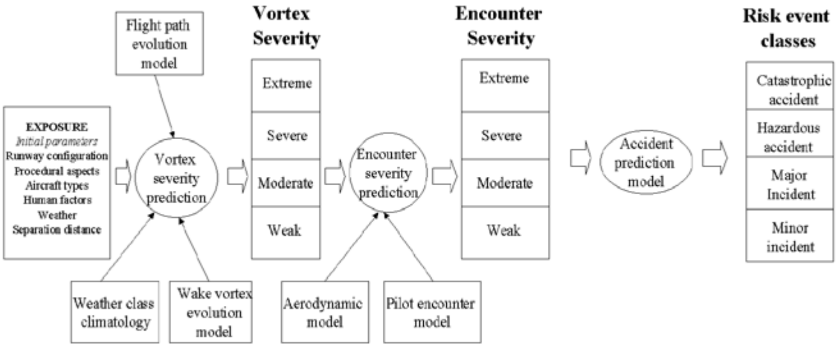

Figure 97: Wake Vortex Induced Risk Assessment (WAVIR).

Basically it is a three step approach. First evolution of the wake vortex generated by a leading aircraft is calculated at a given number of gates along the approach or departure path. The flight path of leader and follower aircraft is specified based on aircraft speed profiles and the nominal trajectory, taking into account uncertainty in speed and position. 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 encounter model used this can be expressed in one or more disturbance parameter (induced roll angle, roll control ratio, loss of height, induced load factor, equivalent roll rate). Finally these disturbances are translated to a certain risk event.

The set-up of the model allows Monte Carlo simulations, using probability distributions for meteorological conditions (stratification, turbulence, wind), aircraft position and speed and other stochastic input parameters. Simulation of a specific scenario, defined in terms of involved aircraft types, flight paths (departure, approach, missed approach, or en-route; interception angle), and the applied separation (horizontal or vertical, distance or time) provides frequency estimates of the risk events in that scenario. This can then be compared with a certain target level of safety in order to establish the anticipated acceptability of the operation.

WAVIR has been used in EC projects (S-Wake, ATC-Wake, I-wake, and Awiator) and supports evaluation of wake vortex safety and required separation distances for:

- Air Traffic Management warning and avoidance procedures (Speijker, September 2006);
- On-board wake detection, warning, avoidance instrumentation (Speijker, October 2006);
- Advanced aircraft wing technology operations (Van Baren, 2007);
- Optimised use of airspace (Van Baren, 2008); and
- New designed high capacity aircraft (Van Baren, 2011).

WakeScene

The WakeScene (Wake Vortex Scenarios Simulation) Package allows assessing the encounter probabilities and the related vortex strengths and can apply different hazard areas behind different wake vortex generating aircraft for different air traffic scenarios (Holzäpfel et al. AST 2009, Holzäpfel et al. JoA 2009). For arrivals the simulation domain extends from the final approach fix to the threshold, for departures it ranges from the runway along different departures routes up to heights of about 3000 ft. Currently, WakeScene is extended to other phases of flight and, in particular, to approaches to closely-spaced parallel runways. In the DLR project ‘Weather & Flying’ it is planned to apply WakeScene for a risk assessment of the WSVBS (WirbelSchleppen Vorhersage und Beobachtungs System, see §4.1.2.2) and for the elaboration of suggestions for a new aircraft separation matrix (re-categorisation, §3.5).

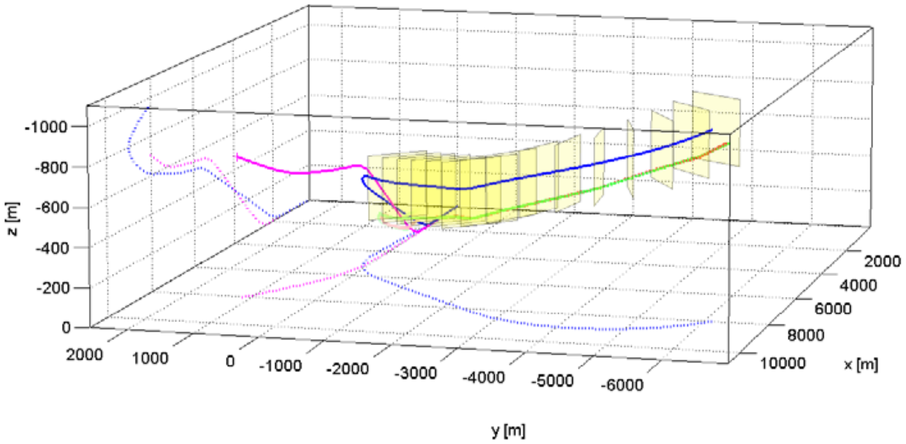

Figure 98: WakeScene simulation of departing aircraft (as analysed in EU project CREDOS, reprinted from Holzäpfel et al. 2009).

The modelling 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-Trajectory Model provides time, speed, altitude, mass, and lift of generator and follower aircraft at different gate positions (simulation planes), using point-mass aircraft models or the Advanced Flight Management System (AFMS) based on the BADA database. A large number of environmental- and aircraft specific parameters influence an aircraft trajectory and its deviations from a nominal flight path (see §5.5). The Meteorological Data Base comprises a one-year statistics of realistic 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 (Frech et al. 2007). Based on vertical profiles of environmental conditions and aircraft parameters, the Probabilistic Two-Phase Wake Vortex Decay and Transport Model (P2P, see §5.1.2.2) simulates the development of wake vortex trajectories, circulation, vortex core radius, and attitude of wake vortex axes. The hazard area module defines an area of interest around the wake vortex. When this area of interest is penetrated by the follower aircraft, this is considered to be a “potential wake vortex encounter”. Different options exist for the area of interest definition. A simple circle with 50 m radius around each vortex or the more differentiated approach of “simplified hazard areas” (SHA) (Schwarz and Hahn 2006), which are dynamically adjusted according to vortex strength and aircraft pairing and designed to ensure operationally safe flight outside of the SHA. The SHA are defined by a (conservative) RCR limit that was determined based on pilot ratings in order to ensure that all relevant aircraft upset parameters stay within their typical operational envelope (Hahn and Schwarz 2007). With the aircraft data required for hazard analysis provided by the Simplified Hazard Area Prediction Method (SHAPe), the SHA can be universally applied to any conventional transport aircraft type (Hahn et al. 2004, Schwarz et al. AIAA 2010, Schwarz 2011).

In cases with potential wake encounters all relevant parameters can be provided to VESA (Vortex Encounter Severity Assessment) which may subsequently perform detailed investigations of the encounter severity.

Validation activities have been conducted for the employed submodels of WakeScene (Holzäpfel et al. JoA 2009). For example, the one-year meteorological data base has been validated against a 30-year wind climatology and a 40-days subset has been compared to field measurement data collected at Frankfurt airport (Frech et al. 2007). Validation activities of the P2P wake vortex model (§5.1) have been conducted using data of over 10,000 cases gathered in two US and six European measurement campaigns. Assessments of the wake prediction skill of P2P based on predictions of meteorological conditions with NOWVIV can be found in (Holzäpfel and Robins 2004, Frech and Holzäpfel 2008).

Monte-Carlo Simulations using WakeScene have been used to investigate the wake vortex encounter probabilities for crosswind departure scenarios within the EU-project CREDOS (see §3.1.5). Sensitivity analyses have been conducted regarding the effects of various crosswind scenarios, departure route combinations, flight path adherence, wake vortex modelling, the development of aircraft separations during the departures, the sample size of the Monte Carlo simulations, aircraft type combinations, aircraft take-off weights, meteorological conditions, airport operation times, and a comparison to approach and landing (Holzäpfel and Kladetzke 2011, Holzäpfel and Kladetzke 2009).

VESA (Vortex Encounter Severity Assessment)

The research work performed by Airbus in the last years regarding wake encounter safety assessment built upon different earlier projects that investigated wake encounter hazards. In the EC-funded S-WAKE project (2000-2003) modeling tools were developed that ultimately lead to the wake vortex encounter simulation platform VESA (Vortex Encounter Severity Assessment) (Luckner et al. 2004; Höhne et al. 2004, Kauertz et al. 2012). VESA is able to simulate the effect of wake vortex encounters on an encountering aircraft by adding vortex models to high-fidelity, six degrees-of-freedom flight simulations using dedicated aerodynamic interaction models to couple the wake vortices with the basic aircraft’s aerodynamics and flight dynamics. Additional elements included were a model for pilot behavior during wake encounters in approach and hazard criteria to assess the severity of the wake encounter, based on single parameters like bank angle or Roll Control Ratio.

The work in the S-WAKE project focused on the approach phase of flight, and the VESA platform had only limited capabilities to be applied to other flight phases. After S-WAKE the capabilities were continuously extended. Most recently within the CREDOS project (2006-2009) for example the platform was extended to the departure flight phase and existing sub models have been further refined. In particular an advanced severity model was integrated that was developed by TU Berlin using data from extensive piloted simulator tests of wake encounters during departure in the A320 THOR development simulator at Airbus in Hamburg (Amelsberg et al. 2008; Amelsberg, 2009). Pilots taking part in this simulator study also provided subjective hazard ratings for each individual encounter through a dedicated questionnaire. The severity model is based on a multi-parameter envelope approach (Wilborn, 2004; Reinke, 2006) that takes into account the main hazards of a wake encounter on an aircraft, including dynamic aircraft reactions and parameters like load factors, flow angles or aircraft attitude. Advantages of such criteria are that they take into account the actual resistance of the encountering aircraft to the disturbance, and that they can in general be applied to all flight phases and encounter conditions, as all possible hazards caused by the wake are considered. Furthermore a new pilot model was developed by TU Berlin capable of conducting take-off and departure as well as recovery from wake encounters in a way representative of real pilots (Amelsberg, 2006). It is based on a neural net, which has been trained to the recorded pilot reactions from the A320 simulator sessions in CREDOS, simulating wake encounters of varying strengths and types.

The new VESA platform was used within the CREDOS project for an assessment of wake encounter risk during the departure phase, using the Frankfurt/Main International Airport environment as an example. For this assessment the VESA platform was connected to the WakeScene tool developed by DLR (Holzäpfel et al. AST 2009; Holzäpfel et al. JoA 2009), which focuses primarily on the frequency of encounters in the airspace environment. WakeScene identifies potentially significant encounters out of a number of departures, but does not consider any influence of the vortices on the encountering aircraft and thus cannot finally assess the severity of the hazard they pose. The identified potential encounters are instead investigated in detail by VESA. In VESA the encounter conditions in terms of wake intercept angles, vortex characteristics and flight state of the encountering aircraft identified in WakeScene are reconstructed. VESA then allows an estimation of the severity of each identified encounter, using the severity model mentioned above applied to the dynamic response of the aircraft. Both results, the frequency of encounters and their respective severity, allow characterizing the wake encounter risk for the considered scenario. In CREDOS different wake turbulence separation times for Heavy-Medium departures with varying crosswind levels have been compared in a relative way with the goal to find a possible crosswind threshold above which a safe reduction or suspension of wake turbulence specific departure separations is possible.

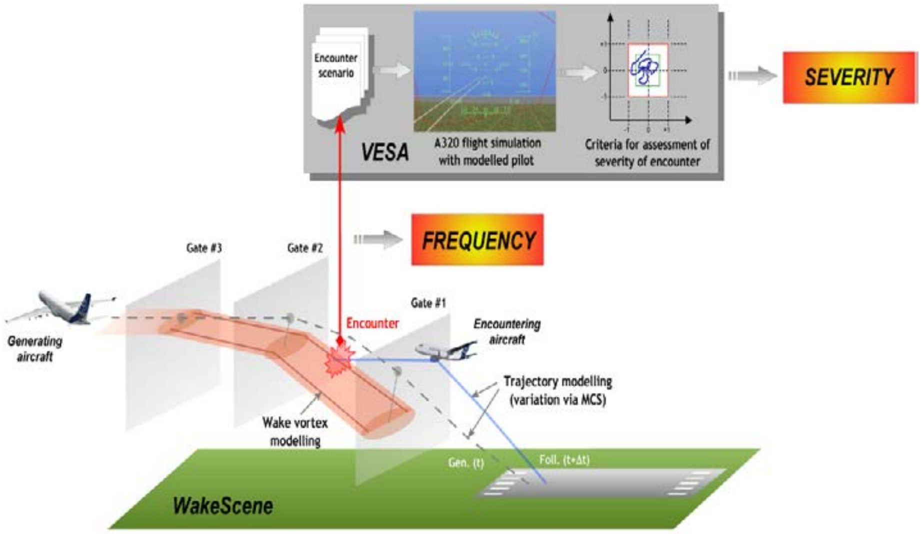

Figure 99: Coupled WakeScene/VESA encounter simulation for departures.

The validation activities undertaken so far for the different sub-models generally show a good quality. The pilot model based on a neural net shows a behaviour representative of real pilots and seems to be a promising approach for this kind of application. It could also be shown that multi-parameter hazard criteria are feasible that correspond reasonably well with pilot judgement of the severity of an encounter (Amelsberg, 2009). Further refinement and validation of the criteria's definition will be necessary however, including expert judgement on which limits are acceptable for the different considered dynamic parameters. Further development in this area will be conducted for example in the frame of SESAR, in which Airbus is involved in several projects concerned with wake vortex topics. WakeNet will be used as a further means to move towards a wider discussion and acceptance of this approach e.g. via dedicated workshops.

Airbus A380 wake vortex safety assessment

In preparation of the Airbus A380 entry into service, Airbus engaged in extensive wake vortex research, measurements, evaluations and analyses. Live trials included ground-based and airborne measurements by LiDAR as well as dedicated wake encounter flight tests involving several different generator and follower aircraft types. Results from these activities are reviewed and evaluated by an international A380 Wake Vortex Steering Group (SG) composed of Airbus, EASA, EUROCONTROL and the FAA as well as ICAO as observer. The A380 Wake Vortex Steering Group has issued its findings from dedicated Safety Assessments to ICAO which in turn has issued several ICAO State Letters to its member states, providing recommendations on safe wake turbulence separations for A380 operations.

The last related ICAO State Letter was issued in July 2008 (ICAO, 2008). In this the A380 radar wake turbulence separation minima for approach have been recommended as follows: no separation requirement for an A380 as follower aircraft, 6 NM for a Heavy following an A380, 7 NM for a Medium and 8 NM for a Light. These recommendations are primarily based on the relative assessment of the A380 wakes' circulations compared to that of other Heavy aircraft already in service. For this, circulation has been measured by ground-based LiDAR. The State Letter does not recommend any special separations for A380 operations in cruise flight – a finding that has been established by direct comparison with existing Heavy aircraft, based on wake encounter flight tests and in-flight LiDAR measurements.

Wake encounter simulations using VESA indicated that the recommendations from the LiDAR-based Safety Assessment for the approach flight phase may still be overly conservative. VESA has shown that vortex circulation is not the only parameter influencing the impact of a wake on an encountering aircraft, but that further characteristics of the wake such as the vortex spacing and core radii play an important role as well. Still, VESA could not be used directly to identify safe A380 separations due to a perceived lack of validation. Given the successful wake encounter tests performed at altitude, Airbus hence engaged in a most extensive wake encounter flight test campaign with the aim to further refine safe separation standards for approach flight conditions. This refinement shall be achieved through evaluation of encounter flight test results that include tests useable for a relative comparison of the wakes behind the A380 and other, reference Heavy aircraft.

Straight-forward comparisons of encounter flight test results already show marginal differences in aircraft responses. To support A380 Wake Vortex SG activities Airbus has developed methods and tools specifically aimed at evaluating wake encounter flight tests by comparing the direct impact of two different wakes on an encountering aircraft. This direct impact is expressed by wake-induced forces and moments acting on the aircraft and can be established from flight testing by comparing the recorded aircraft response with the known aircraft characteristics in calm air. Compared to circulation, direct wake impact established from encounter testing is closer related to relevant operational hazard since wake-aircraft interaction is included. Because the specifics of the encountering aircraft's flight control system are inherently excluded from the evaluated direct wake impact the results obtained can be generalised and the outcome of a relative assessment can be generally applied.

Aiming at objectively documenting flight test conditions as well as showing coherence with ground-based LiDAR measurements, flight test results are furthermore evaluated with regard to the encountered wakes' characteristics and the relative flight path. This is achieved by evaluation of air data recordings in an optimisation process called wake identification.

Despite the promising results, progress towards refined recommendations by the A380 Wake Vortex SG is slower than expected given the scrutiny with which flight test results are analysed and the novelty of the flight test evaluation methods. In the future the Airbus flight test results may be used to further validate VESA as well as other methods and metrics to set safe separation distances, for example in the context of recategorisation.

Airbus method to evaluate potential safety and capacity benefits from static recategorisation (Step I)

At the first major workshop of WakeNet3-Europe, held in January 2009, Airbus presented a study of technical methodology for recategorisation step I ("Recat Step I"), which is defined as a new, static MTOW-based aircraft wake turbulence classification with more than three classes. The goal of the study was to identify if simple recategorisation may deliver safety and capacity gains and to identify potential technical challenges and research requirements. The goal was not to propose a new classification, but mainly a method that has been set-up to evaluate potential safety and capacity benefits from static recategorisation and increased number of categories and to understand potential issues. The methodology presented is depicted in the figure below and can be characterised as follows:

- Representation of all aircraft pairs by the evaluation of a 50x50 matrix of generator / follower aircraft pairs at 10 distinct separation distances ranging from 2.5 to 10 NM.
- Use of generic, probabilistic aircraft models for the generator and the follower aircraft to account for current and future aircraft characteristics and with generalisation achieved through statistical evaluation of up to 161 existing aircraft types.
- Modelling of an operational approach scenario evaluated at a single "gate" along the approach path
- Statistical evaluation of encounter risk through Monte Carlo Simulation of wake generation, wake decay, wake transport and wake encounter as a function of aircraft pairs and separation distance.
- Encounter consequence or severity expressed by wake-induced rolling moment as a function of relative position (distance) between wake vortex and follower aircraft, vortex circulation, spacing and core radius as well as follower aircraft characteristics like speed, span and rolling moment of inertia.
- Modelling of traffic mixes by statistical distributions of aircraft weights representing different airport scenarios.
- Target Level of Safety estimated for current ICAO separations for "Largest individual aircraft risks" as well as for "Average aircraft risks".

- Derivation of minimum pair-wise separation distances based on Target Level of Safety.
- Computation of three different, non-segregated, single runway capacity metrics (average separation between aircraft, number of aircraft operations per hour, payload throughput per hour).
- Establishing of wake turbulence classes or categories based on minimum pair-wise separations with capacity as optimisation goal.

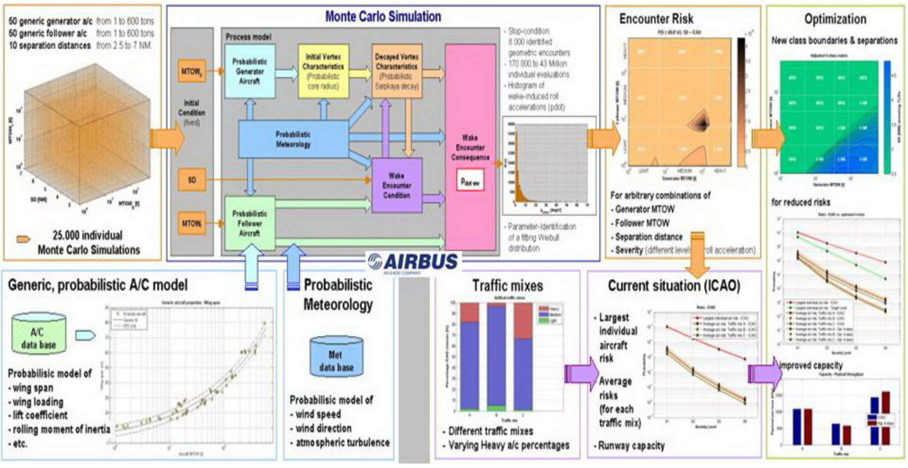

Figure 100: Overview: RECAT method developed by Airbus.

Wake Vortex Scenario Screening Tool

The WV Scenario Screening Tool, available at EUROCONTROL, provides a means of examining and comparing very simple Time-Based Separation and Distance-Based separation scenarios. The WV Scenario Screening tool provides a graphical representation of the positions of the leading and following aircraft in a pair on approach and shows the positions of Wake Vortices generated by the leading aircraft according to a very simple Wake Vortex transport model. The tool also shows the minimum distance from the wake vortices and provides a risk estimate based on an assumed hazard radius for the Wake Vortices, distributions of the vertical and lateral position keeping accuracy of aircraft on an ILS approach.

Wake Encounter Risk Indicator Simulation package

M3S has developed a Wake Vortex Encounter Risk Indicator Simulation package allowing to support the preliminary risk assessment of new concepts of operations (as done for the preliminary safety case of the Time Based Separation concept). This package could also be used to support the development of new concepts of operation or to assess the Wake Vortex Encounter (WVE) risk associated with current real operational situations. The tool is constituted of three separated modules that could be removed and replaced by other ones (provided that the interface with the two other modules is compliant): a) The scenarios definition module, b) The Wake Vortex Simulation module (not developed by M3S, but consisting of the WAKE4D platform developed by UCL), c) The Risk Indicator computation module.

The Scenarios Definition module is used to determine all relevant parameters of the investigated scenario. On the one hand, it allows setting:

- the aircraft characteristics such as the aircraft type, dimensions, weight and lift distribution;
- the aircraft trajectory, i.e. the time evolution of aircraft position (including aircraft navigation errors);
- and the atmospheric conditions such as the wind profile (both head and cross- wind), the atmospheric turbulence and the temperature profile.

On the other hand, it allows describing the application of the new concept of operation by ATCO such as aircraft spacing applied along the flight track or aircraft speed constraints applied.

For prediction of Wake Vortex (WV) behaviour, the WAKE4D platform developed by UCL has been selected and plugged in the risk assessment process. In the WAKE4D the modelling of the aircraft WV behaviour is made using the Deterministic Vortex Model, DVM, or the Probabilistic Vortex Model, PVM (see §5.1). The predictions are conducted in several computational gates along the flight path that move in space with the wind. From the 3-D "gate by gate" DVM (resp. PVM) computations, one obtains the 3-D envelope of the wake. The trajectory can be straight or curved. The computational effort depends on the density of time steps within each gate and the number of gates.

The WAKE4D platform contains also some post-processing routines. The results can be interpolated in a fixed control gate (similar to a LiDAR scanning plane). In PVM mode, one can also count the vortex in a given box as a function of time (useful for potential encounter analyses). For reconstruction of the induced velocity filed a first routine uses a vortex tube segment approach to compute the velocity induced both by the primary and secondary vortices. This approach enables the evaluation of the velocity for complex aircraft trajectory scenarios (e.g., take-off, landing, turns …). A second routine uses the simplified Crow instability model of the WAKE4D, in a vortex filament approach, to compute the 3-D velocity induced by deformed vortices. This evaluation is only applicable to straight aircraft trajectories far from the ground. Both routines evaluate the induced velocity at a hundred of points in real time and can thus be integrated in a flight simulator (as was done in the CREDOS project). The choice of the vortex circulation distribution model is of great importance for encounter analysis.

The WAKE4D, and its subcomponents DVM and PVM, have been used in fast-time and real-time simulations of WVEs as well as a vortex forecast function in experimental detection, warning and avoidance systems in aircraft and on ground. The complete description of the WAKE4D platform is available in (Winckelmans, 2010), which also contains WV prediction results validation against WV measurements performed in the framework of FAR-Wake and CREDOS.

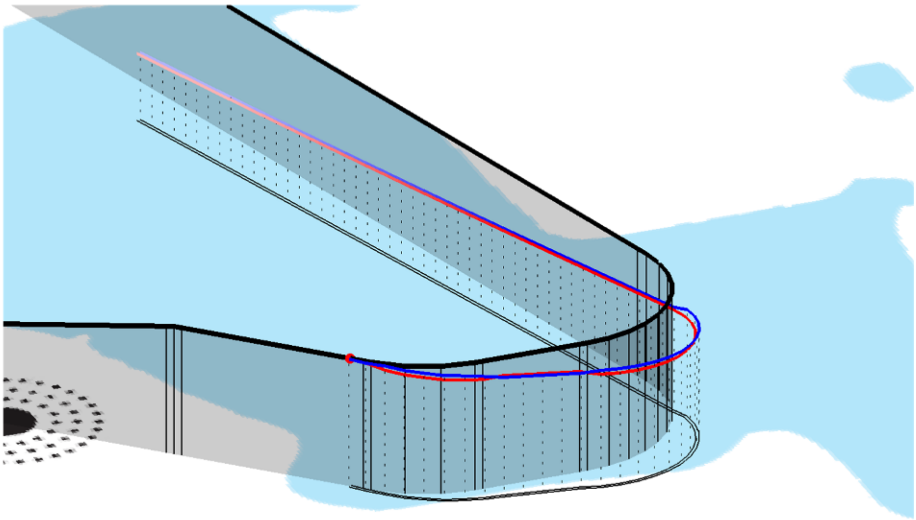

Figure 101: Example of trajectory (thick black line) computed by the pre-processor for an approach to Marseille-Provence airport. A snapshot of the 3-D port (starboard) vortex trajectory is shown in blue (red), the colour intensity being proportional to the vortex circulation.

Based on the Scenario Definition and based on extensive Wake Vortex numerical simulations, the Risk Indicator Computation module allows Wake Vortex Encounter risk assessment through the computation of risk indicator. The risk indicator selected for the study covers the 2 dimensions of wake vortex encounter risk as follows:

the WV Area Encounter probability: the probability for a follower aircraft to penetrate within a wake vortex area defined by geometric considerations and related to the wingspan of leader and follower aircraft; the severity of a potential encounter: the severity is measured through the WV circulation.

Considering the number of factors affecting both aircraft profiles and wake vortex behaviour, including the actual mass of the aircraft, its position with respect to the ground as well as the atmospheric conditions (wind and temperature), the method proposes to follow a relative approach for the risk calculation of potential wake vortex encounter. Relative estimates are felt to have a smaller range of uncertainty and are less susceptible to model simplifications.

ASAT (Airspace Simulation and Analysis for TERPS) is a collection of models and simulations that can be used to analyse safety and risk factors for a large range of aviation scenarios. ASAT is a Monte Carlo Simulation tool that uses statistical input for Aircraft (flight dynamics, propulsion, performance, wake turbulence, on board avionics), Geographical/Geodetic (digital terrain elevation data, obstacles), Environmental (standards atmosphere, non-standards atmosphere, measured wind and temperature gradients data), Navigation ground systems, Surveillance (PRM, ASR-9, ARSR, TCAS, ADS-B), Human factors (pilot, ATC). ASAT can provide answers either in a deterministic or a probabilistic way.

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 auto-land certification.

The system also can generate and track wake vortices and identify encounters between wakes and aircraft in the scenario. As such ASAT is regarded as a candidate for wake vortex risk assessments.

Probabilistic wake vortex hazard model

To calculate the Wake Vortex hazard and 'Simultaneous Runway Occupancy' (SRO) risks for a given target wake vortex separation, the George Mason University (GMU) defines a method (Jeddi, 2008; Jeddi et al. 2007; Shortle et al. 2007; Xie et al. 2005) based on probability distribution functions of:

- *Aircraft spacing* in the common landing path when infinitely many aircraft are in the line to land
- Landing Time Intervals (*LTI*) to the runway threshold
- Inter-Arrival Times (*IAT*) at the final approach fix (*FAF*)
- Aircraft Runway Occupancy Times (*ROT*)

These probability distributions are to be calculated from samples extracted from aircraft time-position track data collected by the multilateration surveillance systems in the vicinity of an airport. Imposed separation, corresponding to the first distribution, is not directly observable from aircraft track data and is obtained using distributions of the other variables. Probability distributions for the locations and strengths of wake vortices are using existing wake vortex models such as the Probabilistic Two-Phase (P2P) model, the AVOSS Prediction Algorithm (APA), and the TASS-Driven Algorithm for Wake Prediction (TDAWP). A safe wake vortex separation threshold is assessed with a hybrid simulation methodology using separation probability distributions. The approach is hybrid as part of the simulation is conducted using a data feed of flight-track data, while the other part is obtained by simulation of wake-evolution models. The approach uses a sample of flight tracks to predict the frequency of potential wake alerts, which is defined as event where the trailing aircraft is in a *region* of space where the wake is likely to be.

6.2.3 Research Needs

The simulation models that support wake vortex safety assessment 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 comparison and validation of sub-models used within different methods is likely to reveal several differences at sub-model level. For instance wake vortex evolution in ground-effect shows some discrepancies. Also the flight path evolution and wake vortex encounter models in the various risk assessment methods are often modelled 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 modelling structure and parameters. The outcome of this research could provide a baseline for modelling 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 still needs to be agreed upon. An effective proposal could be to define a benchmark scenario and apply the various models to conduct a risk assessment for this scenario. This will give an indication of the level of differences between models and will help to identify required accuracies of sub-models to equalize differences to an acceptable level.

The WV behaviour analysis and WVE safety analysis activities are very time consuming and labour intensive and so it takes a long elapsed time before analysis results become available. There is a need for a much more automated and systematic process founded on standard data formats for the wake turbulence measurement data, the correlated aircraft data, and the correlated meteorological data. Automated methods need to be developed for data cleaning which automatically generate an auditable file to support the safety arguments and safety evidence requirements. Automatic methods need to be developed to carry out the safety analysis and generate the safety analysis results. Safety metrics need to be developed against which to assess the safety analysis results. The role of WV behaviour models towards providing safety evidence in support of safety arguments remains an important issue. The challenges associated with the validation of models such that the analysis results can be considered reliable enough to be used as safety evidence remains a research needs challenge. WV behaviour models have the potential to considerably reduce the need for WV behaviour data collection campaigns.

With the deployment of new operational concepts envisaged by SESAR and NextGen, the possibility of encountering wake vortices might increase. Especially 4D-Reference Business Trajectories (RBT) might lead to an increase of crossing, climb and descent through of other aircraft trajectories compared to today. To characterize the impact of these concepts and also the impact of different performance levels of ASAS applications on the Air Traffic System, the following research is recommended:

- Simulation of future air traffic containing estimated traffic mix and 4D-RBT to assess the probability and frequency of wake vortex encounters;
- Assessing the benefit of reduced ASAS Self Separation applications based on airborne Wake Vortex mitigation and alleviation systems;
- In combination with ASAS Self-Separation functions, the need arises to investigate and develop methodologies to mitigate wake vortex encounters en-route.

An innovative method to incorporate the safety benefits of (ground and airborne) wake vortex advisory system in the safety assessment has been developed and applied to two example concepts of operations (Speijker et al., September 2006; Speijker et al., October 2006). Additional research might be directed to further development, verification and validation of such methods, in order to improve the understanding of how the capabilities of these airborne and ground wake vortex systems can properly be taken into account in WV safety assessment and WV safety cases.

6.3 Incident and Accident Monitoring and Analysis

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Jens Konopka – DFS

6.3.1 Overview

Incident Monitoring is a most important means to support operational changes. So far only in the UK a well-structured incident reporting and analysis scheme has been applied to adapt wake turbulence separations according to objective local safety needs. As part of WakeNet, it is foreseen to use these well-known current best practices as a starting point for a wake incident reporting for Frankfurt airport. Experiences from the process to implement an incident reporting and analysis at Frankfurt will be collected and shared with the WakeNet3-Europe Partners. If successful, it might trigger similar attempts at other German and other European airports with wake turbulence related capacity or safety problems.

6.3.2 Current status

6.3.2.1 Wake vortex encounter reporting

NATS and the CAA are still running the voluntary wake vortex encounter reporting scheme in the UK, which was first established in 1972. NATS now has over 5000 wake vortex encounter reports in the UK Wake Vortex Encounter Database. The wake vortex reporting scheme became a national scheme in January 2008, so NATS now also request wake vortex reports from non-NATS airports in the UK.

NATS assesses all wake vortex encounter reports as soon as they are received for severity and then all severe reports are sent onto the appropriate ATC unit for investigation. In order to monitor the safety of current operations at that unit. NATS analyses the wake encounter reports on a quarterly basis. This analysis identifies any particular locations or altitudes where encounters are more likely to occur and determine changes in the wake vortex encounter rate for specific aircraft pairs. This process identifies any aircraft pairs which have a statistically significant increase in the encounter rate compared with previous years. Observed increases in the wake encounter rate for particular aircraft pairs has been used historically to successfully file for differences from the ICAO wake turbulence separation categories (e.g. the splitting of the Medium category).. Since January 2011, NATS have been working directly with a number of UK based airline operators and now obtains the recorded flight data for the wake encounter reports received or a summary of the aircraft performance during the encounter. This provides more objective data on the encounter which enables NATS to classify a much larger proportion of the reported wake encounters in terms of severity. In addition to standard monitoring and analysis activities, the wake vortex database is used for the following safety activities:

- Wake vortex encounters have been correlated with LiDAR data collected at Heathrow airport as part of the Time Based Separation safety validation activities. This has provided a unique opportunity to determine the wake vortex behaviour that directly results in a wake vortex encounter. Wake vortex encounter analysis has also been conducted on the wake vortex database in support of the Feasibility and Options stage of the NATS Procedural Time-Based Separation project.
- Since May 2010, NATS have continued to monitor the wake vortex encounter rate as part of the safety case for the Reduced Time Based Longitudinal Separation (RLongSM) trial.
- The wake vortex database is being used to monitor the number of reports in UK airspace where the A380 was the generating aircraft. The data may be used as evidence to support whether the ICAO recommended separations for the A380 to continue be adopted in the UK.

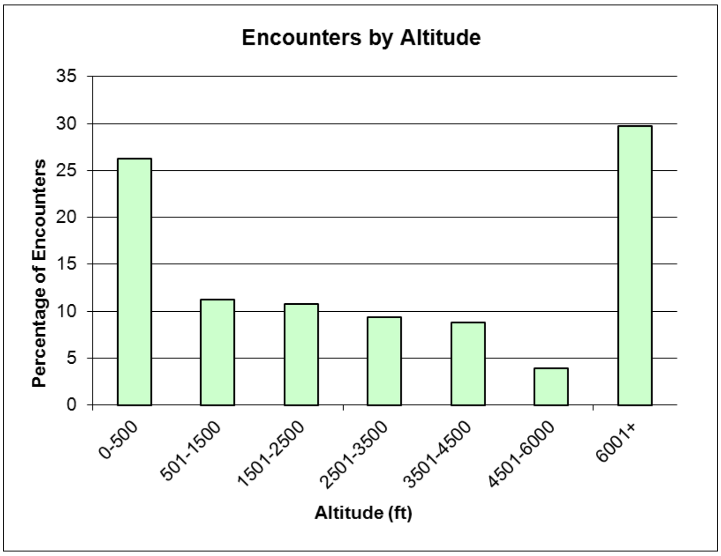

Figure 102: Percentage of the altitude of reported wake encounters from 2008 to 2010.

The majority of publications related to the wake vortex database are confidential to NATS. The graph in Figure 102 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 2008 to 2010 and it can be seen that around one quarter of all reports are from wake encounters at less than 500 ft. This peak may be expected because (i) 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 (ii) 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. Over recent years NATS have seen an increase in the number of wake encounter reports received where the affected aircraft was above 6000ft and therefore in the en-route (TMA and en-route airspace) phase of flight. This is demonstrated in Figure 102 as approximately 30% of the wake encounter reports received between 2008 and 2010 meet this criterion, some of which have caused injury to crew and passengers. The graph also shows that between joining the ILS and above 500 ft there is a relatively low probability of encountering wake vortex which would be expected since the vortices generally sink below the glideslope.

6.3.2.2 Wake Vortex Safety Management System requirements

The CREDOS project provides recommendations for a Wake Vortex Safety Management System for Air Navigation Service Providers with respect to safety policy; safety achievement; safety assurance; and safety promotion. This includes the specification of details for wake vortex safety data collection, data processing and statistical treatment of data to be processed and used as part of the wake vortex safety management system (Speijker, 2008). Such data can be used for wake vortex reporting systems, safety occurrence investigation, safety monitoring. ANSPs may collect and analyse: flight identification data, actual aircraft separation data, meteorological data, wake vortex encounter engineering data, wake vortex evolution data, traffic statistics data, operational practices and procedural data, aircraft configuration data, wake turbulence report forms, as well as data from hazard/risk identification brainstorms. Guidance for the design and set up of an ANSP wake vortex safety survey is also given. In this context, it is recommended to design a checklist and a questionnaire and to perform some statistical analysis on relevant causal factors and on actual aircraft separation data collected with a flight track registration system.

In case a new ATM operation with reduced aircraft separation (preferably supported by new wake vortex advisory systems) has actually been approved, a gradual transition phase from the current operation towards the new operation is proposed. During such transition phase, ANSPs are recommended to (Speijker, 2008):

- Perform *quarterly wake vortex safety surveys* to assess wake vortex safety of normal operations, using (wake vortex safety related) data available from:

  - Air traffic controller logs;
  - ANSP wake vortex safety survey checklists and questionnaires;
  - ANSP wake encounter reporting forms;
  - Flight track registration system data.
- Perform a *yearly analysis of wake vortex safety*. In addition to the above ANSP internal data sources, this could require (wake encounter) data from:
  - ICAO ADREP data;
  - JRC ECCAIRS data;
  - NLR ASR database information;
  - Pilot wake encounter reporting forms;
  - Quick Access Recorder (QAR) data;
  - Meteorological data sources;
  - WAVENDA analysis (Haverdings, 2010).

After the introduction of reduced aircraft separation (at least until it can be concluded that the actual implementation has actually been safe for a couple of years), the following wake vortex safety information will need to be provided on a regular basis (Speijker, 2008):

- Wake vortex safety survey results as part of quarterly safety bulletins;
- Wake vortex safety alerts to the air traffic controllers in case of safety findings and/or safety recommendations resulting from the wake vortex safety surveys;
- Wake vortex safety performance results as part of a yearly performance report.

In recent years, Safety Management Systems (SMS) have become widely used in aviation. After introduction in other domains, it is now also promoted by ICAO, FAA, IATA, FSF and national authorities to support/manage safety improvements. For wake vortex safety monitoring, methods should be put in place to detect changes in systems or operations which may require corrective actions to be taken. The maintenance of (wake vortex) safety records throughout the entire life cycle of a system should provide evidence and argumentation demonstrating that a system is safe for operational use. A complete WV Safety Management System, as proposed by CREDOS, would also require the following (Speijker, 2008):

- An ANSP is already required to have an operational SMS. Normal Operations Safety Surveys (NOSS) are being carried out on a regular basis, the resulting data are fed into the SMS database, and the Safety Manager is required to *add the WV component* to the NOSS.
- The ANSP maintains a database with incidents and accidents, which is accessible for the air traffic controllers, who are required to report on WV encounters and WV separation infringements using reporting forms. Safety performance indicators and targets are maintained and updated regularly.
- Willingness of airlines to provide Flight Data Analysis (FDA) or Flight Operations Quality Assurance (FOQA) data on wake vortex encounters for safety research investigation purposes and for inclusion into the ANSPs Wake Vortex Safety Management System database.

One should be aware that some of these assumptions are more realistic than others. As all the ANSPs in the ECAC region are formally required to implement the ESARRs, it seems reasonable to assume that most ANSPs are using an operational SMS and are also maintaining a database with incident and accidents. However, the willingness of airlines to make Flight Data Analysis (FDA) on wake vortex encounters available is, at present, relatively low due to confidentiality issues. In addition, it is noted that the use of supporting software and data(bases) may depend on commercial arrangements with the owners. Nevertheless, as wake vortex safety awareness within the aviation community increases, it is reasonable to hope that the above requirements for a complete WV SMS are satisfied in the near future. One should note that pilot reports have an added value compared to ATC reports, as they tend to include more details about the effect of the encounter on the aircraft. However, ATC reports are usually more accurate in the description of the actual separation. Pilots should be encouraged to fill in their Airline Safety Reports as wake turbulence report forms or use the ICAO report form, which is currently available.

6.3.3 Research Needs

It will be of particular importance to in-service monitoring that new WV separation procedures continue to show to be safe through quarterly and annual safety trend monitoring. It is still not clear for pilots how they can recognize a wake vortex encounter and distinguish such event from e.g. clear air turbulence. In support of WVE safety monitoring there is therefore a need to supplement the current subjective WVE reporting of pilots with a more systematic approach for monitoring WVEs. There is a need to develop on-board automatic recording of WVE events in such a way that they can be systematically processed after every flight and collected into a global WVE database to support future global WVE safety monitoring and WVE safety analysis activities. As parts of an Automatic WVE Reporting System it is suggested to include 3 elements: a) WVE Identification (including generator identification, b) WVE Severity Assessment, and c) data transmission, storage, and a link with safety management systems. A key enabler would be the current and future air-to-air data link standards. Further human factors research should be aimed at investigating how the reporting rate could be increased and how valid feedback should be provided to pilots and air traffic controllers reporting wake vortex encounters.

As part of WakeNet3, it was foreseen to use the well-known current best practices from the UK wake encounter reporting scheme as a starting point for wake incident reporting for Frankfurt airport. Lessons learnt from the attempted implementation of this incident reporting scheme should be shared with operational stakeholders to potentially help other. European airports with wake turbulence related capacity or safety problems to start their own reporting schemes.

7. Summary

This report describes the state-of-the-art and research needs associated with new operational concepts, their supporting systems, underlying technologies and safety aspects that are linked to aircraft wake turbulence and that are addressing the society's needs of a safe and efficient air transport system as expressed in the goals of the ACAREs group Flightpath 2050.

Encounters with wake turbulence pose a potential hazard for other aircraft including rotorcraft. It directly affects the safety of the air transport system and - by the way this risk is mitigated – has an important impact on airspace and airport capacity.

Based on the significant advances in wake vortex related research achieved in Europe and elsewhere within the last 15 years, activities have progressed from improving the physical understanding of the wake vortex phenomenon itself towards the development of new operational concepts and supporting systems that shall deliver safety and capacity benefits.

Operational changes taking into account wake turbulence aspects have been implemented in various regions of the world during the last few years. Examples include the introduction into world-wide service of the Airbus A380 with its associated safety case for wake turbulence (2008) and the wake-independent departure and arrival operations (WIDAO) in segregated mode at Paris CDG airport (2011). The broader concept of replacing the long-standing ICAO wake turbulence separation scheme – commonly referred to as "Recategorisation" – made significant advances given the dedication of EUROCONTROL and the FAA but its first phase has encountered important challenges and is hence delayed.

In line with this change of focus towards operational concepts and their implementation, and as a consequence of the enlarged diversity of involved disciplines, new research needs have arisen and are addressed in this report.

Uncertainties about acceptable means of compliances, detailed safety arguments and safety criteria seem to have replaced technological aspects from the top of the list of the most critical issues preventing measureable benefits becoming practice. These issues cannot solely be solved through general research but require successful implementations pursued by capable organisations since these become models and inherently define acceptable means of compliance once accepted by regulators. An obvious example is the 2011 wake turbulence safety case for the Boeing 747-8 which borrows its general approach – ground-based LiDAR measurements relative to the B747-400 – from the A380 safety case of 2008. A remaining challenge is the feed-back of detailed results into the research arena which requires that global networking and standardisation activities are continued and fostered.

Successful implementations thus form the basis for the further development of the more challenging new concepts that are promising the most important benefits. These concepts require support by dedicated systems, on the ground and in the air. They involve dedicated data exchange, advanced data processing as well as human operator alerting and support tools. Examples include ground-based advisory systems in support of pair-wise weather-dependent approach and departure separations, automated incident identification and reporting systems and airborne wake encounter hazard mitigation. Their ongoing development is linked with a continuing research need at technology level in what can be described the "traditional" fields of wake vortex research. They include, for example, meteorological data processing and prediction, operational wake vortex behaviour models, weather and wake vortex sensors, wake encounter hazard assessment and mitigation by flight control. But in contrast to the earlier days these fundamental research needs can now more directly be linked to the preparation of new operational concepts and hence be associated with specific benefits.

New challenges are on the horizon since ongoing initiatives like SESAR in Europe and NextGen in the USA will change the way in which air traffic is organised and with it the risk of hazardous wake turbulence encounters. The new systems under development to control and mitigate the wake turbulence risk must remain flexible enough to apply to new operational scenarios that are only in early definition today. And new operational concepts that are not specifically addressing wake encounter risk must carefully be designed to exclude any negative impact on the wake encounter risk, either by outright avoidance or by explicit treatment. Examples include new approach procedures as well as airborne self-separation.

Last but not least, a solid level of fundamental research, i.e. research not directly linked to operational concepts under development, should continue to be pursued since only this may uncover completely new approaches.

The state-of-the art review and individual European research needs identified in the body of this report can be summarized as follows:

Concepts

- Current concept developments should be continued until they become operational.

  Promising concepts have been identified and are under development. These primarily address wake encounter hazards during departure and arrival, hence in the vicinity of constrained airports. Their principle approach is to reduce wake turbulence separations specifically under favourable meteorological conditions and on average by implementing pair-wise separations, i.e. taking into account specific aircraft vulnerability and hazardousness.

- New concepts specifically addressing the wake encounter risk (safety) in the en-route phase of flight should be evaluated.

  Wake vortex encounters in cruise are rare, however they occur and their occurrence is expected to rise with increasing levels of traffic with potentially higher risks due to the increasing diversity of aircraft weights. Currently, there are no wake vortex separations defined for cruise flight and it has to be investigated whether this remains adequate. Current concept developments primarily address wake encounter hazards during departure and arrival, hence in the vicinity of constrained airports. While airborne systems promise to adequately address the wake encounter risk in the en-route phase of flight additional concepts not requiring the installation of new aircraft systems should be evaluated as well.

- Concepts based on new ground systems and those based on new airborne systems need to be further harmonised.

  Currently, both ground-based and airborne systems are under development. Ground-based systems are expected to be the optimal solution for constrained airports whereas airborne systems can provide safety and operational benefits in less constrained environments like smaller airports and during en-route operations for which ground-based solutions are either too costly or not practical. Additional research is needed to assure harmonization between airborne and ground-based wake vortex advisory systems and their individual contributions and roles as part of new wake turbulence separation rules.

- New concepts specifically addressing the wake encounter risk (safety) for helicopter operations (both as wake generator and encountering aircraft) should be evaluated.

  Wake turbulence also relates to helicopter operations which have specific differences compared to fixed wing aircraft operations.

- Concepts have to be expanded or newly developed that properly take into account changes in air traffic organisation and operations pursued as part of SESAR and NextGen.

  Several changes to the air traffic management and air traffic operation under preparation in SESAR and NextGen are expected to affect the wake encounter risk. Concepts currently under development for wake encounter risk management should be expanded to take into account these changes. In principle an assessment of potential impact on wake encounter risk should become a standard for all changes in aircraft airborne operations.

- The concept of a ground-based ATC alerting system applicable to today's ICAO wake turbulence separation system should be evaluated.

Safety gains may be feasible by implementing wake vortex warning systems independently of any change in wake turbulence separations.

- New concepts of reduced wake turbulence separation requirements due to accelerated wake decay through modifications of the ground surface geometry should be evaluated.

  Dedicated modifications of the ground surface geometry allow an acceleration and enhancement of vortex decay independent from environmental conditions. The installation of suitable obstacles at the runway tails has been demonstrated successfully in towing tank experiments and large eddy simulations but demonstration in a flight experiment is still pending.

Systems

- Development of ground-based advisory systems should be continued

  Ground-based advisory systems in support of new operational concepts for landing and departure wake turbulence risk mitigation are under development. Their development should be continued and necessitates further research in a number of underlying technologies and techniques, see further below.

- Development of airborne support systems should be continued

  Airborne advisory systems in support of new operational concepts for landing and departure wake turbulence risk mitigation as well as to mitigate the en-route phase of flight wake encounter risk are under development. Their development should be continued and necessitates further research in a number of underlying technologies and techniques, see further below.

- Additional research is needed to investigate the qualification process for new systems that affect wake encounter risk, and how such systems can be incorporated in the related regulatory framework.

Safety trend monitoring

For all endeavoured changes in wake turbulence separations it is mandatory to regularly monitor in-service that new separation procedures are safe.

- A more comprehensive wake vortex safety and incident monitoring system needs to be developed and established.

  There is a need to supplement or replace the current subjective and voluntary reporting of wake encounters by pilots and controllers by a more reliable system. For this, objective, automated wake vortex encounter reporting tools that are based on aircraft recorded data and that allow systematic processing and collection into a global database need to be developed.

Risk assessment methods

For all operational concepts affecting wake encounter risk there is a need to conduct a comprehensive risk assessment as part of a safety case. No generally accepted method and means of compliance exist for this today. A quite large number of different safety assessment methods have been developed in the past but only a few of them have been approved as part of a successful application. Today's risk assessment models do typically not take into account the effects of (future) advisory systems and aircraft controls. Also, future operational scenarios will lead to additional modelling requirements.

- Additional research is needed to establish guidelines towards generic, acceptable means of compliance and suitable risk assessment models.

  Benchmarking and sensitivity analysis of the available risk assessment models using standardised, realistic test scenarios can provide knowledge about which simplifications would be allowable and where the models would be sensitive to the modelling structure and parameters. Optimally, the activity could lead to the establishment of a toolset of models deemed suitable in the assessment of wake turbulence risk together with a comprehensive set of guidelines and building block arguments. The results of such an activity would help in the preparation of future approval processes and be especially useful in concept and system design.

Wake encounter severity metrics

Severity metrics link the acceptability of a wake encounter with measurable or derivable quantities and hence represent – next to wake behaviour models – a centrepiece in every wake encounter risk assessment. Today, there is still neither an agreed method for "measuring" (i.e. deriving from known consequences of an explicit encounter) nor for anticipating (i.e. predicting based on known influencing factors, especially vortex characteristics) the acceptability of a wake encounter in an absolute form. Current assessment methods focus upon relative comparisons of wake circulation at specified separation times used as anticipation metric. The inherent margins of using such simplistic severity metrics limit potential capacity and safety gains. Modern research methods are moving towards metrics that consider the encountering aircraft's roll inertia and wake induced roll.

- Further research and verification is required to establish agreed methods for measuring the acceptability of encounters (severity metrics).

  Metrics to objectively measure and compare wake encounter severity link encountering aircraft upset parameters with severity levels. They are required in monitoring functions and are a prerequisite to establish severity anticipation metrics (see below). They are to be established based on stakeholder involvement and expert input, aided by pilot-in-the-loop flight simulator experiments, with the simulation models validated against wake encounter flight test results.

  This includes analysing the data and results available worldwide and conducting additional human-in-the-loop tests under conditions and with parameters that have been agreed upon beforehand.

  Updated global guidance is required to establish acceptable metrics and methods for the evaluation of WVE risk to enable the assessment of emerging concepts for operational deployment.

- Further research and verification is required to establish agreed methods for anticipating the acceptability of encounters.

  To enable the assessment of emerging concepts that promise to deliver additional benefits it is necessary to develop and verify more advanced severity anticipation metrics. Severity anticipation metrics link vortex characteristics, encounter circumstances and encountering aircraft state parameters with encounter severity levels. They are to be established for a large variety of encountering aircraft types using wake encounter flight simulation models that have been validated against wake encounter flight test results.

- As the state-of-the-art in modelling has improved significantly over the last years, the advantage should be investigated i) of using more sophisticated models with higher fidelity and ii) of including models for manual or automatic control of the airplane as well as models for severity assessment, which are not included yet.

Wake encounter simulation

- Validation and improvements of various models used for wake encounter simulation (for example aircraft-vortex aerodynamic interaction, pilot behaviour modelling during wake vortex encounters or assessment of severity of wake vortex encounters).
- Further confidence has to be built that aerodynamic interaction models and vortex models used to simulate dynamic wake vortex encounters are correct. Ultimate validation should focus on flight test

results. Although considerable verification and validation work has already been performed the model quality should be further improved.

- Effects of the encountering aircraft on the vortex flow field should be investigated, e.g. by conducting CFD of aircraft wake interaction.

Wake vortex behaviour models

The role of wake vortex behaviour models towards providing safety evidence in support of safety arguments remains an important issue. The challenges associated with the validation of models such that the analysis results can be considered reliable enough to be used as safety evidence remains a research needs challenge.

- Modelling of wake vortex behaviour should be further improved

  Wake vortex decay and transport models are already quite mature and available to support new operational concepts. However, further improvements would enable a better modelling of the wake vortex behaviour, potentially allow increased benefits and have the potential to considerably reduce the need for wake vortex behaviour data collection campaigns. Additional studies should include the further characterisation of the vortex behaviour out-of-ground effect (OGE) in turbulent, stratified (stable or unstable) and sheared atmospheres and of the vortex behaviour in-ground effect (IGE) with head- and crosswind.

- Operational wake vortex models should be further advanced

  Use of wake vortex decay and transport models in ground-based or airborne systems requires the capability to compute in real-time large numbers of wake vortex predictions. Time consuming algorithms must hence be made more efficient in order to be in line with operational requirements. They need to be flexible with regard to varying levels of input data availability and accuracy. They need to be validated for different levels of application (safety net, capacity increase) and different phases of flight. Additional research must cover benchmarking, possibly adaptation and refinement of wake vortex predictor algorithms.

Wake vortex characteristics

- Vortex characteristics directly affecting wake encounter severity need to be determined for real aircraft of varying sizes and configurations

  Vortex characteristics other than circulation, like core size, spacing and tangential velocity distribution, are also important for the characterization of the encounter hazard and need to be established for arbitrary generator aircraft of varying sizes and configurations. Further improvement and validation of existing models could employ different methods: (i) highly resolving simulations considering the flow around the aircraft and the roll-up process, (ii) dedicated remote sensing measurements with e.g. LiDAR or (iii) with aircraft in-situ measurements employing dedicated sensors like a nose boom rake or (iv) tower fly by measurements with dedicated sensors. The vortex core could also be evaluated by pursuing the simulations of far wake vortex systems in turbulent equilibrium and on fine grids, also taking into account Reynolds number effects: to determine vortex core radius “as determined by the fluid mechanics in the far wake and also based on energy arguments (themselves related to induced drag)”.

Validation & development data collections

- Vortex measurements

Any validation of wake vortex models requires a high quality measurement database, both for the vortex characteristics (position and circulation) and the meteorological data. Ideally, each measurement is provided together with an estimate of its measurement error.

Meteo Data

- There is a need to establish cost effective approaches for the provision of the current and forecast glideslope wind conditions e.g. to support procedures/ systems like time-based separations. It should be investigated how wind data based on downlinked airborne measurements, on ground based wind profilers and on local numerical weather nowcasting can be combined in an optimal way.
- A stable and reliable prediction of the weather and in particular of the wind conditions is important which should be adapted to the needs of the ATC system
- Assessment of the spatial and temporal stability of the weather conditions allowing the reduction of wake turbulence separations
- Continued research is needed with regard to the real-time provision of fused meteorological data required for wake vortex predictions onboard aircraft. It is necessary to investigate how this can be derived on-board an aircraft using meteorological data disseminated through data links from multiple, dissimilar sources including air-to-air data link as well as data uplinks.
- Weather prediction methods in particular for wake vortex related quantities (wind, turbulence, thermal stratification) need to be improved. Data fusion methods for weather data nowcasting from several distributed sources (aircraft, ground stations...) need to be developed and validated as an enabler for airborne and ground-based applications.
- The utilization of the previous aircraft flying the approach path as meteorological sensors for the current wind conditions on final approach should be fully explored. This includes the utilization of the current enhanced Mode-S down-linked parameters. There is a need to establish whether these down-linked parameters are sufficiently dependable for utilization by safety related functions e.g. for calculating time based separations.
- Weather data acquired by airborne measurements should complement the ground based meteorological measurements and model based prediction thus increasing the confidence level and covering the area along the glide path. For this purpose, investigation of which airborne measurements can be provided and how they can best be integrated into the existing weather network is needed.
- Development of ADS-B (Automatic Dependent Surveillance – Broadcast) datalink is an opportunity to define each aircraft as a potential source of relevant MET information (wind, EDR,…). Technological challenges should be addressed to consider limited bandwidth in respect with requested high tempo of data downlink for safety nets.
- The accuracy of meteorological data measured by standard instrumentation of aircraft should be reviewed. The provision of the required parameters with the required resolution transmitted via ADS-B and/or AMDAR (Aircraft Meteorological Data Relay) should be advanced.
- Ensemble prediction methods should be employed to improve the prediction skill of average quantities and to quantify the predictability of specific weather situations in terms of the spread of these quantities. An economical approach for numerical weather prediction appears the combination of time-lagged ensembles and spatial ensembles enhanced by data assimilation schemes.
- In response to these needs, Combined Weather Monitoring and Prediction Systems should be evaluated. Algorithms to deduce robust eddy dissipation rate estimates from various measurement sources and forecast models should be developed.

Airborne wake vortex sensors

- Continued research is needed to advance the technology of forward-looking air data sensors. Airborne, short range, forward-looking air data sensors are required to enable novel technologies for the suppression of wake impacts, especially those affecting the roll axis, by flight control. Such sensors need to reliably measure air velocities in front of an aircraft during all phases of flight and with high availability and accuracy in the order of 1 m/s or below. LiDAR is regarded as a possible enabling technology. Sensor technology has the potential to apply to other aircraft flight control functions. Flight testing of on-board forward-looking sensors fully integrated with flight control should be conducted for feasibility demonstration.
- Continued research is needed to identify and advance fundamental technologies for the mid- to long-range detection, tracking and possibly characterisation of wake vortices. Such a sensor would enable novel airborne wake vortex concepts permitting wake avoidance based on measurement instead of model predictions, with the associated increase in accuracy and acceptance.
- Evaluation of advanced sensor-model-fusion technology to improve mid- to long-range sensor capability with regard to wake vortex detection, tracking and characterisation.

Ground based wake sensors

- Radar and LiDAR simulators should be developed, by coupling the 3D output of Large Eddy Simulations (LES) of ambient atmosphere with electromagnetic model taking into account the different scattering characteristics of each sensor. These simulators should be dedicated to assess capability of each sensor to detect wake-vortex and to retrieve Wind/EDR in different weather conditions and analyze their complementarities. These models should be validated and calibrated by sensors trials on airports.
- Range and probability of wake-vortex detection could be improved by power emitters/sources increase of respective X-band Radar and 1.5 micron LiDAR. These high-power sensors technologies should be developed at low cost for civil application. These sensors should be able to monitor in 3D based on agile scanning technology.
- Wake vortex detection, circulation retrieval and EDR assessment should be defined for new emerging Radar and LiDAR sensors. These processing techniques should be adapted for individual sensors or for collaborative suite of sensors. Upgrade of processing of existing sensors could be envisaged in an intermediate step.

Operational procedures/ human-machine-interface (HMI)

- Definition and assessment of the HMI and ATM component requirements and operational procedures allowing the air traffic controller to apply weather dependent wake turbulence separations
- The level of automation of the new procedures like time-based separations and procedure changing modes should be evaluated concerning to what is required and acceptable.
- Definition of the requirements and operational procedures allowing the flight crew to safely apply the controller proposed weather dependent wake turbulence separations.
- The monitoring function which is an important element of the safety system should be designed so as to be supportive to the controller.
- Additional research is needed with regard to the appropriate way of alerting pilots, the identification of a resolution manoeuvre and the necessary guidance for such a manoeuvre in case of airborne wake vortex system activation.

Wake alleviation at the source

Promising results have been obtained for wake vortex alleviation with specific concepts e.g. related to wing loading and multiple vortex pairs. The concept which appears to have the biggest potential is related to the dynamics of four-vortex systems. Future research should be pursued to carefully understand the mechanisms and check the efficiency of such concepts and devices in order to reach sufficiently high TRLs.

Wake impact alleviation

- Additional research is needed towards the real-time, online characterization of a wake vortex (determination of the wake properties like strength and position) based on multiple information sources including existing as well as novel aircraft sensors and using enhanced technologies like model-sensor filters. Such wake characterisation can provide significant benefits over directly using sensor measured velocities in combination with novel wake encounter alleviation flight control techniques.
- Evaluation of novel flight control concepts for improved stabilisation in wake encounter situations.
- Evaluation of the impact of the vortex flow field on aircraft air data sensors and associated effects on flight control stabilisation capabilities.

Data collections

- There is a need for a more automated and systematic process founded on standard data formats for the wake turbulence measurement data, the correlated aircraft data, and the correlated meteorological data. Automated methods need to be developed for data cleaning which automatically generate an auditable file to support the safety arguments and safety evidence requirements.

Meteo data base

- Meteorological data measurements are required for correlation with wake vortex behaviour measurements. Meteorological climatology information is required to support business case analysis activities and to identify and establish the range of meteorological scenarios that each of the wake vortex concepts needs to be subjected to in the validation activities.

Wake vortex behaviour data base

- There is still only a limited amount of wake turbulence behaviour measurement data being collected through measurement campaigns. This is a concern as this is holding back the wake vortex behaviour analysis activities that need to be conducted to generate the understanding and the evidence to satisfy the wake vortex encounter safety concerns and to support the wake vortex encounter safety arguments. Consideration should be given to how to cost- effectively carry out continuous and simultaneous data collections over several key sample positions on aircraft paths to be protected such as on the final approach path from turning on to join the localiser until touchdown, and on the initial departure path from take-off rotation until the departure aircraft diverge on to standard lateral or vertical separations. Data collections are required in a variety of atmospheric conditions and aircraft configurations to better understand the combined impacts of wind strength and direction and atmospheric turbulence with other meteorological conditions e.g. stratification.
- Measurements of wake vortex characteristics and evolution (decay and transport) and the corresponding meteorological conditions (wind, turbulence, eddy dissipation rate, temperature and temperature gradients) at high altitudes should be performed for model validation.

- More wake turbulence behaviour measurement data, correlated with meteorological data such as wind conditions, is needed to support safety cases.

Flight tests

- Wake vortex encounters in cruise should be investigated in flight tests and in flight simulators taking the impact of simulator limitations into account.
- Flight experiments should be conducted to derive vortex characteristics (see above in vortex model).

Wake encounter flight simulation

- The results of Large Eddy Simulations (LES) and of simplified operational models should be used in wake encounter studies. This can be done in flight simulators and compared to the results of flight experiments.

Training and awareness

- Wake vortex awareness and avoidance techniques should be developed and should be used to enhance regular airline pilot (and air traffic controller) training taking into account the improved understanding of encounter physics and operational implications.

Benefit assessments

- Assessment of the potential benefits for various airports considering the distribution of their wind conditions throughout the year

Capacity analysis methods and metrics

- Methods to account for diverse influencing factors like uncertainties, operational modes, airport design and procedures, traffic mix as well as the selected metric need to be refined. In order to produce comparable results a holistic methodology is recommended for future studies.
- Selected capacity metrics should be validated with regard to the real operational benefit representative of society’s need.

Exchange of information and availability of data

- The information and data which is available worldwide can be of high benefit for many purposes. First of all there should be an exchange on what is available in detail. In a second step the actual information and data could possibly be exchanged on a case-by-case basis.

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9. Glossary

ACARE	Advisory Council for Aeronautics Research in Europe
ACARS	Aircraft Communications Addressing and Reporting System
ADREP	Accident/Incident Data Reporting System
ADS-B	Automatic Dependent Surveillance Broadcast
AESA	Active Electronically Scanned Array
AIAA	American Institute of Aeronautics and Astronautics
AIM	Aerodynamic Interaction Model
AMAN	Arrival Manager
AMC	Acceptable Means of Compliance
AMDAR	Aircraft Meteorological Data Relay
ANS	Air Navigation Service
ANSP	Air Navigation Service Provider
APA	AVOSS Prediction Algorithm
APAWR	Active Phased Array Weather Radar
AOT	Airport Operations Team
ARSR	Air Route Surveillance Radar
ASAS	Airborne Separation Assistance System
ASAT	Airspace Simulation and Analysis for TERPS
ASR	Air Safety Report
ASR-9	Airfield Surveillance Radar 9
ATC	Air Traffic Control
ATM	Air Traffic Management
ATMOS	Air Traffic Management and Operation Simulator
ATPA	Automated Traffic Proximity Alert
ATS	Air Traffic Service
ATTAS	Advanced Technologies Testing Aircraft System
AVOSS	Aircraft Vortex Spacing System
AWIATOR	Aircraft Wing with Advanced Technology Operation
AWO	All Weather Operations
BAA	British Airport Authority
BADA	Base of Aircraft Data
CAA	Civil Aviation Authority
CAASP	Centre for Advanced Aviation System Development
CAP	CAA Publication
CASA	Centre for Collaborative Adaptive Sensing of the Atmosphere
CDG	Paris Charles de Gaulle Airport
CDM	Collaborative Decision Making
CONOPS	Concept of Operations
COSMO	Consortium for Small-Scale Modelling
CPU	Central Processing Unit
CREDOS	Crosswind Reduced Separation for Departure Operations
CROPS	Crosswind Operations
CS	Certification Specifications
CSPR	Closely-Spaced Parallel Runway
CW	Continuous Wave
D2P	Deterministic Two-Phase Wake Vortex Model
DAP	Downlink Aircraft Parameters
DAR	Digital Array Radar
DBF	Digital Beam Forming
DBS	Distance-Based Separations

DFS	DFS Deutsche Flugsicherung GmbH
DLC	Direct Lift Control
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DMAN	Departure Manager
DSNA	Direction des Services de la Navigation Aérienne
DTOP	Dual Threshold Operation
DVM	Deterministic Wake Vortex Model
DWA	Detection, Warning and Avoidance
EASA	European Aviation Safety Agency
EC	European Commission
ECAC	European Civil Aviation Conference
ECCAIRS	European Co-Ordination Centre for Aviation Incident Reporting Systems
EDDF	Frankfurt International Airport, ICAO-Code
EDR	Eddy Dissipation Rate
EGLL	London Heathrow Airport
EGPS	Enhanced Ground Proximity warning System
ERR	Equivalent Roll Rate
ESARR	EUROCONTROL Safety Regulatory Requirements
EU	European Union
EUROCONTROL	European Organisation for the Safety of Air Navigation
FAA	Federal Aviation Administration
FAF	Final Approach Fix
FANOMOS	Flight Track and Noise Monitoring System
FAR-Wake	Fundamental Research on Aircraft Wake Phenomena
FDA	Flight Data Analysis
FHA	Functional Hazard Assessment
FOQA	Flight Operations Quality Assurance
FP7	7th Framework Program of the European Commission
FRA	Frankfurt International Airport, IATA-Code
FSF	Flight Safety Foundation
GMU	George Mason University
GPS	Global Positioning System / Satellite Navigation
GPU	Graphical Processing Unit
GPWS	Ground Proximity Warning System
HALS	High Approach Landing System
HERMES	Heuristic Runway Movement Event Simulation
HIL	Human In-the-Loop
HMI	Human Machine Interface
IAH	Houston International Airport
IAT	Inter Arrival Times
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IFR	Instrument Flight Rules
IGE	In Ground Effect
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
IR	Implementing Rules; also: Infrared
ITWS	Integrated Terminal Weather System
JAA	Joint Aviation Authorities
JAR	Joint Aviation Requirements
JAXA	Japan Aerospace Exploration Agency
LES	Large Eddy Simulation

LFPG	Paris Charles de Gaulle Airport
LHR	London Heathrow Airport
LiDAR	Light Detection And Ranging
LMU	Ludwig-Maximilians-Universität München
LOS	Line of Sight
LOSA	Line Operations Safety Audit
LLWAS	Low Level Wind Shear Alert
LTI	Landing Time Interval
MEM	Memphis International Airport
MET	Meteorological
MOPA	Master Oscillator- Power Amplifier
MPAR	Multifunction Phased Array Radar
MSL	Modified Staggered Left
MTOW	Maximum Take-Off Weight
N	Brunt-Väisälä Frequency
NASA	National Aeronautics and Space Administration
NATS	National Air Traffic Services
NCAR	National Center of Atmospheric Research
NERL	NATS En-route Plc.
NGE	Near Ground Effect
NLR	Nationaal Lucht- en Ruimtevaartlaboratorium
NOSS	Normal Operations Safety Surveys
NOWVIV	Nowcasting Wake Vortex Impact Variables
NRC	National Research Council Canada
NWRA	NorthWest Research Associates
OCD	Operational Concepts Document
OCM	Optimal Control Model
ODE	Ordinary Differential Equation
OGE	Out of Ground Effect
ONERA	Office National d'Études et de Recherches Aérospatiales
OSED	Operational Service and Environment Definition
P2P	Probabilistic Two-Phase Wake Vortex Model
PANS	Procedures for Air Navigation Services
PIO	Pilot-Induced Oscillation
PPI	Plan Position Indicator
PRM	Precision Runway Monitor
PSSA	Preliminary System Safety Assessment
PU	Public
PVM	Probabilistic Wake Vortex Model
PWS	Pair Wise Separation
QAR	Quick Access Recorder
RADAR	Radio Detection And Ranging
RASS	Radio Acoustic Sounding System
RBT	Reference Business Trajectories
RCR	Roll Control Ratio
RECAT	Re-Categorization
RFAS	Reduced Final Approach Separation
RHI	Range Height Indicator
RLongSM	Reduced Time Based Longitudinal Separation
RMS	Root Mean Square
RNAV	Area Navigation
ROT	Runway Occupancy Times

RTCA	Radio Technical Commission for Aeronautics
RTS	Real Time Simulation
RWY	Runway
SAM	EUROCONTROL Safety Assessment Methodology
SARPS	Standards and Recommended Practices
SES	Single European Sky
SESAR	Single European Sky ATM Research
SFO	San Francisco International Airport
SHAPe	Simplified Hazard Area Prediction method
SID	Standard Instrument Departure
SJU	SESAR Joint Undertaking
SME	Small and Medium Enterprises
SMS	Safety Management System
SODAR	Sound Detection And Ranging
SOIA	Simultaneous Offset Instrument Approaches
SPR	Safety and Performance Requirements
SRC	Safety Regulation Committee
SRA	Strategic Research Agenda
SRIA	Strategic Research and Innovation Agenda
SRO	Simultaneous Runway Occupancy
SSEP	Self Separation
STG	Staggered
SWIM	System Wide Information Management
SYNOP	Surface Synoptic Observations
TAAM	Total Airspace and Airport Modeler
TASS	Terminal Area Simulation System
TAWS	Terrain Awareness and Warning System
TBS	Time-Based Separations
TCAS	Traffic Collision Avoidance System
TDAWP	TASS Driven Algorithm for Wake Prediction
TDWR	Terminal Doppler Weather Radar
TEMP	Upper Air Soundings
TERPS	Terminal En-Route Radar Procedures
TKE	Turbulent Kinetic Energy
TMA	Terminal Manoeuvring Area
TRL	Technology Readiness Level
TSO	Technical Standard Order
TUB	Technische Universität Berlin
TUBs	Technische Universität Braunschweig
UCL	Université Catholique de Louvain
UK	United Kingdom
US	United States
USA	Ultra Sonic Anemometer; also: United States of America
UV	Ultraviolet
VAD	Velocity Azimuth Display
VESA	Vortex Encounter Severity Assessment by Airbus
VIPER	Fast-time Wake Vortex Model by NWRA
VLJ	Very Light Jet
WAKESCENE	Wake Vortex Scenarios Simulation Package
WAKE4D	4D Wake Vortex Transport and Decay Simulation Platform
WAVENDA	Wake Vortex Encounter Detection Algorithm
WaVoP	Wake Vortex Prediction model

WAVIR	Wake Vortex Induced Risk assessment
WDS	Weather Dependent Separation
WEAA	Wake Encounter Avoidance and Advisory system
WEPS	Wake Encounter Prevention System by Airbus
WHAS	Weather Hazard Advisory System
WIDAO	Wake Independent Departure Operation
WN3E	WakeNet3-Europe
WSP	Weather Systems Processor
WSVBS	Wake Vortex Prediction and Monitoring System
WSWS	Wirbelschleppen – Warnsystem (Wake Vortex Warning System)
WTMA	Wake Turbulence Mitigation for Arrivals
WTMD	Wake Turbulence Mitigation for Departures
WTR	Wind Temperature Radar
WV	Wake Vortex
WVAS	Wake Vortex Advisory System
WVDSS	Wake Vortex Decision Support System
WVE	Wake Vortex Encounter
WVM	Wake Vortex Model
WVTF	European Wake Vortex Task Force

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