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Aircraft trailing vortices/Tourbillons de sillages d'avions

Research towards a wake-vortex advisory system for optimal aircraft spacing

Thomas Gerz [a,*], Frank Holzäpfel [a], Wayne Bryant [b], Friedrich Köpp [a],
Michael Frech [a], Arnold Tafferner [a], Grégoire Winckelmans [c]

[a] *Deutsches Zentrum für Luft- und Raumfahrt, Institute of Atmospheric Physics, Oberpfaffenhofen, 82230 Wessling, Germany*
[b] *National Aeronautics and Space Administration, Langley Research Center, Hampton, VA 23681, USA*
[c] *Mechanical Engineering Department, Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium*

Abstract

Wake turbulence is a major concern for busy airports since it limits capacity. Solutions for new aircraft staggering procedures are sought which relax the current separations but keep safety on a high level. Systems which advice air-traffic control on wake-vortex behaviour under present and expected weather conditions will, hopefully, contribute to such a solution. Knowledge on transport and decay of wake vortices in the atmosphere is presented. Concepts and designs of wake-vortex advisory systems in Europe and the USA are outlined. European wake-vortex measurement and prediction campaigns are described where the components of such systems have been tested successfully. ***To cite this article: T. Gerz et al., C. R. Physique 6 (2005).***

Résumé

Recherches sur des systèmes de détection des tourbillons pour réduire les distances de séparation entre avions. L'un des principaux objectifs des recherches sur les tourbillons de sillages d'avions est l'assouplissement des normes qui fixent les distances de séparation entre avions, à l'atterrissage et au décollage. Ces changements doivent en même temps assurer une amélioration de la sécurité en regard du danger que représentent les tourbillons de sillage. La réalisation de ces objectifs s'appuie en particulier sur le développement de systèmes opérationnels de détection et de caractérisation in situ des tourbillons, systèmes qui doivent être couplés à une capacité de prévision de la météorologie locale. On effectue dans cet article une revue des effets de l'environnement atmosphérique sur la dynamique des tourbillons. On décrit ensuite divers systèmes de détection et de décision développés en Europe et aux USA. On présente notamment quelques résultats de campagnes de mesure réalisées pour valider diverses composantes de ces systèmes. ***Pour citer cet article : T. Gerz et al., C. R. Physique 6 (2005).***

Keywords: Aircraft wake vortices; Atmosphere; Air traffic control; Optimal aircraft spacing

Mots-clés : Tourbillons de sillage ; Atmosphère ; Contrôle aérien

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[*] Corresponding author.
E-mail address: Thomas.Gerz@dlr.de (T. Gerz).

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1. Introduction

Wake vortices are generated unavoidably by an aircraft as a consequence of its lift. Whereas the topology of the young wake reflects the wing architecture and details of the wing configuration, it turns out that the circulation of a vortex of the mature wake can be described by ‘global’ parameters, such as aircraft weight, speed, and span. A wake vortex is potentially hazardous because of the rolling moment it may impose on a following wake encountering aircraft. Therefore, the International Civil Aviation Organisation (ICAO) put into force separation standards between leader and follower aircraft for approach, landing and take-off to allow safe flight operations. Aircraft are grouped into three weight classes with assigned static separations varying between 2.5 (the ‘radar separation’) and 6 nautical miles for approach and landing. These separations must be observed when the airport operates under instrumented meteorological conditions. When visual conditions apply, the separations may be relaxed on pilot’s request.

Today, the capacity of busy airports is often limited by the separation rules. It turns out that the rules are over-conservative under many meteorological conditions since wind and turbulence often account for sufficient drift and decay of the vortices. On the other hand, when the cross-wind is low and the atmosphere is calm (no turbulence) and thermally neutrally stratified, intense vortices may persist around the glide path for longer times than anticipated by the current separation rules. Hence, aircraft wake vortices are a concern for aviation both in terms of capacity and safety. It is a relevant economic factor for airlines, air safety providers and airports, so much the more as the air transportation market is expected to expand strongly in the future. This pressure motivates the stakeholders as well as the aviation authorities to find a solution of the wake turbulence problem for an efficient air traffic management. The research community came up with the hypothesis that airport capacities can be increased whilst at least maintaining today’s high safety levels with a smart combination of forecast and observation tools for wake vortices and the local weather around airports, joint by advanced aircraft performance and guidance capabilities, and a smooth integration of these tools into the air traffic control (ATC) environment which would allow dynamic (weather depending) separations between aircraft.

Such a wake-vortex advisory system would be a solution to dynamically optimise aircraft spacing during approach, landing and take-off. The requirements related to such a system are threefold: First, the wake-vortex behaviour under varying meteorological conditions must be understood, predicted for sufficient time in advance, and monitored at the airport site and/or from the aircraft [1]. Second, from an ATC operational point of view [2], such a system must be reliable and robust in terms of the predicted safe separations between aircraft pairs, the forecast horizon for separations, and the forecasted changes from one separation procedure to another. Third, the International Federation of Air Line Pilot’s Associations (IFALPA) would accept reduced separations between aircraft if it can be shown that, within probability bounds, wake vortices have either left the flight corridor or decayed to the level of ambient turbulence.

The paper has the objective to summarise efforts undertaken in Europe and the USA in conceptually sketching, building and testing wake-vortex advisory systems for ATC. In the USA, the Aircraft Vortex Spacing System (AVOSS) was developed and employed by the National Aeronautics and Space Administration (NASA) to demonstrate a real-time wake behaviour and detection system [3]. The project finished in August 2000 with a demonstration of feasibility and potential capacity gains at the Dallas-Fort Worth International Airport. As the follow-on activity, the *Wake Turbulence Research Program* was jointly established by NASA and the Federal Aviation Administration (FAA) [4]. It elaborates strategies for short-term, mid-term and long-term solutions of the problem where emphasis is now put on concepts directly relevant for ATC. The very first attempt, though, was the Vortex Advisory System for a single runway at Chicago O’Hare Airport which relied on wake transport following the concept of a ‘wind ellipse’ [5]. In Europe, the French concept *Système Anticipatif de Gestion des Espacements* aimed at reduced separations for departing aircraft based on wind measurements and a wake vortex transport model [6]. In Germany, the Wake Vortex Warning System has been developed under contract by DFS Deutsche Flugsicherung GmbH for aircraft approaching the closely spaced parallel runways at Frankfurt Airport [7]. The system aims at the independent use of the two parallel runways under favourable (low) cross-wind conditions. Other work is mainly conducted within national projects like *Wirbelschleppe* (*Wake Vortex*) of the Deutsches Zentrum für Luft- und Raumfahrt (DLR) and in projects like *WAVENC*, *S-Wake*, *ATC-Wake*, *M-FLAME* and *I-Wake*, co-funded by the European Commission and the project partners. These projects aim at the understanding of wakes in the atmosphere, the safety assessments for approach procedures and the determination of encounter probability and severity, the development of a system to predict and monitor wake vortices and its integration in an air-traffic control environment, and the development and test of a ground-based as well as air-borne wake vortex detection system based on a Doppler LIDAR (light detection and ranging) with a pulsed laser. Finally we note that research between Europe and the USA is co-ordinated by two wake vortex networks, *WakeNet2-Europe* and *WakeNet-USA*.

To complete the overview, we remark the tremendous research which has been and is performed on the subject of wake-vortex alleviation by constructive measures on aircraft configurations. Refs. [8,9] give an overview over the respective work in America and Russia. In Europe the projects *EUROWAKE*, *C-Wake* and *AWIATOR* aimed at controlling the wake vortices and searching devices for wake minimisation at the origin. The Office National d’Etudes et de Recherches Aérospatiale (ONERA) in

France is conducting national programmes in this matter, as well as fundamental wake-vortex research [10], and a joint project has been established in the framework of the ONERA–DLR Partnership in Transport Aircraft Research [11].

Section 2 summarises the physics of trailing wake vortex pairs in the atmospheric boundary layer. Section 3 outlines concepts for wake vortex advisory systems and describes the technical components for weather and wake prediction and observation as well as safety assessment. Section 4 shows results obtained during three European field campaigns, and Section 5 describes the efforts undertaken in the USA to design and develop a wake-vortex avoidance system. Section 6 concludes the paper.

2. Wake vortices in the atmospheric boundary layer and encounter probabilities

It is evident that the atmosphere has a strong impact on drift and decay of aircraft wake vortices. The key atmospheric parameters that influence vortex transport and lifetime are ambient wind, turbulence, wind shear and thermal stratification. The physics of wake vortex decay in the atmosphere is now well understood [12–18]. Generally, it is the interaction of the (primary) wake vortices with ambient atmospheric turbulence, thermal stratification, engine jets etc. which forms coherent secondary structures of azimuthal and vertical vorticity which wrap around the primary (axial) vortices and penetrate into the vortex oval [19]. The underlying mechanism is vortex stretching and tilting. Vertical streaks of counter-rotating vorticity are generated midway between the wake vortices that are effective in exchanging fluid in between the wake vortex pair. This exchange of fluid across the centre plane enables the rapid mutual compensation of wake vortex intensity.

Wind shear or wind-shear layers are candidates that may cause tilting of the vortex pair, accompanied by increased vortex separation and larger lifetimes of one of the vortices; furthermore, vortices may rebound or stall in shear layers [20–23]. The vortex with the same rotation sense as the background shear layer penetrates through the layer and continues its descent while drifting with the wind. The vortex with a rotation opposite to the shear layer decelerates, stalls and eventually may rebound. Parametric investigations carried out by numeric simulation have demonstrated that vortex trajectories are very sensitive to vortex and shear layer parameters [24]. From an operational point of view neither predictions nor actual measurements can be accurate and representative enough to allow one to forecast the trajectory of a vortex which interacts with background wind shear in a deterministic manner. Similar arguments hold for the impact of atmospheric turbulence on the wake vortex evolution. Since the dynamic and thermodynamic processes in the atmospheric boundary layer are highly stochastic at temporal and spatial scales at which the trailing vortices evolve, also the prediction of wake vortices must be probabilistic.

Cross-wind carries the vortices away from the flight corridor. An analysis [25] of observed wake vortices out of ground proximity (from data bases collected at Memphis Airport) revealed that a cross-wind of 2 m/s is sufficient to carry away all vortices out of the corridor of ±30 m width in less than 70 s such that the next aircraft can safely follow in 2.5 nautical miles distance. Climatology surveys show that such cross-wind levels exist in many major airports around the world [26]. Moreover, a downward trailing vortex pair tends to clear the glide path vertically (unless it hits the ground). On the other hand, if only wake demise is considered, the Memphis data also indicate that at best 88% (70%) of the vortices are decayed for a combination of medium-weight (heavy-weight) aircraft behind heavy-weight aircraft separated by 5 (4) nautical miles [25,27]. This implies that even for aircraft which are separated according to the ICAO rules, a fraction of the vortices still possesses significant intensity. However, the interaction of the atmospheric turbulence with the trailing vortex pair does not only provoke vortex decay, but, beforehand, results in a quick loss of alignment and a reduction of coherence of the vortices as the atmospheric eddies locally deform parts of the vortex tube by advection. Flight observations and results from computer simulations clearly show that turbulence in convective (thermally unstable) weather situations enforces a strong deformation and decay of the vortices throughout the boundary layer [16,17]. In American and European flight tests one could further observe that the vortex tubes are twisted and turned already by weak atmospheric eddies at least at low altitudes (below about 300 m).

Hence, even in the case of weak cross-wind, reduced vertical vortex descent, and long-living wake portions, the ICAO separations – and most of the time also the 2.5 nautical miles separation applicable under visual flight rules – are safe because (a) the wake vortices loose coherence and become patchy; (b) the probability to encounter those patches is already small; (c) the probability that the fuselage hits the vortex core (to induce maximum roll moments) is even smaller; and finally (d), the exposure time is very short compared to the time needed to cause significant roll due to the inertia of the aircraft. We conclude that even when an aircraft encounters a vivacious section of a vortex on final approach, it will not automatically roll or pinch in a dangerous manner [28]. The wake turbulence incident and encounter statistics confirm that reasoning: No major incidents or accidents have ever happened when pilots obey the ICAO separation rules. Moreover, an evaluation of several thousand flight data records conducted in *S-Wake* [27] showed that aircraft do encounter wake vortices during approach statistically a few times a day at a large airport (about 4 to 5 encounters out of 700 landings) but the crews do not recognise these harmless encounters as wake turbulence but as atmospheric turbulence.

To sum up, the mechanisms rank as (i) horizontal transport; (ii) downward vertical transport; (iii) vortex tube deformation (loss of vortex alignment); and (iv) wake vortex decay. In altitudes lower than about one wing span, the vortices are also in contact with the surface, which results in an additional (reduced) lateral drift of the lee (luff) vortex, a rebound away from the ground and an accelerated decay compared to low turbulence conditions. Hence, for vortices in ground proximity the mechanisms above are altered as (i) is reduced, (ii) is not effective or reversed, (iii) is increased and (iv) remains unchanged or is increased.

3. Concept and functionality of key elements of a wake-vortex system

An ATC system for dynamic aircraft spacing operations has to predict the transport and decay of aircraft vortices along take-off routes and glide paths with a forecast horizon of a few minutes up to an hour. Monitoring of wake vortices should allow one to assess the behaviour of the vortices from the point where aircraft intercept with the glide path (at about 1200 m height) down to the runway threshold. The system must be reliable, robust, and economically feasible in order to enable its usage within air traffic management procedures. Fig. 1 [29] sketches the principal components of such a Wake Vortex Prediction and Monitoring System, WVPMS. The WVPMS delivers its output, i.e., a proposed safe aircraft spacing for a given runway layout and a certain time horizon, to the air-traffic controllers. Next, the key elements of such a system as sketched in the figure are described in detail.

3.1. Weather forecasting

The basis for prediction of wake-vortex behaviour is the knowledge of the key meteorological parameters as function of forecast time, location and height. This information in principle can be provided by extrapolating the measurement data to obtain the future atmospheric state (persistency forecast) [30,31] which is suitable for forecast horizons of several minutes as, e.g., needed for aircraft departures. The other method is to numerically solve the basis equations which approximate the atmospheric state (i.e., its momentum, mass, heat, water content) as done in weather forecast models. This method is appropriate for air-traffic scheduling purposes with a time horizon of one or more hours.

The prediction of a future state of the atmosphere with a numerical forecasting system is in mathematical terms an initial-value and boundary-value problem. Short-term forecasting (or ‘nowcasting’) the weather in a local area like an airport environment is particularly delicate since it requires an adequate spatial resolution of local details in orography, land-use, and soil type to compute correct fluxes of kinetic energy, sensible and latent heat, and turbulence from the surface into the atmosphere and vice versa. Further, a sufficient temporal resolution of all meteorological parameters at the lateral boundaries is necessary to capture frontal passages and smaller-scale events like, e.g., thunderstorms which travel from outside into the forecast domain.

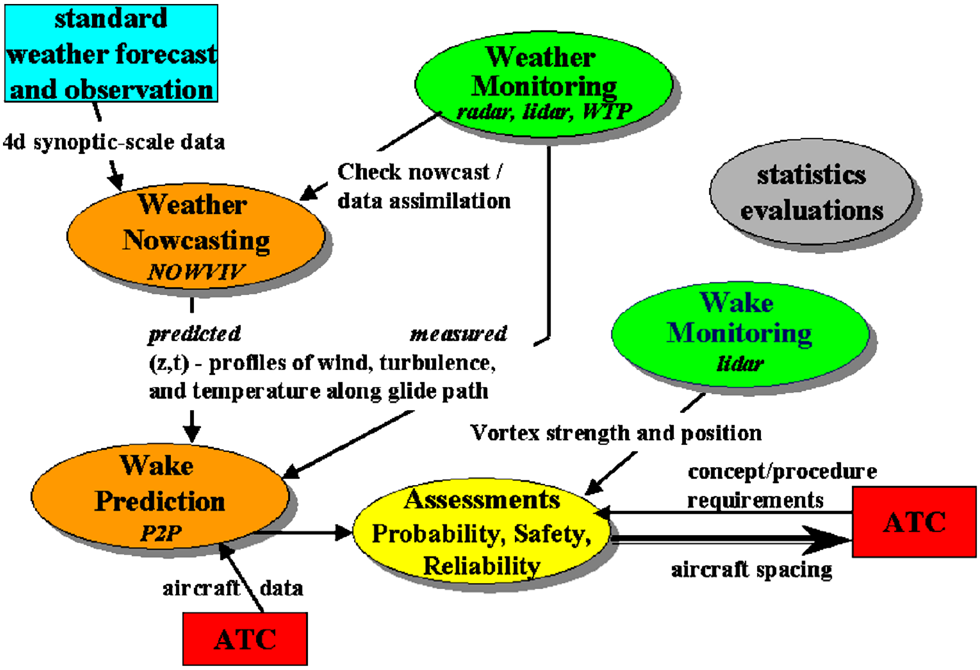

Fig. 1. Concept of a wake vortex prediction and monitoring system (WVPMS).

The level of turbulence in the atmospheric boundary layer is the key quantity to predict wake vortex decay. Measures of turbulence are the kinetic energy of the small-scale eddies (turbulence kinetic energy, TKE) and the rate at which the energy of these eddies dissipates (energy dissipation rate, EDR). For aircraft wake vortices the atmospheric eddies in the scale range of one metre to a few hundred metres (i.e., from vortex core size to some aircraft spans) are responsible for vortex deformation and dissolution. Averages in time should correspond to the typical vortex life time, hence 2 to 3 minutes. However, in meteorology turbulence quantities are typically averaged over 30 minutes, hence including fluctuations which are by far too large for the dimensions of a trailing vortex pair. It is appropriate to use EDR as the turbulence measure in the wake vortex context in order to reduce the effect of an averaging window on the result obtained. If the flow obeys Kolmogorov's inertial sub-range theory the choice of EDR would be ideal because the result indeed does not depend on the averaging window as long as it lies within that sub-range. The EDR concept works quite well under turbulent atmospheric conditions but it may fail when the turbulence is weak and sporadic and basic assumptions are not fulfilled. Moreover, measurements tend to overestimate EDR when the turbulence levels are low. Pragmatic parameterisations of EDR may be acceptable for operational solutions as long their limits are understood.

DLR has developed the weather-nowcasting system NOWVIV (nowcasting of wake vortex impact variables) by considering all these requirements. The kernel of NOWVIV is a version of the mesoscale model MM5, developed at the Pennsylvania State University and the National Center of Atmospheric Research, as used by the Forecasting System Laboratory in the National Oceanic and Atmospheric Administration in the USA [32]. NOWVIV has been adapted to particular sites in Europe (Oberpfaffenhofen and Frankfurt in Germany, Tarbes in France) taking into account detailed terrain, land-use, and soil-type information. In order to capture advective weather features, as, e.g., fronts, and adequately represent their evolution by the models' physics before they enter the terminal area of the airport, two model domains have been centered on each airport site, see Fig. 2. The outer domain and the inner 'nest' have horizontal grid resolutions of 6.3 and 2.1 km, respectively. Each of them has 40 grid points in both horizontal directions and covers a domain of about 245 and 80^2 km^2. The domains interact 'two-way', i.e., computed quantities in the nest are fed back to the outer domain. As a good representation of the boundary layer is of particular importance for predicting wake vortex impact variables, a quite high vertical model resolution has been chosen for the lower model atmosphere, starting with 8 m at the ground and increasing to about 50 m at 1 km and nearly 100 m at 2 km height. For initial and boundary conditions, NOWVIV employs data from the operational weather forecast model ('Lokalmodell', LM) of the German Weather Service [33]. LM covers most of the area of Europe, has a resolution of 7 km horizontally and increases

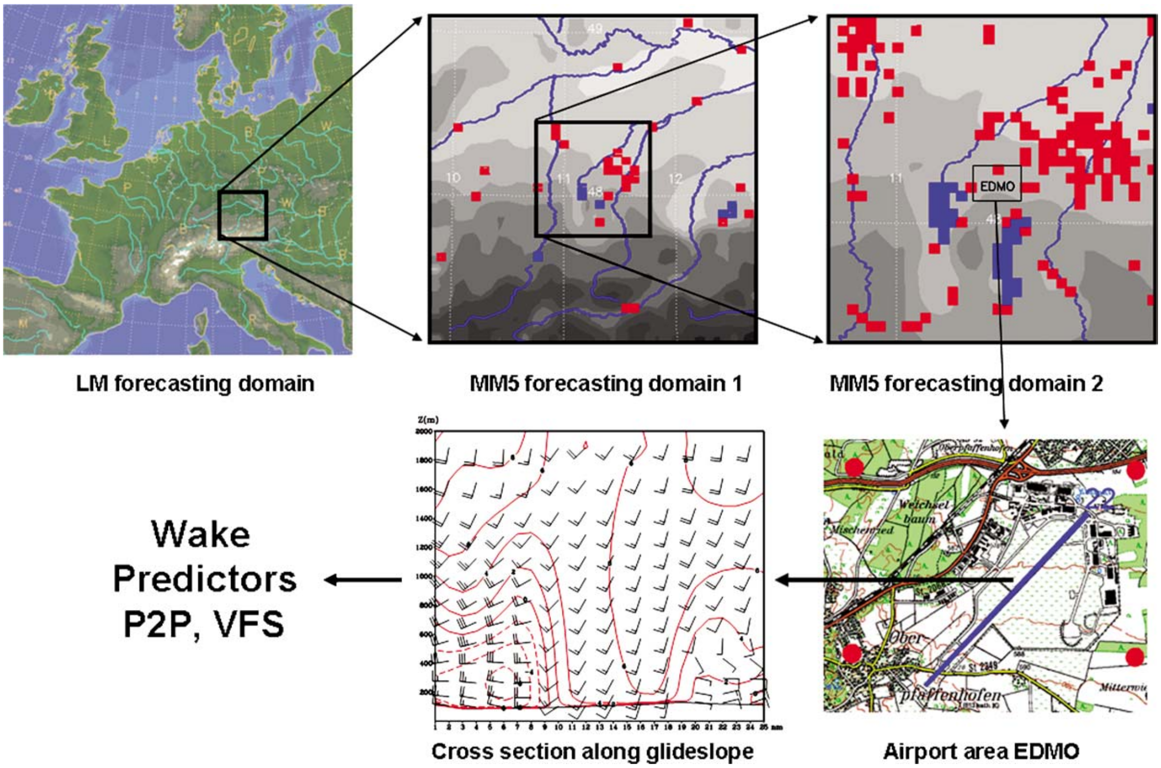

Fig. 2. Logic and processes in the NOWVIV model chain.

vertically from about 60 m at the ground to 200 m at 1 km and 400 m at 2 km altitude. A new set of forecasted quantities is provided every 12 hours which serve for updating the boundaries of the MM5's outer domain at 1 hour time increments. At grid points surrounding the runway and the glide slopes time series of vertical profiles of wind, virtual potential temperature, turbulence kinetic energy, and eddy dissipation rate are computed. At output NOWVIV transfers these wake vortex impact parameters in 10 minutes intervals to the parametric wake-vortex transport and decay models P2P and VFS, see Section 3.3.

3.2. *Weather monitoring*

Besides a weather forecasting tool, a WVPMS further requires meteorological measurement equipment which is capable of monitoring the key quantities in the terminal area from ground up to at least 1200 m altitude with an adequate temporal and spatial resolution. Such sensors are wind and temperature profilers, as RADAR (radio detection and ranging) and SODAR (sound detection and ranging) combined with a RASS (radio acoustic sounding system), wind LIDAR, and sensors installed in commercial aircraft.

A SODAR emits an (audible) acoustic pulse in the frequency range of about 1500 to 4500 Hz into the atmosphere and receives a back scattered signal caused by natural atmospheric turbulence. Scattering of the acoustic waves occurs while the pulse propagates through natural density fluctuations. The received acoustic signal is shifted in frequency (Doppler Shift) from the emitted signal which allows one to determine the velocity of the air mass. SODAR use 3 or 5 beams with one beam pointing vertically and with the other beams tilted by about 5 to 10° and different by 90° in azimuth to obtain the three orthogonal components of the wind vector. The RASS technique relies on RADAR waves which are back scattered on artificially generated sound waves (e.g., by a SODAR); the propagation speed of sound is measured from which the virtual temperature can be inferred. This back scattered signal shows much better statistical properties compared to the SODAR or RADAR signal. The RASS effect requires that the RADAR wave length must be exactly two times of the acoustic wave length in order to allow a constructive interference (Bragg condition) [34]. Depending on equipment, configuration and analysis technique a SODAR/RASS can provide 2–10 min averages of wind and temperature profiles with a vertical resolution of 10 to 50 m. The variance of a (e.g., vertical) velocity component serves as a measure for turbulence.

A Doppler LIDAR emits light into the atmosphere and receives the signals reflected by aerosols and small dust particles. The Doppler shift between the transmitted and received signals is a measure of the velocity of the air volume which contains the reflecting material along the line-of-sight (LOS) of the laser beam. Such a system is capable to measure both the ambient wind and the velocity signatures of wake vortices. The 2 µm pulsed Doppler LIDAR developed by DLR is based on the transceiver unit MAG-1 from CLR Photonics [35]. It transmits pulses of 2 mJ energy and 500 ns length into the atmosphere with a pulse repetition rate of 500 Hz. The transmit-receive telescope is an off-axis type with an aperture of 108 mm. The amplified return signal and the reference signal are fed to the data-acquisition and recording unit where it is sampled with a rate of 500 MHz [36]. The LOS spatial resolution is 3 m. The DLR LIDAR operates either in a conical scan mode, where the laser beam points upward and, moving around a cone, measures vertical profiles of the three wind components and turbulence above the LIDAR [37], or in a vertical scan mode, where the laser pulses oscillate between elevation angles of 0 to 30° and, hence, measure vertical profiles of the LOS velocity (i.e., one component of the roughly horizontal wind vector). Two independently programmable rotating wedges allow the switching between the modes. In the atmospheric boundary layer, the range of the pulsed LIDAR is more than 10 km to measure wind velocities; it is limited to about 2 km for measurement of the velocity signatures of aircraft wake vortices due to the increasing separation of the measurement radials with increasing range. From the Doppler LOS velocities also height profiles of the turbulence energy dissipation rate (EDR) can be obtained with a relative error of about 33% when the level is about $10^{-5}\ \mathrm{m}^2/\mathrm{s}^3$ or larger [38].

AMDAR data (Aircraft Meteorological Data Relay) [39], which are collected by aircraft of commercial airlines, have the advantage to deliver measurements along the glide slope where the wake vortices evolve. Measured and transferred data include time, position-latitude, position-longitude, pressure altitude, wind speed and direction, and static air temperature. Transmission of humidity and turbulence data (EDR) is planned but not yet put into practice. A major drawback is the relatively coarse vertical resolution of roughly 100 m. In future, AMDAR will classify EDR values in 7 turbulence classes ranging from EDR smaller than 0.001 to EDR larger than $0.512\ \mathrm{m}^2/\mathrm{s}^3$. However, since the measurement range required for vortex prediction is roughly 10^{-6} to $0.05\ \mathrm{m}^2/\mathrm{s}^3$, the lowest turbulence class will be insufficient. Furthermore, manoeuvre loads during approach significantly adulterate the EDR measurements and the averaging time during approach is too small to obtain meaningful EDR values [40].

3.3. *Real-time prediction of wake transport and decay*

The primary objective of a parametric wake vortex model is to reliably predict vortex positions and strengths in real-time in order to guide readjustment of aircraft separations. For this purpose, the model should consider all effects of the first order impact parameters that are aircraft configuration, wind, turbulence, temperature stratification, wind shear, and proximity of the ground. To take into account the stochastic characteristics of wake vortex behaviour, the model should predict a deterministic (mean) evolution together with envelopes for vortex trajectories and strengths combined with clearly specified probabilities. From the number of suggested wake vortex models (see [41] for a list of models) only a few comply with most of the listed requirements. In the following, two models, the P2P and the VFS, will be introduced to illustrate challenges, methods, and capabilities connected to current real-time wake vortex modelling.

3.3.1. The probabilistic two-phase model P2P

The Probabilistic Two-Phase wake vortex decay and transport model (P2P) has been developed by DLR and is described in detail in [41,42]. P2P is designed to include as much knowledge as possible gained from both experimental and numerical wake vortex research with a focus on operational needs. The model concept comprises the following elements:

- P2P employs a well-defined and experimentally accessible definition for vortex strength, i.e., a mean circulation $\Gamma_{5\text{–}15}$. For theoretical reasons and properties of the LIDAR technique it is beneficial to compute the circulation as an average over distances from the vortex core centre (here for radii between 5 and 15 m) [43].
- The complex wake vortex behaviour found in observations and simulations illustrates the challenges connected with the development of a thorough real-time model. Therefore, the concept used for the model development was to reproduce the detailed and complex wake vortex behaviour as found in LES by simple equations for vortex evolution. Since there is no rigorous solution for the evolution of turbulent vortex pairs, the hydrodynamical basis of P2P relies on the equation that describes the spatio-temporal circulation evolution of the decaying potential vortex. In P2P, this relation is extended and adapted to LES results of different research groups to describe vortex decay and descent.
- For the prediction of vortex circulation, the concept of two-phase circulation decay is pursued, as anticipated by LES [17, 18] and confirmed by Doppler-LIDAR measurements [36]. The equation to parameterise vortex decay is written:

  $$\Gamma^*_{5\text{–}15} = A - \exp\bigl[-R^2/\nu^*_1(t^* - T^*_1)\bigr] - \exp\bigl[-R^2/\nu^*_2(t^* - T^*_2)\bigr]$$

  where all quantities have been normalised (marked by *) by intrinsic wake, thus aircraft, parameters as initial vortex spacing b_0 and descent speed w_0. The slow turbulent diffusion phase is described by the second term, the rapid decay phase by the third term of the equation. The onset time of rapid decay at T^*_2 and the respective decay rate, which is adjusted by the effective viscosity ν^*_2, are functions of ambient turbulence and stratification, where the former is characterised by the normalised eddy dissipation rate. T^*_1 and ν^*_1 control decay in the diffusion phase, R corresponds to a mean radius, and A is a constant to adjust $\Gamma^*_{5\text{–}15}$ at $t^* = 0$.
- Linear relations between descent speed and circulation hold only if the circulation value attributed to the wake vortices represents the velocity induced at the neighbouring vortex. For a radii-averaged circulation as $\Gamma_{5\text{–}15}$, this is not valid. Therefore, the parameterised descent rate obeys a non-linear dependence on circulation which allows for a reduction of circulation without the reduction of the descent rate during the early vortex evolution and for stagnating and rebounding vortices with non-zero circulation in strongly stably stratified environments. These features are in accordance with LES and observation data.
- P2P predicts a probabilistic wake vortex behaviour as precise deterministic wake vortex predictions are not feasible operationally. P2P varies decay parameters in subsequent model runs and it adds various static and dynamic uncertainty allowances that consider the increased scatter of vortices in turbulent and sheared environments.
- Further developments of P2P were accomplished regarding circulation decay, effects of axial wind and glide slope angle, and axial and cross-wind shear.

Wake-vortex shear-layer interaction is extremely sensitive to a number of shear layer parameters [44,24]. Ref. [42] illustrates that sufficiently precise observations and, in particular, predictions of shear-layer characteristics are hardly feasible. Only probabilistic approaches may succeed. A series of measurements suggests that the interaction of wake vortices with shear layers ($\partial v/\partial z$) can be categorised by a normalised shear rate according to $\mathrm{sh}^* = \partial v/\partial z \cdot b_0/w_0$. Tilting and stalling or even rebounding vortices, as depicted in Fig. 3, are only observed when wake vortices penetrate shear layers with $|\mathrm{sh}^*| > 1$. For the parameterisation within P2P, the wind velocity difference across a height difference of b_0, $\Delta v = \partial v/\partial z \cdot b_0$, normalised by the vortex descent speed, w_0, can be used as a superimposed shear-induced propagation velocity, v^*_{sh}. If wake vortices encounter a shear layer with $|\mathrm{sh}^*| > 1$, the normalised shear velocity widens the envelopes for vortex transport in analogy to the approach proposed for turbulent spreading [41]. Some observed cases (Fig. 3) further provide evidence that also axial wind shear may cause similar effects as pure cross-wind shear. This may be explained by the fact that wake vortices in the atmospheric boundary layer usually are deformed immediately, whereby the vortices become susceptible to both components of vertical shear. As a consequence, v^*_{sh} employs the magnitude of both vertical wind shear components.

To evaluate the probabilistic model performance, probability density distributions (PDD) are computed which set wake vortex measurement data into relation to the predicted uncertainty allowances. In a second step, the probabilistic model output

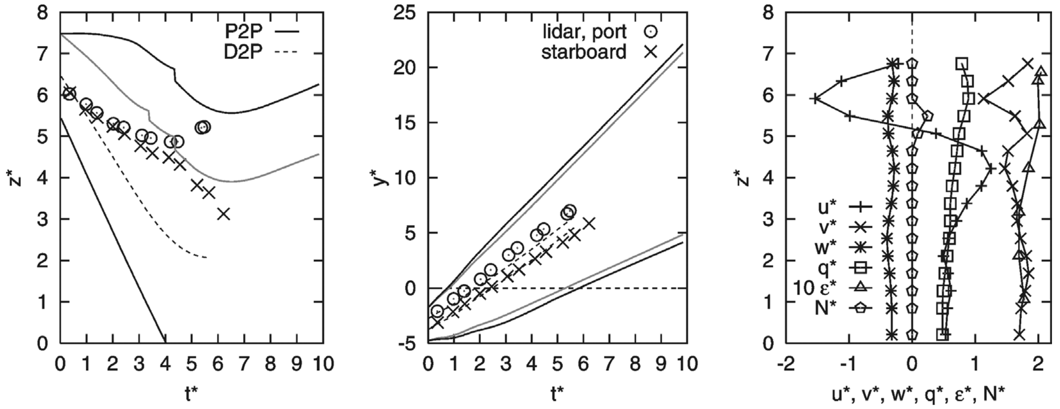

Fig. 3. Measured (symbols) and predicted (lines) evolution of normalized vertical (z) and lateral (y) positions of trailing vortices penetrating a pronounced shear layer. Dashed lines denote deterministic behavior, black (grey) solid lines the probabilistic envelope with (without) the shear-layer model. Right, vertical profiles of normalized environmental data which serve as input for P2P where u, v, w denote axial, cross and vertical wind components, q, ε, N denote turbulence velocity, eddy dissipation rate and Brunt–Väisälä frequency, respectively.

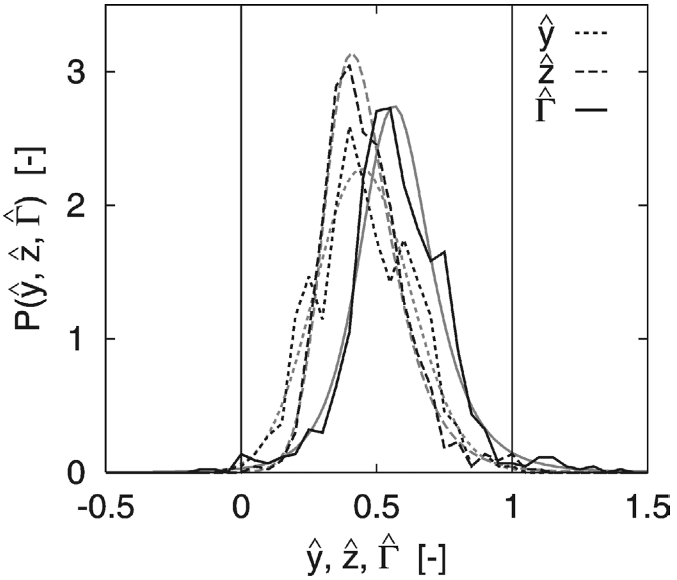

Fig. 4. Probability density distributions of measured lateral position, vertical position, and circulation of wake vortices normalized with respect to the uncertainty bounds predicted by P2P. Fits of respective unbounded Johnson distributions denoted by grey lines.

may be adjusted to arbitrary confidence levels. For this purpose, the value of every single vortex datum is normalised according to $\hat{y} = (y_{\text{meas}} - y_l)/(y_u - y_l)$. This equation, which here is exemplified for lateral position y, assigns the value one to a vortex measurement situated on the predicted upper bound (index u) and is zero for measurements on the lower bound (index l). Measurements of the whole vortex evolution – from generation to decay – are included in the statistics. The PDD shown in Fig. 4 employs data of 49 over-flights out of 2 campaigns, 6 days, and 872 vortex observations. Only over-flights are used where vortex and meteorological data were measured completely and with high quality. Therefore, the PDDs should mainly represent the intrinsic variability of vortex evolution and to a lesser extent the uncertainties of the input parameters to P2P. The data sample includes many long-lived and complex cases with, for example, pronounced shear effects. Note that the PDD for vortex descent is skewed due to a few cases with retarded descent caused by shear layers. The flanks of the PDDs decline steeply when approaching the probabilistic bounds 0 and 1 which indicates that the applied uncertainty allowances are close to an optimum. The P2P model could predict wake vortex behaviour conservatively in 99.7, 99.7, and 97.9% of the observations for lateral position, vertical position, and circulation, respectively. Fig. 4 demonstrates further that unbounded Johnson S_U distributions (grey lines, [45]) fit the PDDs reasonably well. The fits pass the Kolmogorov–Smirnov goodness-of-fit test at a significance

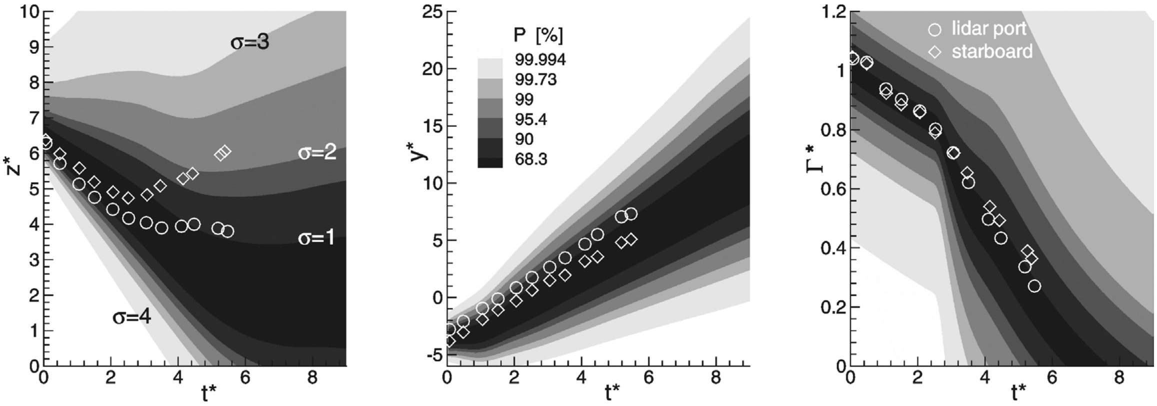

Fig. 5. Prediction of envelopes for vortex evolution with six different confidence levels. Symbols denote LIDAR measurement data.

level 0.05. Hence, these valid PDD fits are likely to provide probability estimates that can be extrapolated beyond the range of the finite number of experimental measurements which was used so far.

Quantitative knowledge of wake vortex prediction skill is required to estimate risk probabilities of reduced wake vortex spacing systems. An advantage of the established PDDs is that this requirement can be fulfilled. That is, predictions of envelopes which constitute arbitrary probabilities can be prescribed. Fig. 5 shows the temporal evolution of six selected confidence levels for vortex positions and circulation and the respective LIDAR measurement data for a specific aircraft over-flight. As in Fig. 3, which shows the subsequent over-flight at almost identical meteorological conditions, the vortices penetrate a pronounced axial wind shear layer. However, in contrast to Fig. 3, it is now the starboard vortex which rebounds. This indicates that random deformations of the vortices may render either vortex susceptible to axial wind shear. Evidently, this is a situation which can not be predicted deterministically. As the observed rebound is relatively unlikely, the rebounding vortex quits the 2σ-envelope (95.4%).

The described methodology adapts and improves P2P prediction skill. The approach allows to continuously enhance P2P performance based on further high-quality measurement data being used to augment the statistical basis of the PDDs. Herewith, the model output does not only gain probabilistic substance but it is also modified concerning the predicted mean, variance, skewness, and kurtosis. The approach ultimately allows the model to 'learn' the physics which is not yet included in its primary physical and probabilistic parameterisation.

3.3.2. The vortex forecast system VFS

The Vortex Forecast System (VFS) is an operational wake vortex predictor, based on the method of discrete vortices [46], that is able to realistically simulate complex wake vortex behaviours, depending on atmospheric and ground proximity conditions. It was developed by partners from Russia, Canada and Belgium, under a contract with Transport Canada (TC) and its Transportation Development Center [47,48]; it was then further enhanced at Université catholique de Louvain, Belgium [49]. The VFS uses discrete atmospheric profiles as inputs (cross-wind, head wind, turbulence, temperature) with cubic-spline interpolation. VFS assumes an universal near wake where two vortices of circulation Γ_0 and $-\Gamma_0$ are separated by $b_0 = sb$ ($s = \pi/4$ for elliptical wing loading, b is the wing span). A generic circulation profile is used that was calibrated on wakes shortly after rollup and on aircraft wake data. It is expressed

$$\frac{\Gamma(r)}{\Gamma_0} = 1 - \exp\left(-\beta_i\left(\frac{r}{b}\right)^2 \Big/ \left(1 + \left(\frac{\beta_i}{\beta_o}\left(\frac{r}{b}\right)^{5/4}\right)^p\right)^{1/p}\right)$$

where $\beta_o = 10$ and $\beta_i = 500$ define the typical outer and inner characteristic sizes, respectively; p controls the maximum velocity amplitude; it does not affect its location ($r_c/b \approx (\beta_o/\beta_i)^{4/5}$); $p = 3$ or 4 are typical values. The circulation profile is discretised up to $R = b_0/2$, using discrete vortices. For instance, one discrete vortex in the centre, plus 3 layers (8 vortices in the first layer, 16 in the second layer and 24 in the third layer), for a total of 49. The number of layers varies depending on applications. The far wake evolution prediction is based on cross-plane (two-dimensional) simulations with discrete vortices. It includes the following models:

- *Transport model*. The discrete vortices are convected by the atmospheric wind (including wind-shear and thermal stratification effects) and the velocity induced by all other discrete vortices according to the Biot–Savart law. Each discrete vortex induces $\Gamma(r) = \Gamma_p(1 - \mathrm{e}^{-r^2/\sigma^2})$ with $\sigma^2 = \sigma_0^2 + 4\nu_e t$, $\sigma_0 = 0.05b$ and $\nu_e \approx 0.01\ \mathrm{m}^2/\mathrm{s}$. The primary discrete vortices are also subjected to the decay, wind-shear and stratification models, whereas the secondary discrete vortices, which are generated in ground vicinity in order to capture the viscous ground effects, are not. 'Mirror' discrete vortices are assumed below the ground plane to ensure no-through flow at the ground.

- *Decay and time-to-demise models*. The decay model $\mathrm{d}\Gamma_p/\mathrm{d}t = -C_\eta \Gamma_p / t_{\mathrm{demise},0}$ with $C_\eta = 0.3$ [47], takes into account the atmospheric turbulence effects, using either EDR or TKE. The 'time-to-demise' $t_{\mathrm{demise},0}$ [50,51] is used as an 'accumulated damage' time to take into account a possibly varying EDR profile. The 'fraction of time-to-demise attained' as the wake evolves is also computed as a function of EDR. When it reaches one, the rapid decay phase starts (by, e.g., doubling C_η). The 'time-to-demise' evaluation was recently further improvement, following [41,42], to take into account the impact of the stratification effects, i.e.,

  $$T^*_{\mathrm{demise}}(\varepsilon^*, N^*) = T^*_{\mathrm{demise},0}(\varepsilon^*) \exp\bigl\{-0.185 T^*_{\mathrm{demise},0}(\varepsilon^*) N^*\bigr\}$$

  where ε^*, T^*, and N^* describe normalised values of EDR, time, and Brunt–Väisälä frequency, respectively. Note that the time constant in the EDR-based decay equation is still $t_{\mathrm{demise},0}$; the additional circulation decay due to stratification effects is provided by an additional model (see below).
- *Near-ground and in-ground effects* (*NGE and IGE*) *models*. NGE effects are taken care of by use of the mirror discrete vortices. Viscous IGE effects become active when one of the primary vortex centroids is below a critical distance d_{crit} (typically set equal to b). Secondary discrete vortices are produced to represent the separation of the boundary layer formed on the ground due to the close presence of the primary vortices. A critical velocity, v_{crit}, is first determined according to Γ_0, d_{crit}, and an estimated boundary layer thickness δ (typically set to $0.05b$). More specifically, $v_{\mathrm{crit\_port}}$ is the ground parallel velocity induced by the wake vortices (plus their images) when those are at altitude d_{crit}, as measured at δ above the ground and just below the port vortex; idem for $v_{\mathrm{crit\_starb}}$; $v_{\mathrm{crit}} = \sqrt{(v^2_{\mathrm{crit\_port}} + v^2_{\mathrm{crit\_starb}})/2}$. Then, at each pre-defined time interval, Δt (the time between allowed production of secondary vortices), the lateral positions of the separation points, $y_{\mathrm{s\_port}}$ and $y_{\mathrm{s\_starb}}$ are determined as the locations for which the lateral induced velocity is equal to 70% of that evaluated at δ above the ground and just under the considered vortex. If the velocities v_{s} at those locations are larger than v_{crit}, secondary vortices are generated at those points to capture the vorticity flux of the separating boundary layer. Their strength is

  $$\Gamma_{\mathrm{p\_port}} = -v^2_{\mathrm{s}}(y_{\mathrm{s\_port}}, \delta_{\mathrm{port}})\Delta t/2 \quad \text{and} \quad \Gamma_{\mathrm{p\_starb}} = v^2_{\mathrm{s}}(y_{\mathrm{s\_starb}}, \delta_{\mathrm{starb}})\Delta t/2$$

  Comparisons with numeric simulations and Memphis and Dallas-Fort Worth databases [47,52,49] have shown that this model is able to simulate realistic ground effects.
- The *wind-shear effects model* is designed to capture the effects due to non-uniform variation of the cross-wind with altitude. The shear parameter is $S_h = (b_0^2/V_0)\,\mathrm{d}\Omega/\mathrm{d}z$, where Ω is the vorticity associated with the cross-wind shear. In the first model [47], the wind shear effects were simulated by acting on the vortex circulations as $(\mathrm{d}\Gamma/\mathrm{d}t)_{\mathrm{shear}} = -\alpha_{\mathrm{sh}} S_h V_0 v_{\mathrm{BS}}$ with α_{sh} the model coefficient and v_{BS} the Biot–Savart velocity of the vortices. In a second approach [53], based on a more phenomenological model, the wind-shear vorticity displaced by the port vortex is estimated and leads to an acceleration (or deceleration) of that vortex; and conversely for the starboard vortex. This model amounts to an added vertical velocity, $v_{\mathrm{shear}} = \pm\beta_{\mathrm{sh}} S_h V_0$ (sign depends on which vortex) with β_{sh} as model coefficient. For cases with strong shear, this model was shown to be more appropriate than the first one. The model is damped when the wake is IGE as β_{sh} varies linearly from the ground up to an altitude equal to b and is constant above (typically 0.4–0.5). Further improvements could amount to a mixed model, thus acting on both the circulation and the vertical velocity.
- *Thermal stratification effects model*. This model is an improvement of Greene's model [54], considering the 'accumulated effects' and leading to

  $$\bigl(\mathrm{d}^2 z/\mathrm{d}t^2\bigr)_{\mathrm{strat}} = -\int_{z_0}^{z} N^2(z)\,\mathrm{d}z$$

  where z and z_0 represent the present and initial wake altitudes and N is the Brunt–Väisälä frequency. The mixed model is

  $$(\mathrm{d}v/\mathrm{d}t)_{\mathrm{strat}} = \beta_{\mathrm{str}}\alpha^2_{\mathrm{str}}\bigl(\mathrm{d}^2 z/\mathrm{d}t^2\bigr)_{\mathrm{strat}} \quad \text{and} \quad (\mathrm{d}\Gamma/\mathrm{d}t)_{\mathrm{strat}} = -(1-\beta_{\mathrm{str}})\alpha^2_{\mathrm{str}}(2\pi b_0)\bigl(\mathrm{d}^2 z/\mathrm{d}t^2\bigr)_{\mathrm{strat}}$$

  with typically $\alpha_{\mathrm{str}} = 0.65$ and $\beta_{\mathrm{str}} = 0.75$. The coefficients control the net displacement amplitude of the wake, as in [54], and the ratio between the two model parts, respectively.

The VFS described so far delivers deterministic positions and circulations of the port and starboard vortices. The position of each vortex is the vorticity centroid, computed using the primary discrete vortices. The 'total circulation' of each vortex is the sum of the circulations of the primary discrete vortices. The 'circulation within a circle of prescribed radius' (typically

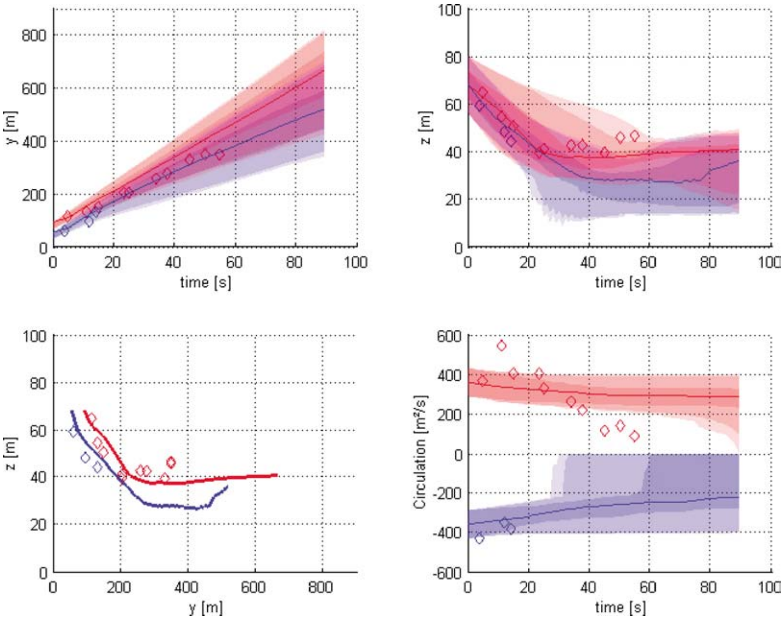

Fig. 6. P-VFS results (Monte Carlo using 810 VFS runs) of case DFW 20217 which reflect wake vortices in ground proximity and wind shear; median (line), 50, 95, and 98 percentiles are shown.

$R = b_0/2$) is the sum of all circulations (primary and secondary discrete vortices) contained within that circle. The induced velocity field can also be computed, as to be used for risk assessment studies, LIDAR measurement modeling, visualisations, and so on.

In a further step, parametric multiple runs of the VFS are performed (P-VFS) in order to obtain a probabilistic wake vortex behaviour [49,55]. Monte Carlo simulations take into account the variations and uncertainties of the profiles of the atmospheric variables, the parameters of the wake-generating aircraft, and the physical model parameters of VFS. P-VFS provides the evolution of a three-dimensional area in which the vortices have a large (e.g., 98%) probability of residence. Fig. 6 shows a typical P-VFS result of a case from the Dallas-Fort Worth campaign. The wake evolution was affected by ground and wind shear, leading to tilting of the vortex system and to asymmetrical ground and rebound effects.

3.4. *Safety zones*

The parameterised real-time wake vortex models provide probabilities of positions and intensities of the vortices at discrete vertical gates (oriented perpendicular to flight direction) along the glide path as function of time after aircraft passage. The next step is to assign a border around each vortex position which discriminates a potentially hazardous area around a vortex from non-hazardous regions. Most commercial airports today employ an instrumented landing system (ILS) which electronically guides an aircraft along the glide path from the intercept down to the runway threshold. According to the ICAO, aircraft have to follow the ILS slope but may deviate from the nominal glide path by a certain amount. The German air safety provider, DFS, has demonstrated in the so-called FLIP study [56] that the aircraft landing in Frankfurt Airport follow the ILS path with much greater accuracy than claimed by ICAO. One possible definition of the safety border at a certain gate could be an area around the glide path according to the ICAO or FLIP tolerances, enlarged by a static area in which the vortices may be hazardous [57], that the vortices of the predecessor aircraft would have to have left, when the follower aircraft enters the gate. This approach has the advantage that no decision has to be made about the severity of the vortex strength, since the decision only depends on wake-vortex transport. On the other hand, it is also a very conservative solution which may reduce or even impede expected capacity gains. Another solution for a safety border would allow the presence of vortices in the flight path tolerance area when their strengths lie below a threshold, so that a potential encounter of an aircraft with that vortex would not be hazardous. However, in the past, the definition of such a (non-zero) threshold turned out to be a Gordian task since it involves not only aerodynamical and flight-control issues but also depends on the altitude at which the encounter occurs and – last but not least – on the pilot's flight experience [8,1].

The DLR proposal for a solution of the safety-zone problem is as follows: For encounters in the glide path corridor, the aircraft's roll response is the dominating motion. The worst case occurs when the wake vortex is oriented parallel to the glide

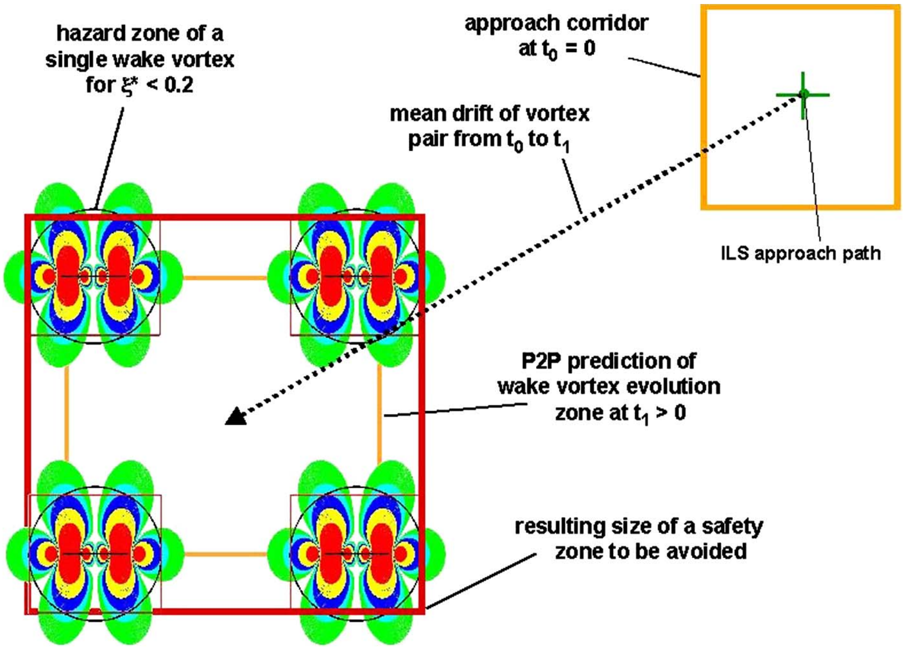

Fig. 7. The zone in which possibly hazardous wake vortex encounters may occur. Logic and determination of the area are adapted from [59].

path and the following aircraft is permanently exposed to the vortex flow field in a quasi stationary flight. The area around a vortex to be avoided, the 'vortex hazard area', can be calculated using the control power which is required to compensate the vortex-induced roll and normalised by the maximum available control power of the encountering aircraft, expressed in terms of aileron deflection [58]. The idea is to find a limit for the required aileron deflection which guarantees an acceptable aircraft behaviour and to approve this limit by pilots after ground and in-flight simulator tests. Flying outside this area is then definitely not hazardous. It is worth noting that, due to the employment of a non-hazard criterion rather than a hazard criterion for the accepted aileron deflection, a flight into the vortex hazard area does not automatically result in a dangerous situation.

Fig. 7 demonstrates how the size of the safety zone is determined for one gate along the glide path: From the approach corridor at the time of aircraft passage (t_0) the shed vortices move and decay according to the local weather. P2P (or VFS) has predicted an area of possible vortex positions at $t = t_1$. The Simplified Hazard Area Prediction (SHAPe) model [60] computes a rectangular vortex hazard area for a specific aircraft pairing where the dimensions of that area are defined according to the accepted roll-control power (e.g., 20% as in the figure with $\xi^* < 0.2$). The vortex hazard area is then added to the (rectangular) area of possible vortex positions, forming the entire 'hazard zone'. Hence, the required safety zone is the domain outside the hazard zone. One important aspect is that the hazard zone is not static but moves, depending on wake transport and shrinks according to wake decay. It is obvious that as soon as the hazard zone no longer overlaps the approach corridor or has shrunk to size zero, an aircraft can safely follow the wake generating aircraft ahead of it. Again note that touching or entering the hazard zone does not automatically infer dangerous encounters; moreover, the chance to hit a vortex at all is small, see Section 2.

3.5. *Detection and characterisation of aircraft wakes*

The pulsed Doppler LIDAR developed by DLR provides vertical wind and turbulence profiles (conical scan) and it can watch corridors for wake vortex and wind shear (scans in vertical or horizontal planes). There are several possibilities to position the ground-based LIDAR for airfield surveillance. Two examples are sketched in Fig. 8. One position (shown left) is approximately one km sideways and a few kilometres before the threshold. From this position, the approach (take off) corridor is alternately scanned in two or more vertical planes. This allows the observation of the cross-wind, including wind shear, and the monitoring of wake-vortex trajectories and strength at several sections of the glide slope. Fig. 9 shows an example of LOS velocities measured by the ground-based LIDAR during the WakeTOUL campaign 2002 in *C-Wake* [36]. This quick-look presents one vertical scan of 20° elevation where the data from 480 to 1300 m range are plotted. The colour-coded area shows the line-of-sight (LOS) wind components with increasing velocity towards higher altitudes. The discrete pattern in the middle of the scan sector is the signature of a wake-vortex pair. After signal and image processing, pronounced wind-shear situations and characteristics of wake vortices can be identified.

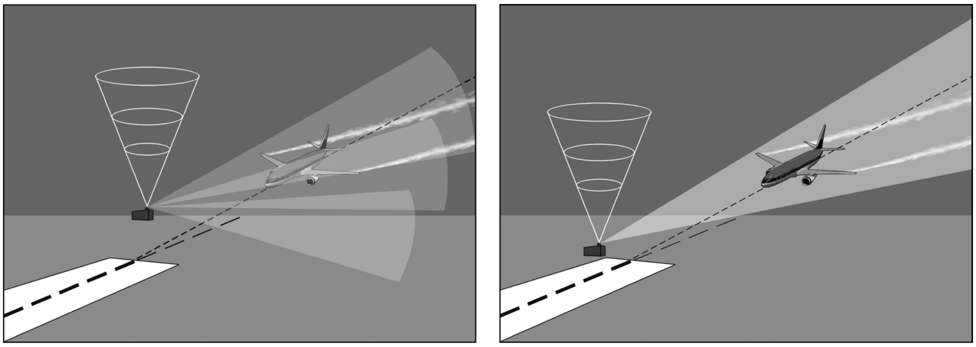

Fig. 8. Two examples of positioning the ground-based LIDAR for coverage of the approach or departure area.

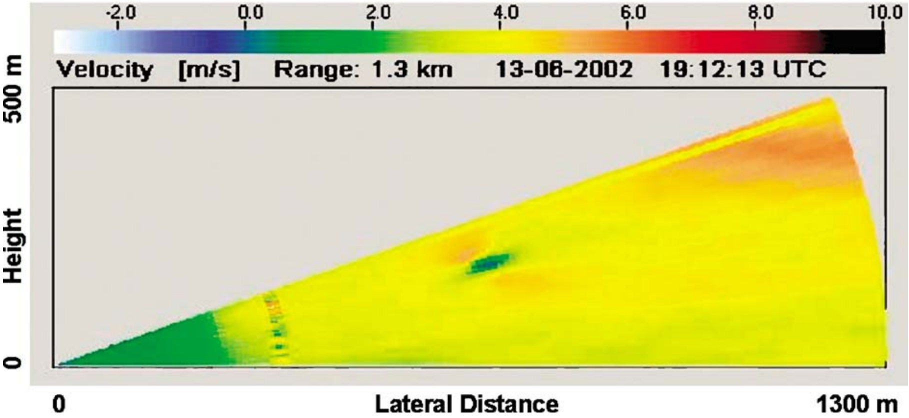

Fig. 9. Immediately available line-of-sight components of the wind field with signatures of a wake vortex pair as measured by the 2 µm pulsed LIDAR in a vertical cross-section perpendicular to the flight path.

The second possibility to survey the airfield with a pulsed LIDAR is a position close to the runway threshold (Fig. 8, right). For observation of the landing traffic, it performs sector scans in a plane roughly inclined by the angle of the glide path. For take-off configuration, the inclination angle can be adapted to the envisaged angle of a departing aircraft. In the inclined scanning sector, the behaviour of the cross-wind component is continuously observed and dangerous wind-shear situations can be detected. Moreover, it is possible to detect cases of stalling or rising wake vortices, e.g., vortices rebounding from atmospheric shear layers or influenced by the ground effect.

3.6. Safety assessment and analysis

The use of the products of the WVPMS in ATC, i.e., predicting safe optimum aircraft spacing for a certain time horizon and monitoring wakes and weather for alert in case of unforeseen events or system failure, must contribute to and guarantee the all-over safety. To this end, the WVPMS tools need to be thoroughly assessed in terms of functionality, stability, reliability and area of applicability of all its components. Furthermore, a safety analysis has to estimate safety levels related to wake-vortex encounters. In particular, safety estimates are required of current wake-vortex separation standards, as well as estimates based on new wake-avoidance technologies and new separation standards.

Tools for safety assessment and analysis have been developed in the *S-Wake* project [27] for wake-vortex induced risk related to single runway approaches under reduced and standard aircraft separations. The Nationaal Lucht- en Ruimtevaartlaboratorium, NLR, in the Netherlands has developed the probabilistic wake vortex induced risk assessment tool WAVIR [61]. The methodology is based on a stochastic framework that incorporates sub-models for wake vortex evolution, wake encounter, and flight path evolution, and relates severity of encounters to possible risk events. Appropriate separation distances for different operational and weather conditions were derived, using a method with proposed risk requirements derived from wake encounter incident data. It was confirmed that the largest runway capacity improvements might be achieved through exploiting favourable wind conditions. In particular cross-wind and strong head-wind conditions appear favourable and might allow reduced separation minima. The evaluated wake-vortex risk-mitigation measures further show that the risk related to single runway approaches is reduced most effectively in the area close to the runway threshold. Therefore, weather based prediction, monitoring and warning systems should focus on keeping the safety level high near the runway threshold.

3.7. ATC requirements, concepts and procedures, and element integration

In order to beneficially use the products of a wake forecasting and observation tools in modern air-traffic management, many procedural aspects of ATM and ATC have to be considered: the airport infrastructure, the surveillance equipment, layout and usage of the runways, traffic mix, diurnal variation of traffic, glide path angles, different glide-path intercept altitudes, navigation performance, etc. This involves all ATC providers as en-route, approach, tower and arrival/departure managers. Moreover, an integrated ATC wake vortex safety and capacity system must include a human–machine interface (HMI) for the air traffic controllers which meets their requirements and does not enhance their workload.

To this end, an interdisciplinary project has been launched among European partners from research, air-traffic control, and system-development industry. This *ATC-Wake* project [62] aims at incorporating all respective elements and tools for an optimum safe spacing of aircraft on arrival into an integrated platform. The platform will serve as a test-bed environment

(i) to assess the interoperability of the integrated system with existing ATC systems in Europe;
(ii) to assess the safety and capacity improvements that can be obtained by applying the system in airport environments; and
(iii) to evaluate its operational usability and acceptability by pilots and controllers.

Both tactical and strategic benefits will be analysed. On the tactical side we expect considerable scope for local hour-by-hour improvements of the arrival-flow management with potentially large reduction of delays and fuel savings, particularly for aircraft in holding patterns; on the strategic side a scheduled increase in arrival/departure slots seems feasible and even a few slots per day at a busy airport would be of great value.

In the project, the requirements from operations and users have been elaborated, concepts and procedures for future aircraft spacing have been developed and then the resulting requirements for the technical system parts have been derived [2]. The considered ATC system includes a communication system between air and ground (voice and data), a surveillance system (radar data), a flight data processing system and a workstation for the air-traffic controller (HMI) to visualise aircraft data (position, level, speed) and flight information. Finally, the system shall provide separations between aircraft for landings and departures. For landings, the final approach path is considered which starts at a point in space reached by all aircraft (the final approach fix, FAF) and ends at the touchdown zone. Along this path all aircraft fly almost identical trajectories (bounded by the ILS tolerances). For departures, only the initial climb path is considered since aircraft soon follow different trajectories. But the initial climb paths themselves vary strongly between aircraft of different type and weight as these properties lead to different rotation points and climb rates.

As a result of the inventory four functional components have been proposed and will be realised in the integrated platform of *ATC-Wake*:

- The ‘separation mode planner’ determines the applicable mode of separation (standard or new procedure). The wind profile as predicted by NOWVIV is compared to a look-up table and the safe separation is chosen. The look-up table contains safe cross-wind profiles offline deduced for a specific airport by the safety assessment tool WAVIR [61], i.e., these cross-winds carry the vortices of all aircraft out of the glide path corridor in the required time. The time horizon of the prediction to be considered for arrival sequencing is 40 min using an automated arrival manager. The separation mode planner proposes a minimum separation for a certain period of time to the ATC Supervisor who appoints the minimum separation to be applied for approach or departure phases as well as the landing rate to be used for arrival sequencing.
- The ‘wake predictor’ predicts – in real time – transport and decay of wake vortices from individual aircraft in the final approach or climb paths. It assesses the suitability of the separations previously proposed by the separation mode planner. The wake predictions provided by P2P and VFS rely on a persistency forecast of the meteorological profiles which stem from a best-fit analysis of the most recent ground-based or air-borne measurements and nowcast data. The prediction is updated in intervals of about 2 s, according to the update rate of aircraft positions by the ATC-RADAR, and has a time horizon for arrivals of about 6 min which is the time the aircraft needs from entering the critical arrival area (FAF) until touch-down and for departures of about 2 min which is the time from takeoff until the end of the initial climb path. The prediction is displayed on the HMI screen by the ‘vortex vector’ which is the projection of the potentially hazardous domain on the glide or climb path.
- The ‘wake detector’ shall monitor the approach or departure corridor and detect wake vortex positions of individual aircraft in the critical areas. Detection is performed using a ground-based or air-borne pulsed Doppler LIDAR which scans parts of the glide or climb slope.

- The ‘wake monitoring and alert’ component informs the air-traffic controller in case of malfunction of system parts or in case of a significantly wrong prediction which raises the risk of a wake vortex encounter (i.e., vortices are detected along the glide path although the glide path was predicted to be vortex-free). This component plays the role of a ‘safety net’.

4. Field campaigns to test the system components

The European wake vortex forecasting and measuring campaigns, which have been accomplished at airports in Oberpfaffenhofen (Germany) 2001 and in Tarbes (France) 2002 and 2003, have been used in order to test the individual components and tools of the WVPMS. The first two campaigns, named WakeOP [63] and WakeTOUL [29], were conducted with partners from Airbus, ONERA, QinetiQ, and DLR within in the framework of the DLR project *Wirbelschleppe* and the European project *C-Wake*. These were the first wake measurement trials where four-dimensional weather nowcasts for a local area and subsequent wake predictions were performed in an operational mode. The 2003 campaign in Tarbes was part of the EU project *AWIATOR* and accomplished by the partners Airbus, ONERA, NLR, and DLR. The two modules NOWVIV and P2P of the WVPMS for weather and wake prediction, respectively, have been utilised to forecast the appropriate weather and to plan and guide the over-flights of the aircraft.

The wind along the flight track was measured by the standard instrumentation of the aircraft. For WakeOP also the wind field in horizontal layers around the airport was scanned by monostatic and bistatic multiple-Doppler weather radar [64]. In Tarbes we employed a SODAR (METEK DSDPA.90-24) together with a RASS (MERASS at 1274 MHz) which provided 10-minutes averaged profile of wind components and temperature at a vertical resolution of 10–20 m. The typical measurement range was 500 m starting at $z = 40$ m. A sonic anemometer with a sampling frequency of 20 Hz was mounted on a 10 m mast close to the SODAR/RASS system. This tool provided turbulence kinetic energy spectra from which EDR at 10 m height could be derived; for larger altitudes TKE and EDR were deduced from the standard variation of the vertical velocity from SODAR scaled by the anemometer value at 10 m. Profiles of cross-wind, TKE and EDR have also been sampled by the pulsed 2 µm LIDAR with an averaging window of 5 min. The measurement equipment was completed by multiple 10 µm continuous-wave LIDAR [65] and a 2 µm pulsed LIDAR [36]. The primary objective of the campaigns in *C-Wake* and *AWIATOR* was to trace the vortex trajectories and characterise the vortex decay with hitherto unrivalled accuracy. This was achieved by triangulating the data from 2 continuous-wave LIDAR and by applying the pulsed LIDAR.

Fig. 10 demonstrates that cross-wind and EDR profiles deduced from LIDAR and SODAR agree satisfactory well taking into account that the two systems were displaced by about 2 km across the airport. Fig. 11 compares wind profiles from SODAR measurements and NOWVIV 24-h predictions in the lower boundary layer up to 700 m altitude during the time of the day [66]. Data are shown in altitudes only where quality-proofed raw data from SODAR/RASS could be obtained. Noticeably, NOWVIV was able to forecast the nocturnal low level jet which evolved between 1 and 7 hours UTC albeit some overestimation of the wind maximum. Later in the day, wind speed is reduced in both observation and forecast. After 15 hours the agreement becomes worse which is not surprising considering the long forecast time for a local scale wind field. Fig. 12 illustrates the variability of the local horizontal wind system close to the ground as predicted by NOWVIV for the same date and location as in Fig. 11. During night time the flow is controlled by the stream of cold air from the mountains in the south towards the plane around and north of Tarbes airport. In the morning at 09 UTC (which is also local time at Tarbes), we still observe a wind from south in the

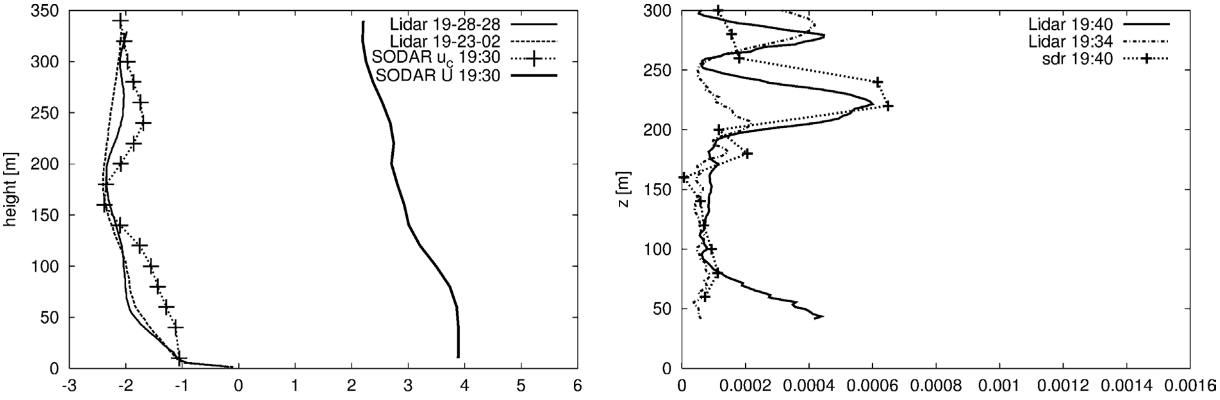

Fig. 10. Vertical profiles measured by SODAR and LIDAR on an evening at Tarbes Airport during the WakeTOUL campaign; left: wind (U) and cross-wind (u_C), right: EDR.

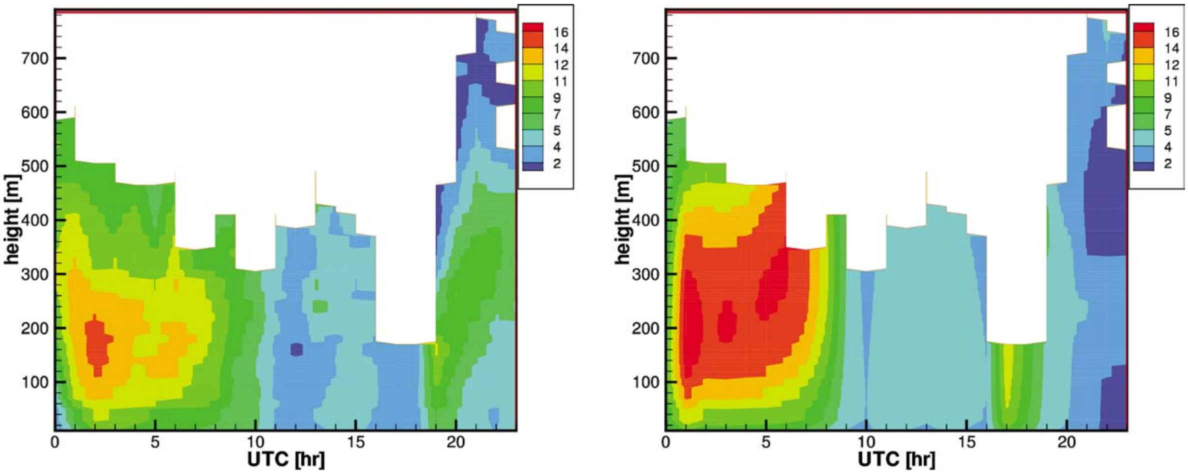

Fig. 11. Measured (left) and predicted diurnal evolution of the wind speed profile on 14.06.02 at Tarbes Airport during the WakeTOUL campaign (colour code in m/s).

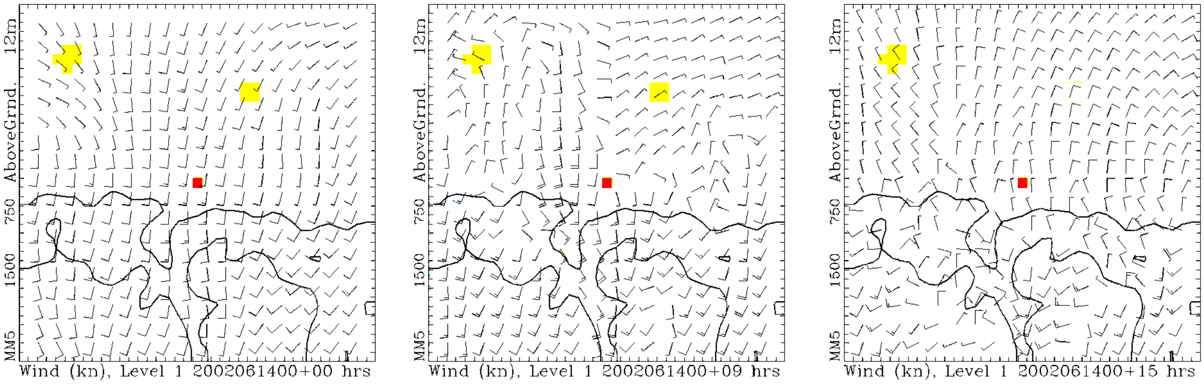

Fig. 12. NOWVIV 24-hours forecast of the horizontal wind field (in knots) above ground in a 80 km × 80 km area around Tarbes airport (dot in centre) on 14 June 2002 during WakeTOUL. Patches mark the cities of Pau (left) and Tarbes; the solid lines indicate two orography levels of the Pyrenees. Three forecasts for 00, 09 and 15 hours UTC are depicted.

mountainous region but the plane in the north gets more and more controlled by local convective cells driven by solar radiation to the ground. In the afternoon the plane is heated up and a general motion towards the Pyrenees is predicted. After sun set the reverse procedure will occur. This sequence aims at demonstrating the complexity of local wind fields which have to be faced in 'real' terrain around many airports.

A statistical analysis of the hourly profiles of wind and temperature from NOWVIV 24-hours forecasts and from SODAR/RASS measurements on 19 days during WakeOP and 21 days during WakeTOUL reveals that, compared to observations, NOWVIV predicts generally 1 to 2 m/s higher cross-wind with a rms error of 2.5 m/s and 2 to 3 K lower potential temperature than observed with a rms error of 2 K (Fig. 13). It is however noteworthy that the local fine-grid nowcasting model (NOWVIV with MM5) reduces the rms error in wind speed prediction by 34% compared to the coarser scale model (LM). The evaluated forecast-skill scores indicate that at present we may use local numerical weather forecasts with a nested fine-grid resolution for planning purposes in ATC (e.g., 'the separation mode planner') but an observation system is mandatory for short-term predictions in operational wake-vortex applications ('the wake-vortex predictor'). Nevertheless, during the WakeOP campaign, which was accomplished in less complex terrain, the skill of P2P with NOWVIV input was similar to the skill of P2P with input from observation systems [42].

Fig. 14 shows an evaluated example of the evolution of the wake of a large transport aircraft in the measuring plane of the pulsed LIDAR. The left graph depicts a series of vortex-pair positions as obtained by 8 scans; the right part of the figure shows the decay of the vortex circulation during the observation period after over-flight. The performance of the real time wake predictor P2P for an aircraft over-flight has been shown in Figs. 3 and 5. They all reveal that the pulsed LIDAR is capable for long-term detection and full-scale characterisation of wake vortices. With this tool wake vortices can be measured over a range

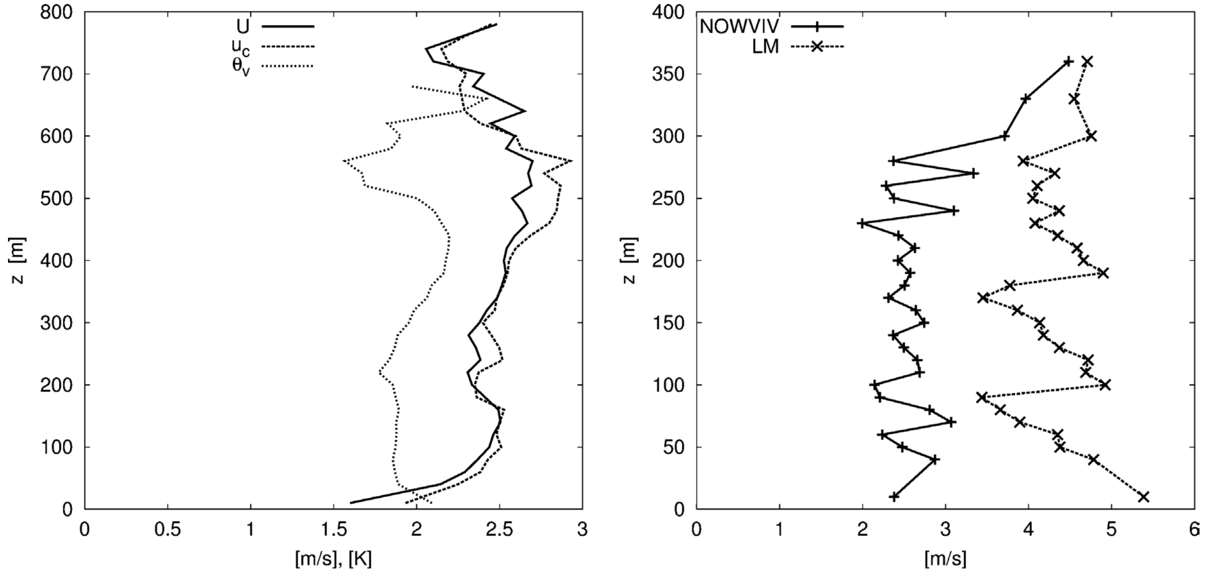

Fig. 13. Left: Vertical profiles of root-mean-square (rms) errors of NOWVIV 24-hour forecasts compared to SODAR/RASS measurements based on 21 days during WakeTOUL; wind speed (solid), cross-wind speed (dashed) in m/s, virtual potential temperature (dotted) in K. Right: Comparison of rms-error profiles of wind speed from NOWVIV (+) and the LM model (x).

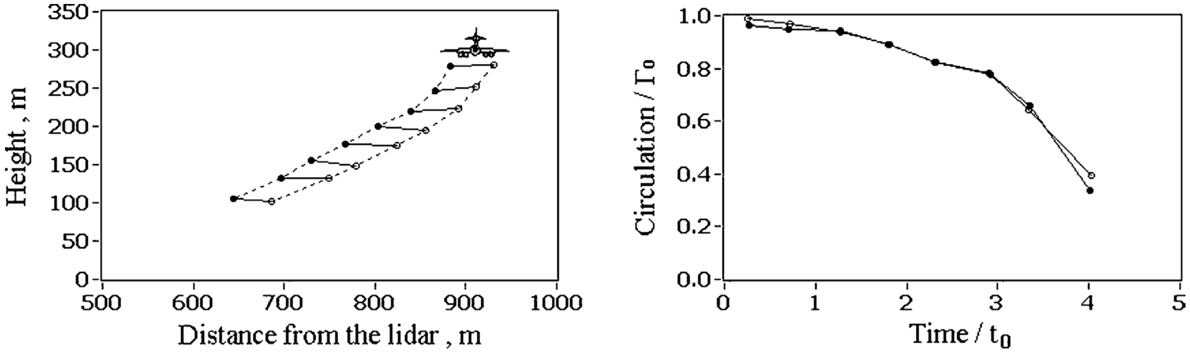

Fig. 14. Trajectories (left) and circulations (right) of the starboard (open circles) and port vortex (full circles) of a large transport aircraft measured by the pulsed LIDAR.

of more than 1 km rendering the vortex core position as accurate as 5 m along the laser beam provided that the signal-to-noise ratio is sufficiently high. This dramatically increased field of view (compared to continuous-wave LIDAR) allows one to observe wake vortices from their generation to a progressed state of decay. The data show that the circulation decays in two phases as predicted by large-eddy simulations [17,18] and that the spacing of the two vortex cores and the tilt angle of the vortex pair can be deduced with high confidence.

In order to estimate possible capacity gains when employing a WVPMS on an airport, the potential of safe reduced aircraft separations was computed for an airport with a runway layout as in Frankfurt, i.e., two closely-spaced parallel runways (518 m apart), with the weather data as forecasted by NOWVIV during the WakeOP campaign in Oberpfaffenhofen. 466 landings for each weight-class combination were considered with a wake-generating aircraft of 400 tons ('heavy') or 136 tons ('medium'). P2P was used to compute the wake characteristics along the glide path at 13 control gates assuming glide-path deviations typical for Frankfurt [56] and superimposing a static potential hazard area around the vortex centres of half the initial vortex spacing. The preliminary result suggests that in 15, 20, and 38% of landings of heavy–heavy, heavy–medium, and medium–light aircraft combinations, respectively, separations could be reduced in the mean to 87, 95, and 100 s for single-runway approaches, hence gaining 19 to 46 s per landing. Furthermore, the separation could be reduced to the minimum radar separation (2.5 nautical miles) in 47 to 88% of the landings on parallel runways.

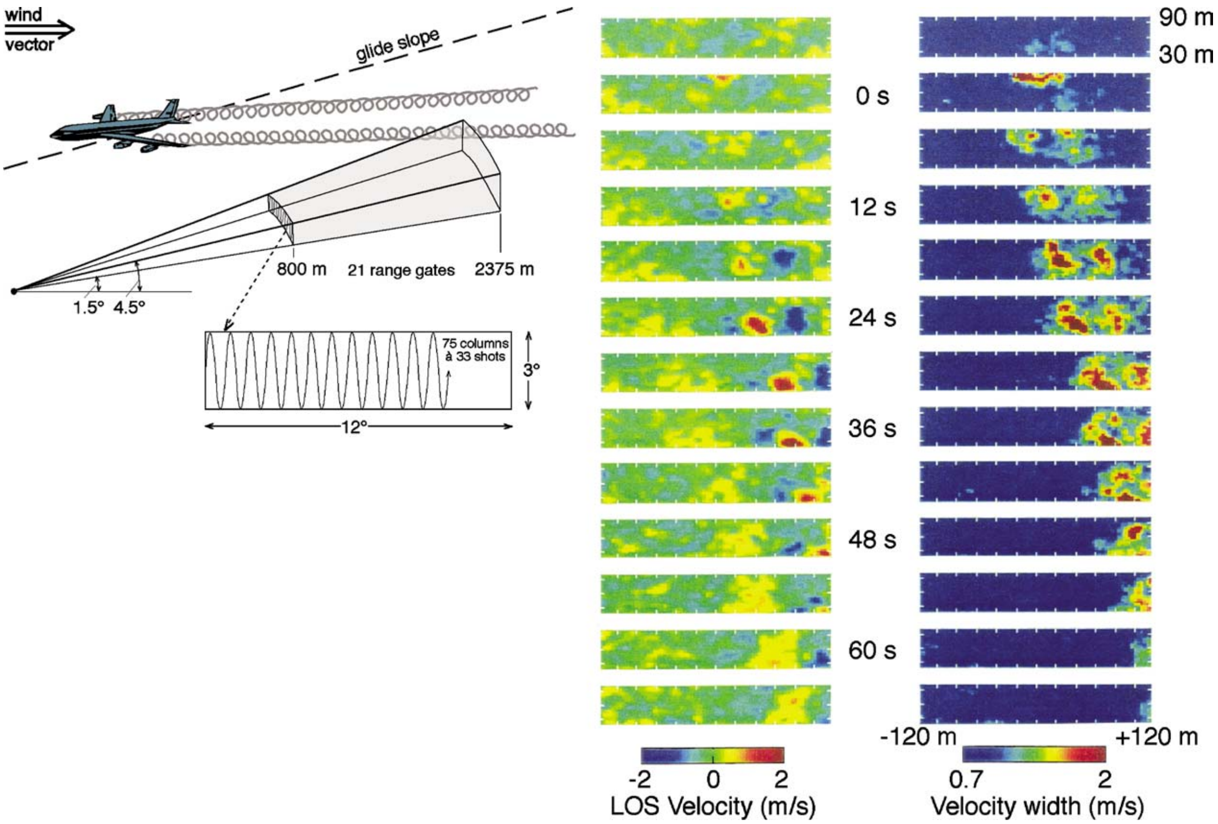

Fig. 15. Strategy of wake-vortex detection from ground (left) and measured LIDAR signatures (right) as demonstrated in the *MFLAME* project 2000 at Toulouse Blagnac.

The feasibility of watching an inclined corridor with respect to wake vortices and strong wind shear by a ground-based LIDAR (with a set-up as sketched in Fig. 8, right) has been demonstrated during the *MFLAME* project in 2000 at the airfield Toulouse–Blagnac [67]. On the left-hand side of Fig. 15, the strategy of wake-vortex detection is sketched. A corridor of 12° in azimuth and 3° in elevation was covered every 6 s by a fast saw-tooth scan. The longitudinal extension of the observation area between 800 m and 2375 m was defined by 21 range gates of 75 m length. On the right-hand side, the processed plots of the LOS velocity and the velocity width are shown for range gate No. 5 covering the range from 1100 m to 1175 m. At this range, the sensing area has an extension of about 240 m times 60 m. The colour plots on the right-hand side of the figure represent 13 scans from 6 s before until 66 s after the over-flight of a large aircraft. Especially in the plots of velocity width, the descent of the vortex pair and the lateral displacement due to the cross-wind blowing from left can be observed.

5. Research and developments in the USA

5.1. *The aircraft vortex spacing system, AVOSS*

Between 1991 and 2000, NASA developed AVOSS (Aircraft VOrtex Spacing System), a ground-based wake vortex system, to demonstrate the feasibility of providing weather dependent wake vortex spacing criteria for ATC use. The system provided automated collection of relevant weather data, prediction of wake vortex behaviour, derivation of safe wake vortex spacing criteria, estimation of system benefit, and comparison of predicted and observed wake vortex behaviour. AVOSS was developed to satisfy several concept demonstration and research requirements such as:

(1) automate assimilation of relevant weather and aircraft information for wake prediction;
(2) convert wake predictions to spacing values and estimated runway throughput;
(3) operate fully automated to screen data or provide real-time decisions;

(4) automate collection of performance statistics and error (diagnostic) statistics;
(5) provide flexibility in field campaigns and for iterative system implementation;
(6) operate with specific sensors deployed, and in batch mode for sensitivity studies.

The demonstrator was not required to provide an interface to ATC nor have the reliability or safety feedback mechanisms required for actual spacing reduction. The system design process was complicated by the lack of specific requirements. For example, specifications such as altitude and weather domains to be considered, sensor resolution and accuracy, system update rates, and ATC information requirements were not available. Even with respect to known functional requirements, such as wake vortex drift and decay prediction, the state of the art did not allow specification of a weather system (parameters, resolution, accuracy required) to produce the needed inputs. The development approach taken was one of iterative builds, learning, and refinement.

Available knowledge at the project outset was used to field an initial system for the purposes of testing sensors, collecting a complete aircraft/wake vortex/weather data set for numerical model validation, and answering sub-system performance issues needed to perform more detailed system design. The resulting deployments to the Memphis International Airport in 1994 and 1995 [68,69] were optimised for scientific data collection and testing of advanced continuous-wave LIDAR for wake detection and tracking. The instrumentation, which was assembled in co-operation with the National Oceanic and Atmospheric Administration, the Lincoln Laboratory of the Massachusetts Institute of Technology, the Volpe National Transportation Systems Centre, FAA, and others, was the most comprehensive used to that date for wake vortex studies. Data from these campaigns were used in the validation of numeric wake-vortex simulation models [21], for evaluating existing and new algorithmic wake-vortex prediction models [70], refining and validating planetary boundary-layer simulation models [71], and refinement and selection of sensors for use in AVOSS. The Memphis field systems were moved to the Dallas-Fort Worth International Airport (DFW) in 1997 for integration into the initial AVOSS. Components added for the DFW tests (not present at Memphis) were a pulsed wake-vortex LIDAR [72], two identical acoustic SODAR, and the networks required for real-time linkage of all systems to a central location to support AVOSS operation. The DFW AVOSS systems performed two separate functions namely (i) gathering additional scientific data for validation of numeric wake vortex and planetary boundary layer models and for wake algorithm development; and (ii) operation and refinement of an automated wake vortex spacing system. To this end, the field sensors represented a superset of those sensors finally required by an operational system.

The DFW installation was used from late 1997 through 2000 to incrementally test the AVOSS concept, refine the concept and sub-systems, and perform a system capability demonstration in July 2000. It was judged to be more efficient to begin operations with existing maturity levels of each component, and then learn which functions were most critical to system operation and performance prior to focusing on specific subsystem refinements. The demonstrated system contained an initial implementation of most functions required for an operational system, but without the robustness needed for an operational system [3].

5.2. The wake turbulence research program, WTRP

After AVOSS concluded in 2000, the FAA and NASA developed a joint *Wake Turbulence Research Program* (*WTRP*) to address all airport capacity constraints related to wake turbulence avoidance and mitigation procedures. This research, development, and operational implementation programme is designed to produce a time-phased series of enhancements in airport arrival and departure operations, based on three expected initial implementation periods: near-term (2006–2008), mid-term (2008–2010), and far-term (2010+) [4]. Phase I employs a set of data collection and analysis technologies in support of the entire programme. Phases II and III are supported by the Phase I data effort, and also include additional technologies in active systems that sense and predict weather and wake-vortex variables to determine if reduced wake separation standards can be used safely – a concept termed Wake Vortex Avoidance System (WakeVAS).

Phase I of *WTRP* is intended to increase arrival capacity at airports with closely spaced parallel runways (CSPR) between 1000 and 2500 feet apart. Currently, independent parallel ILS approaches with 1.5 nautical miles separation are permitted to CSPR with runway centreline spacing of at least 2500 feet. FAA's research will determine whether the required minimum runway centreline spacing for this procedure can be reduced to approximately 1000 feet when the leading aircraft belongs to the medium or light weight categories. In other words, it has to be proven that the vortices shed by these aircraft never drift to the neighbouring runway. Phase I would result in 'static' air-traffic procedure changes available on all weather conditions, and does not involve any operational system to authorise the procedures. The FAA is now collecting data from an extensive suite of test equipment for more than a year at the St. Louis, MO airport, using the following sensor and data acquisition systems:

- RADAR, a Mode-S squitter receiver, and a multi-lateration Airport Surface Detection Equipment (ASDE, Model X) [73] to provide accurate and precise lateral aircraft positions on the approach, and to identify aircraft types and model, that enable the correlation of aircraft weight categories (and a range of possible landing weights) and aircraft position with the characteristics of the wakes generated by them.

- Vertical laser range finders on the approach paths for each runway to provide precise aircraft altitudes, which will be correlated with other aircraft data and wake position measurements. Pressure sensors co-located with the range finders serve as event markers and for estimating aircraft weight.
- Two large ‘wind line’ arrays (lines of anemometers on 3 and 12-foot poles) installed between the parallel runways to continuously record wake transport in ground proximity (capable of sensing wakes up to 100 feet above the ground).
- SODAR measure wake height and strength directly above them up to 400 feet and provide a continuous altitude profile of wind direction and speed between 70 and 500 feet. SODAR are used to verify that winds sensed by the wind line after aircraft passage are from wakes.
- Additional wind data is collected from an anemometer on a 30 foot pole and from the airport’s Automated Surface Observing System (ASOS, [74]).
- LIDAR are positioned along the parallel runway approach paths and detect, track, and visualise the position and movement of wake vortices at various points on the approach, out-of-ground, near-ground and in-ground proximity, by scanning in different planes and distances from the runways. The LIDAR also take periodic high-resolution wind measurements up to several thousand feet altitude throughout the entire airport area. The systems run in an ‘unmanned’ mode, allowing continuous data collection.
- These sensors are linked to the Wake Turbulence Computer Center Network, and the data is accessible remotely through workstations to enable data monitoring at various locations, and data processing at the Volpe Transportation Center.

Phase II includes the use of CSPR with staggered runway thresholds (a further ‘static’ procedural change element), and the mid-term WakeVAS elements involving active systems. One Phase II element is aimed at increasing departure capacity on CSPR down to the smallest runway centreline spacing permitted in instrument conditions (700 feet) with all weight categories of aircraft as leaders. Another Phase II element is aimed at increasing single runway departure capacity in both visual and instrument conditions. The Phase II WakeVAS research will determine whether ground-based systems that sense and predict winds in the airport area can enable safe reductions in current arrival and departure wake separation distances when specified weather conditions exist. Phase II will employ the data collection technologies used in Phase I, and extend their use, with other technologies, to develop operational systems that can sense and predict winds that determine wake movement and indicate to controllers when ‘wake independent conditions’ will exist for an approach path and runway. This higher level of technology application is expected to provide more capacity benefits than Phase I (by applying at additional airports and with additional types of aircraft in the lead), but with a higher cost of research and development, certification, and acquisition of the WakeVAS systems, and with ongoing operation and maintenance costs.

Phase III systems include additional ground-based and airborne technologies to sense atmospheric turbulence and wake position, and to reduce aircraft positional variation and improve the surveillance of aircraft position. These technologies may include: air-to-ground weather data down-link; required navigational performance area navigation (RNP RNAV) systems; automatic dependent surveillance-broadcast (ADS-B), and cockpit display of traffic information (CDTI). Phase III may provide additional capacity gains by enabling ‘wake independent conditions’ to be determined most often at an airport, based on the most complete information on the position of aircraft and their wakes, and all relevant weather conditions, but at the highest cost.

6. Conclusions and outlook

Transport and decay of aircraft wake vortices in the atmosphere is understood. Consensus has been achieved that predicting the wake evolution requires probabilistic approaches in order to account for the stochastic nature of the atmospheric processes at the temporal and spatial scales of the aircraft wakes, in particular in turbulent environments and for the complex interaction of vortices with wind-shear layers. Neither weather predictions nor actual measurements in the atmospheric boundary layer can be accurate and representative enough to allow the forecasting of the decay and trajectory of a vortex deterministically. Gaps in knowledge, however, still exist with respect to wake vortices in ground proximity, jet-wake interaction, and details of vortex instability mechanisms (for the latter, see the paper of Jacquin et al. in this issue). To answer these open issues the *FAR-Wake* project has recently be launched in Europe.

The components for prediction, observation, and safety assessment, NOWVIV, P2P, VFS, SHAPe, WAVIR, pulsed LIDAR, and RADAR/SODAR/RASS combinations, constitute the corner stones of the European Wake Vortex Prediction and Monitoring System (WVPMS) which is suited to fulfil the operational requirements of modern air-traffic control and management to safely optimise aircraft separations. The components of the WVPMS have been developed and improved within the projects *S-Wake*, *ATC-Wake*, *MFLAME*, *I-Wake*, *C-Wake*, and *AWIATOR*, co-funded by the EU and many partners, and in the DLR project *Wirbelschleppe*. Strong efforts are currently underway in *ATC-Wake* to link WVPMS outputs to the human machine interfaces used by air-traffic controllers and to build up the integrated system platform.

The experience gathered during several field trials has shown that a pulsed Doppler LIDAR is the most promising tool for monitoring the approach and departure corridors at airfields with respect to wake vortices and cross-wind profiles. RADAR/SODAR/RASS may be seen as a robust instrument combination which can be used in an operational environment on an airport site. Even though the temporal and spatial resolution is coarser than that of a LIDAR, it provides all wind components and temperature in real-time and in all weather conditions. Ideally, both types of instruments should be available for operational purposes. With an experimental design as employed during WakeOP, WakeTOUL, and the *AWIATOR* 2003 campaign, measured atmospheric profiles are only available for one NOWVIV grid point. Hence, meteorological information along the glide path is only available from NOWVIV forecasts. These forecasts as well as wind data collected by the aircraft along its flight track in WakeOP attest the substantial variability of wind along the glide path, e.g., due to land surface heterogeneity. Therefore, in the future also the meteorological data collected by commercial aircraft (like AMDAR) will be integrated into the WVPMS. Finally, a dual-Doppler or bistatic weather RADAR surveying the larger-scale wind field in the terminal area will contribute to increasing system performance.

The forecast cycle of the weather forecasting model of the Deutscher Wetterdienst, DWD, will be shortened to three hours by the end of 2005; that is, boundary values for NOWVIV would then be updated every three instead of twelve hours. This should noticeably improve the forecast quality as weather events approaching the NOWVIV domain are easier to recognise and the flow field in the NOWVIV area is in better balance with the external forcing. The forecast quality should further improve when a new version of NOWVIV, currently under development, will assimilate observation data from RADAR and AMDAR into the model runs.

Components of the WVPMS so far have been used in campaigns dedicated to wake characterisation with specifically organised aircraft over-flights and at Frankfurt Airport for collecting wake data of heavy aircraft. Within its project *Wirbelschleppe*, DLR prepares a three months forecast and observation campaign 2006 at Frankfurt Airport where the entire WVPMS including an off-line ATC environment will be tested. It is currently planned to broaden this campaign with German and European partners in order to address also aircraft separations for departures (planned project *CREDOS*) and aviation meteorology issues in general. The goal is to initiate a European Integrated Terminal Weather System.

In the USA, the WakeVAS research provides the FAA and the aviation industry with technically feasible technology options that increase capacity while meeting safety requirements through enhanced wake turbulence procedures. The *Wake Turbulence Research Program*'s multi-phase approach provides intermediate solutions. Periodic reviews of benefits, risks, and costs of the *WTRP* elements are designed to support programme management decisions on each phase. The FAA and economy will then decide which WakeVAS capability enhancements should be implemented based on traffic projections and the consequent market demand for additional airport capacity, balanced against the initial and continuing cost for the ground-based and possibly airborne systems that are required for each WakeVAS concept of operation.

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References

[1] T. Gerz, F. Holzäpfel, D. Darracq, Commercial aircraft wake vortices, Progr. Aerosp. Sci. 38 (2002) 181–208.
[2] G. Astegiani, D. Casanova, E. Isambert, J. van Engelen, V. Treve, Final report WP 1000 system requirements, ATC-Wake Deliverable D1_5, 2003, 41 pp.
[3] D.A. Hinton, J.K. Charnock, D.R. Bagwell, Design of an aircraft vortex spacing system for airport capacity improvement, in: AIAA Proc. 2000-0622, 2000.
[4] P. Fiduccia, W. Bryant, S. Lang, FAA/NASA wake turbulence research program, J. Air Traffic Control 46 (1) (2004) 17.
[5] J.N. Hallock, Vortex advisory system safety analysis, vol. I: Analytical model, Report FAA-RD-78–68, I, Cambridge, MA, DOT Transportation Systems Center, 1978.
[6] C. Le Roux, A. Corjon, Wake vortex advisory system implementation at Orly airport for departing aircraft, Air Traffic Control Quarterly 5 (1997) 31–48.
[7] T. Gurke, H. Lafferton, The development of the wake vortex warning system for Frankfurt airport: Theory and implementation, Air Traffic Control Quarterly 5 (1997) 3–29.
[8] V.J. Rossow, Lift-generated vortex wakes of subsonic transport aircraft, Prog. Aerosp. Sci. 35 (1999) 507–660.

[9] V.V. Vyshinsky, Flight safety, aircraft vortex wake and airport operational capacity, Trudy TsAGI 2641 (1999) 17.

[10] E. Coustols, L. Jacquin, F. Moens, Status of ONERA research on wake vortex in the framework of national activities and European collaboration, in: Proc. of the European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS), Jyväskylä, 2004, p. 10.

[11] E. Coustols, E. Stumpf, L. Jacquin, F. Moens, H. Vollmers, T. Gerz, Minimised wake: a collaborative research programme on aircraft wake vortices, in: AIAA Proc. 2003-0938, 2003.

[12] T. Gerz, T. Ehret, Wake dynamics and exhaust distribution behind cruising aircraft, in: The Characterization & Modification of Wakes from Lifting Vehicles in Fluids, AGARD CP 584, 1996, pp. 35.1–35.8.

[13] F. Risso, A. Corjon, A. Stoessel, Direct numerical simulations of wake vortices in intense homogeneous turbulence, AIAA J. 35 (1997) 1030–1040.

[14] J. Han, Y.-L. Lin, S. Pal Arya, F.H. Proctor, Large eddy simulation of aircraft wake vortices in homogeneous atmospheric turbulence: vortex decay and descent, in: AIAA Proc. 99-0756, 1999.

[15] T. Gerz, F. Holzäpfel, Wingtip vortices, turbulence, and the distribution of emissions, AIAA J. 37 (10) (1999) 1270–1276.

[16] F. Holzäpfel, T. Gerz, M. Frech, A. Dörnbrack, Wake vortices in a convective boundary layer and their influence on following aircraft, J. Aircraft 37 (6) (2000) 1001–1007.

[17] F.H. Proctor, G.F. Switzer, Numerical simulation of aircraft trailing vortices, in: Proc. 9th Conference on Aviation, Range and Aerospace Meteorology, Orlando, 2000.

[18] F. Holzäpfel, T. Gerz, R. Baumann, The turbulent decay of trailing vortex pairs in stably stratified environments, Aerosp. Sci. Technol. 5 (2001) 95–108.

[19] F. Holzäpfel, T. Hofbauer, D. Darracq, H. Moet, F. Garnier, C. Ferreira Gago, Analysis of wake vortex decay mechanisms in the atmosphere, Aerosp. Sci. Technol. 7 (2003) 263–275.

[20] R.E. Robins, D.P. Delisi, Numerical study of vertical shear and stratification effects on the evolution of a vortex pair, AIAA J. 28 (4) (1990) 661–669.

[21] F.H. Proctor, Numerical simulation of wake vortices measured during the Idaho Falls and Memphis field programs, in: AIAA Proc. 96-2496, 1996.

[22] F.H. Proctor, D.A. Hinton, J. Han, D.G. Schowalter, Y.-L. Lin, Two-dimensional wake vortex simulations in the atmosphere: Preliminary sensitivity studies, in: AIAA Proc. 97-0056, 1997.

[23] T. Hofbauer, T. Gerz, Shear-layer effects on the dynamics of a counter-rotating vortex pair, in: AIAA Proc. 2000-0758, 2000.

[24] T. Hofbauer, Numerische Untersuchungen zum Einfluss von Windscherung und Turbulenz auf Flugzeugwirbelschleppen, DLR-FB 2003-01, Köln, 2003, p. 111.

[25] M. Frech, T. Zinner, Wake vortex behaviour classes and their initial validation, J. Aircraft 41 (3) (2004) 564–570.

[26] P. Agnew, D. Hoad, Climatology study of world airports in the context of wake vortex behaviour classes, in: Proc. 10th Conference on Aviation, Range and Aerospace Meteorology, Portland, 2002.

[27] A. de Bruin, L. Speijker, H. Moet, B. Krag, R. Luckner, S. Mason, S-wake, assessment of wake vortex safety, NLR Technical Report 2003-243, 2003, 76 pp.

[28] R.E. Loucel, J.D. Crouch, Flight-simulator study of airplane encounters with perturbed trailing vortices, in: AIAA Proc. 2004-1074, 2004.

[29] T. Gerz, M. Frech, K.-U. Hahn, F. Holzäpfel, F. Köpp, C. Schwarz, I. Smalikho, A. Tafferner, Atmospheric impact on wake vortex development, in: Proc. of the European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS), Jyväskylä, 2004, p. 14.

[30] M. Frech, F. Holzäpfel, T. Gerz, J. Konopka, Short term prediction of the horizontal wind vector within a wake vortex warning system, Meteorol. Appl. 9 (2002) 9–20.

[31] M. Frech, F. Holzäpfel, A probabilistic prediction scheme for wake vortex evolution in a convective boundary layer, Air Traffic Control Quarterly 10 (2002) 23–42.

[32] G.A. Grell, S. Emeis, W.R. Stockwell, T. Schoenemeyer, T. Forkel, J. Michalakes, R. Knoche, W. Seidl, Application of a multiscale, coupled MM5/chemistry model to the complex terrain of the VOTALP valley campaign, Atmos. Environm. 34 (2000) 1435–1453.

[33] G. Doms, U. Schaettler, The nonhydrostatic Limited Area Model LM (Lokal Modell) of DWD. Part I: Scientific Documentation, Deutscher Wetterdienst, Offenbach, 1999.

[34] E.M. North, A.M. Peterson, RASS, a remote sensing system for measuring low-level temperature profiles, Bull. Amer. Meteor. Soc. 54 (1973) 912–919.

[35] S.W. Henderson, P.J.M. Suni, C.P. Hale, S.M. Hannon, J.R. Magee, D.L. Bruns, E.H. Yuen, Coherent laser radar at 2 µm using solid-state lasers, IEEE Trans. Geosci. Remote Sensing 31 (1993) 4–15.

[36] F. Köpp, S. Rahm, I. Smalikho, Characterisation of aircraft wake vortices by 2-µm pulsed Doppler lidar, J. Atmos. Oceanic Tech. 21 (2004) 194–206.

[37] I. Smalikho, V. Banakh, F. Köpp, Ch. Werner, Laser remote sensing of the mean wind, Atmos. Oceanic Opt. 15 (2002) 607–614.

[38] I. Smalikho, F. Köpp, S. Rahm, Measurement of atmospheric turbulence by 2-µm Doppler lidar, DLR-Report 200, 2004, p. 37; J. Atmos. Oceanic Tech., in press.

[39] World Meteorological Organisation, Aircraft Meteorological Data Relay (AMDAR) Reference Manual, WMO-No. 958, Geneva, 2003, p. 24.

[40] L.B. Cornman, C.S. Morse, C. Cunning, Real-time estimation of atmospheric turbulence severity from in situ aircraft measurements, J. Aircraft 32 (1) (1995) 171–177.

[41] F. Holzäpfel, A probabilistic two-phase wake vortex decay and transport model, J. Aircraft 40 (2) (2003) 323–331.

[42] F. Holzäpfel, R.E. Robins, Probabilistic two-phase aircraft wake vortex model: Application and assessment, J. Aircraft 41 (5) (2004) 1117–1126.

[43] F. Holzäpfel, T. Gerz, F. Köpp, E. Stumpf, M. Harris, R.I. Young, A. Dolfi-Bouteyre, Strategies for circulation evaluation of aircraft wake vortices measured by lidar, J. Atmos. Oceanic Tech. 20 (8) (2003) 1183–1195.

[44] T. Hofbauer, F. Holzäpfel, Behavior of aircraft wake vortices subjected to wind shear, in: AIAA Proc. 2003-3813, 2003.

[45] G.J. Hahn, S.S. Shapiro, Statistical Models in Engineering, Wiley & Sons, New York, 1967.

[46] G. Winckelmans, Vortex methods, in: E. Stein, R. de Borst, T.J.R. Hughes (Eds.), Encyclopedia of Computational Mechanics, 3, Wiley & Sons, New York, 2004.

[47] W. Jackson, M. Yaras, J. Harvey, G. Winckelmans, G. Fournier, A. Belotserkovsky, Wake vortex prediction – an overview, Phase 6 and Project Final Report, P 13629E, 2001.

[48] G. Winckelmans, H. Jeanmart, Demonstration of a wake vortex prediction system: the Vortex Forecast System (VFS), in: Proc. 5th WakeNet Workshop on Wake Turbulence and the Airport Environment, Langen, 2001.

[49] G. Winckelmans, V. Treve, L. Bricteux, VFS results on the benchmark for wake vortices IGE, in: Proc. WakeNet-USA and WakeNet2-Europe Workshop on The Prediction of Wake Vortices in Ground Effects in an Operational Context, New Orleans, 2004.

[50] T. Sarpkaya, A new model for vortex decay in atmosphere, in: AIAA Proc. 99-0761, 1999.

[51] T. Sarpkaya, R.E. Robins, D.P. Delisi, Wake-vortex eddy-dissipation model predictions compared with observations, in: AIAA Proc. 2000-0625, 2000.

[52] G. Winckelmans, P. Ploumhans, Prediction of aircraft wake vortices in takeoff and landing, Phase 4 Final Report, TP 13374E, 1999.

[53] G. Winckelmans, F. Thirifay, P. Ploumhans, Effect of non-uniform wind shear onto vortex wakes: parametric models for operational systems and comparison with CFD studies, in: Proc. 4th WakeNet Workshop on Wake Vortex Encounter, Amsterdam, 2000.

[54] G.C. Greene, An approximate model of vortex decay in the atmosphere, J. Aircraft 23 (1986) 566–573.

[55] G. Winckelmans, V. Treve, O. Desenfans, Real-time safety advising system in reduced wake vortex separations operation, as developed in ATC-Wake, in: 2nd WakeNet2-Europe Workshop on Capacity Gains as Function of Weather and Weather Prediction Capabilities, Langen, 2004.

[56] H. Frauenkron, J. Biegholdt, M. Maiss, P. Nalpanis, E. Smith, FLIP – flight performance using Frankfurt ILS, a statistical evaluation of navigational performance of ILS-approaches at Frankfurt International Airport, DFS German Air Navigation Services, Air Traffic Management Division, Offenbach, 2001.

[57] V.J. Rossow, Reduction of uncertainties in prediction of wake-vortex locations, J. Aircraft 39 (2002) 587–596.

[58] K.-U. Hahn, Coping with wake vortex, in: Proc. 23rd International Congress of Aeronautical Sciences, 2002, pp. 732.1–732.14.

[59] K.-U. Hahn, Wake vortex encounter avoidance, in: First Workshop of WakeNet2-Europe, London-Heathrow, November 11–12, 2003.

[60] K.-U. Hahn, C. Schwarz, H. Friehmelt, A simplified hazard area prediction (SHAPe) model for wake vortex encounter avoidance, in: Proc. 24th International Congress of Aeronautical Sciences, 2004.

[61] L. Speijker, S-Wake – final report for work package 4 probabilistic safety assessment, NLR Technical Report 2003-248, 2003, p. 59.

[62] See: http://www.nlr.nl/public/en/index.php?pid=6100.

[63] T. Gerz, Wake vortex prediction and observation: Towards an operational system, in: Proc. 3rd ONERA-DLR Aerospace Symposium, Paris, 2001, p. 10.

[64] K. Friedrich, M. Hagen, Evaluation of wind vectors measured by a bistatic Doppler radar network, J. Atmos. Oceanic Tech. 21 (2004) 1840–1854.

[65] F. Köpp, I. Smalikho, S. Rahm, A. Dolfi, J.-P. Cariou, M. Harris, R.I. Young, K. Weekes, N. Gordon, Characterisation of aircraft wake vortices by multiple-lidar triangulation, AIAA J. 41 (2003) 1081–1088.

[66] M. Frech, A. Tafferner, The performance of the model system NOWVIV to forecast the horizontal wind over an airport, in: Proc. 10th Conference on Aviation, Range and Aerospace Meteorology, Portland, 2002.

[67] M. Keane, D. Buckton, M. Redfern, C. Bollig, C. Wedekind, F. Köpp, F. Berni, Axial detection of aircraft wake vortices using Doppler lidar, J. Aircraft 39 (2002) 850–862.

[68] S. Campbell, T. Dasey, R. Freehart, R. Heinrichs, M. Matthews, G. Perras, Wake vortex field measurement program at Memphis, TN, in: AIAA Proc. 96-0399, 1996.

[69] T. Dasey, S. Campbell, R. Heinrichs, M. Matthews, R. Freehart, G. Perras, P. Salamitou, A comprehensive system for measuring wake vortex behavior and related atmospheric conditions at Memphis, Tennessee, Air Traffic Control Quarterly 5 (1) (1997) 49–68.

[70] R.E. Robins, D.P. Delisi, G.C. Greene, Development and validation of a wake vortex prediction algorithm, in: AIAA Proc. 98-0665, 1998.

[71] D.G. Schowalter, D.S. DeCroix, Y.-L. Lin, F.H. Proctor, S.P. Arya, M.L. Kaplan, Turbulent statistics in the atmospheric boundary layer: A comparison of large eddy simulation with observations, in: 11th Symposium on Boundary Layers and Turbulence, March 27–31, 1995, Charlotte, NC.

[72] C.L. Britt, D.P.C. Nguyen, G. Koch, Pulsed lidar measurements of aircraft wake vortices at DFW and JFK, in: AIAA Proc. 99-0982, 1999.

[73] See: http://www.sensis.com/docs/128/.

[74] See: http://www.faa.gov/asos/.