The ATC-Wake Predictor system and its potential use to increase the capacity at airports

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Abstract
The ATC-Wake project is funded by the EC under the “Information Society Technology” Programme. Main objective is the development of an Air Traffic Control Wake Vortex Safety and Capacity Integrated Platform (IP). This IP is used to evaluate interoperability with existing ATC systems, to assess possible safety and capacity improvements, and to evaluate operational usability and acceptability for air traffic controllers. It constitutes an essential step for installation of an “integrated ATC decision support system” at airports, enabling air traffic controllers to safely apply new optimised weather based aircraft spacing. The system integrates four new wake-vortex related subsystems: a Separation Mode Planner component (based on a weather forecasting and nowcasting system), a Predictor component (based on the weather nowcasting system and on a wake vortex prediction system), a Detector component (based on weather and wake sensors), a Monitoring and Alerting component (which notifies the air traffic controllers in case of a discrepancy between prediction and detection information), as well as Human Machine Interfaces to the controllers. Used in combination with new wake vortex safety regulation, the ATC-Wake System will provide both tactical and strategic benefits, while maintaining the required level of safety. This paper focuses on the ATC-Wake Predictor, which predicts for individual aircraft the wake vortex behavior in the pre-defined arrival or departure area(s). Prediction is performed using probabilistic wake vortex prediction models fed by real-time meteorological data (most recent nowcast data as well as ground or down-linked airborne measurements) from the time the aircraft reaches a critical arrival area entry until it lands and from the take-off until it leaves the critical departure area. The prediction quality being directly related to input data quality (meteorological and radar data), a safety buffer is applied to satisfy accuracy requirements of Air Traffic Controllers and/or regulatory authorities. The prediction is updated in short intervals (6 seconds) and the information is provided to ATC through a HMI in the form of a Wake Vortex Vector. It is also vaulted/assessed by wake vortex measurements (performed by the Detector).

Glossary

AMAN arrival manager
ATC air traffic control
Introduction

The ATC-Wake project is funded by the EC under the “Information Society Technology” Programme (IST-2001-34729). Main objective is the development of an Air Traffic Control Wake Vortex Safety and Capacity Integrated Platform. This IP is used to evaluate interoperability with existing ATC systems, to assess possible safety and capacity improvements, and to evaluate operational usability and acceptability for air traffic controllers. This platform is an essential step for installation of an “integrated ATC decision support system” at airports, enabling air traffic controllers to safely apply new optimised weather based aircraft spacing. The system integrates a Separation Mode Planner component, a Predictor component, a Detector component, a Monitoring and Alerting component, as well as Human Machine Interfaces to the controllers [1,4, 18-21, 25]. Used in combination with new wake vortex safety regulation, the ATC-Wake System will provide both tactical and strategic benefits, while maintaining the required level of safety.

The Separation Mode Planner (SMP) handles the planning phases. It shall not be described here in detail. It is based on weather forecasting and nowcasting, and is coupled to safety assessment of the various conceivable separation distances using the WAVIR toolset [17]. For landing, the SMP forecasts a safe landing rate 40 minutes in advance: this allows the Arrival MANager system (AMAN) to organise the traffic en-route before the entrance in the TMA.

This paper focuses on the ATC-Wake Predictor, which predicts for individual aircraft the wake vortex behavior in the pre-defined arrival or departure area(s). Prediction is performed using real-time available meteorological data from the time the aircraft reaches a critical arrival area entry until it lands and from the take-off until it leaves the critical departure area. It is made using the probabilistic wake vortex behavior prediction systems (P-VFS and P2P), and uses inputs from weather nowcasting and monitoring, surveillance systems (radar), flight data processing systems, and databases on airport layout and aircraft characteristics (span, weights, speeds). The meteorological data consist of the most recent nowcast data as well as ground or down-linked airborne measurements (wind/temperature profiler, wind/temperature aloft). The ATC-Wake Predictor determines, in real-time, the part of the flight track that potentially might be affected by wake vortices. The quality of wake vortex behavior prediction is directly related to the quality of the input data (meteorological and radar data). A safety
buffer has to be applied to satisfy accuracy requirements of Air Traffic Controllers and/or regulatory authorities. The prediction is updated in short intervals (6 seconds) and the information is provided to ATC through a Human Machine Interface, in the form of a Wake Vortex Vector (WVV). The HMI was evaluated, tested, and further improved through real-time approach/tower research simulator sessions. The prediction is also vaulted/assessed by measurements of the wake vortex behavior of preceding aircraft: the task performed by the wake Detector. This paper presents the structure of the Predictor and its underlying sub-systems, and illustrates its potential use to increase the capacity of airports by safely reducing separation under certain conditions.

Within the ongoing ATC-Wake project, an Integrated Platform (IP) is developed, where the various data provider systems are emulated, using the results of a Total Airport and Airspace Simulator (TAAM, performed by Eurocontrol Experimental Center), a radar emulator (developed by THALES), weather databases (measurements and NOWVIV forecasting and nowcasting by DLR) and wake vortex predictors (P-VFS and P2P). The ATC-Wake IP is developed through a Virtual Private Network (VPN) based environment, enabling partner’s access to the virtual IP at their own premises/sites, each partner having its own computer in the ATC-Wake project zone. The functional integration of the various tools from the partners (workflow, inputs, outputs, databases) in the IP is achieved using SPINEware as Middleware technology (from NLR [16]).

**The weather nowcasting and monitoring system**

In order to predict wake vortex behaviour, the atmospheric parameters (wind, temperature and turbulence profiles) influencing wake vortex decay and transport must be known. Weather nowcasting provides forecast of the relevant atmospheric parameters in the airport environment. Here NOWVIV (Nowcasting Wake Vortex Impact Variables) is used which consists of a high resolution mesoscale weather forecast model (MM5) designed to provide realtime 3-D-weather information in the terminal area with a lead time of 3-12 hours and a planned update rate of 1 hour [3]. NOWVIV has a horizontal resolution of 2.1km, 12-50 m in the vertical, and considers orography and detailed land use maps to predict realistic boundary layer features. NOWVIV is driven by standard weather forecast provided by the German Weather Service (DWD) and continuously assimilates data from weather observation systems installed in the airport environment. The weather monitoring may consist of Radar, Profiler measurements or any other data source around the airport environment. NOWVIV provides meteorological profiles about every nautical mile along the glide path. The output of NOWVIV is used by the SMP to decide on the safe separation mode. The weather observations in the terminal area are fused in order to obtain a best-guess of the atmospheric state in real-time along the glide path with an update rate of two minutes. These data are used as input to the wake predictors P-VFS and P2P. The ATC-WAKE IP is tested using data from the two dedicated European wake measurement campaigns WakeOP and WakeToul. There a SODAR/RASS (wind, turbulence, temperature) and a 2µm Lidar (cross wind, turbulence) provided the necessary meteorological profiles to describe the wake transport and decay measured by Lidar systems. The nowcasting and observation system has been tested successfully during those measurement campaigns [9].

Precipitation cloud motion estimation by radar can also be useful for nowcasting of the wind field. This task is challenging: indeed, during thirty minutes, the morphology of weather cells (their growth and decay) can change considerably because meteorological phenomena are characterized by distributed systems with motion across a wide spectrum of scales and with topological changes. THALES has solved the tracking and forecasting of these evolving dynamic systems by matching morphological skeletons of previous radar reflectivity images, smoothing and interpolating a dense wind field that deforms weather cell shapes and provides a good estimation of their position for the next thirty minutes. This nowcasting of wind field provides reliable wind profile information along the glide slope at different altitudes, in a form accessible to the wake predictors. Estimating wind field and weather cells motion by tracking their morphological skeletons is an innovative processing entitled SKEWIND. To our knowledge, no study has focused on this kind of techniques. Skeletons features methods are more robust than classical centroid features methods in case of complex shapes, non-linear deformation and topological changes. To validate qualitatively the wind field estimation provided by SKEWIND, THALES has exploited data from DLR’s POLDIRAD in Doppler monostatic or bistatic modes, see Fig. 1. The main goal was to prove that the horizontal wind field could be successfully estimated from a sequence of radar reflectivity images, without additional Doppler information. Indeed, most large airports already have at their disposal meteorological information of radar reflectivity through meteorological radars (radar integrated in a national network, close to the airport) or through the weather channel of a primary radar [2].
The wake vortex behavior predictors

The Predictor system relies on the real-time prediction of wake vortex (WV) behavior: transport and decay. Nowadays, WV prediction models take into account the aircraft types (span, weight), the flight conditions (position, velocity and trajectory), the weather conditions along the glide slope (cross-wind and head wind profiles, thermal stratification profile, turbulence profile), the wind shear effects (significant vertical variation of the wind) and the ground proximity effects: near ground effects (NGE) and in ground effects (IGE, where secondary vorticity produced at the ground significantly affects WV transport and decay). In ATC-Wake, the two main European real-time models are being put to use (and also further developed and validated): the “Probabilistic use of the Vortex Forecast System” (P-VFS) and the “Probabilistic Two-Phase Decay model” (P2P).

The VFS is a deterministic WV predictor based on the method of discrete vortices (discrete “vortex particles”): those are used to model the aircraft wake vortices (the “primary” vortices) and the “secondary” vortices generated near the ground when IGE. The VFS was developed by an international team (SABIGO of Russia, Oracle Telecomputing Inc. and M. Yaras of Canada, and G. Winckelmans of Belgium), in the framework of the 1994-2000 Transport Canada (TC) “Wake Vortex Project”, see [13,23]. The VFS produces one deterministic WV prediction (transport and decay) in each “computational gate” (a vertical 2-D slice of space), taking into account the generator aircraft type (span, weight), speed and altitude. A summary description of the models implemented in VFS, including the further improvements done after completion of the TC project, can be found in [24,26]. All models are implemented using an “accumulated damage” approach, so as to capture the variations of the input profiles with altitude. The evaluation of the “demise time” uses the formulation based on the atmospheric turbulence (using the “eddy dissipation rate”, EDR) and modified for stratification effects: following [8,9]. Two decay models are implemented: the EDR-based decay model, but further calibrated based on large-eddy simulations (LES), and the TKE-based model. The two-phase decay approach is also implemented, following [8,9]: in VFS, this is done by increasing the coefficient in the decay model after the demise time has been reached. A two-equation model is used to capture the stable stratification effects [26], acting on both the circulation decay and the vertical acceleration, and consistent with behavior obtained from LES [6]. A non-uniform wind shear model is also implemented [22] which also accounts for tilting effects of the WV system. The inviscid NGE are modelled using image vortices; the viscous IGE effects are modelled using secondary vortex particles produced near the ground at the location of the separating boundary layers. The stratification, wind shear, and ground models allow to capture complex WV behaviors (e.g., tilting effects and rebound effects).

Figure 1: wind field estimation along a glide slope, as produced by SKEWIND applied to radar sequences.
Precise deterministic WV predictions are however not feasible operationally. Primarily, turbulence, by its nature, deforms and transports the vortices in a stochastic way and leads to considerable spatio-temporal variations of vortex positions and strengths. This is even more true in complex situations such as near ground behavior and behavior under wind shear conditions. Moreover, the uncertainties on aircraft parameters (weight, speed, position) and the variability of environmental conditions must also be taken into account. Probabilistic modelling and assessment is clearly required. An upper software layer was thus developed by UCL, for “probabilistic use of the VFS”: the “P-VFS”. It is based on Monte Carlo type simulations (many VFS runs) using the uncertainties/variants of the aircraft generator parameters, of the input weather profiles, and of the model coefficients. An example of prediction results, for one computational gate, is shown in Fig. 2.

The P2P model [8-11] is the other predictor used in the Predictor system. As P-VFS, the P2P accounts for the effects of the wind components, wind shear, turbulence, stable thermal stratification, and ground proximity. The model equations are derived from the analytical solution of the spatio-temporal circulation evolution of a decaying potential vortex and are adapted to wake vortex behaviour as observed in LES and experiments [6,7]. Vortex decay progresses in two phases: a diffusion phase followed by rapid decay, see Fig. 3. The descent rate obeys a non-linear dependence on circulation which allows for stagnating or even rebounding vortices in case of strongly stably stratified environments, as observed in LES and experiments.

The output of P2P consists of confidence intervals for vortex position and strength (see Fig. 3). This is achieved by performing three subsequent runs with variations of the decay parameters and by adding uncertainty allowances which depend on ambient turbulence and wind shear. The predicted envelopes enclose 99.7%, 99.5%, and 97.6% of observations for lateral position, vertical position, and circulation, respectively (based on a sample of 49 overflights). A recently developed approach [5,11] allows to map statistics of vortex measurement data onto the probabilistic output such that envelopes of arbitrary probability can be predicted.
The P2P approach is thus different than that of the P-VFS. Yet, the purpose (probabilistic assessment of WV transport and decay) is similar: they output confidence intervals for vortex position and strength \([10,24]\). In ATC-Wake, both modelling approaches are considered complementary. Their joint use, within the ATC-Wake IP, further increases the level of confidence on the WV behavior probabilistic prediction, and thus enhances the quality of the information provided to the ATC controllers (see also \([4,5,25]\)).

![Figure 3](image)

**Figure 3**: Measured (symbols) and predicted (lines) evolution of normalized vertical and lateral positions and circulation of wake vortices, as provided by P2P: deterministic behavior (dash) and probabilistic envelopes (solid).

The ATC-Wake platform handles such probabilistic simulations and assessments for all gates corresponding to all aircraft in the airport area (a “gate” being defined as the plane crossed by one aircraft at one time; they are created every 6 seconds). The proper reconstruction of the complete WV situation, using all dynamic gates and a 3-D space-time reconstruction, finally ends up providing the time evolution of the “3-D danger volume” in which the WV could be found: the usable results required by the ATC-Wake Predictor system. An example of danger zone evolution, as done in the ATC-Wake virtual IP, is shown in Fig. 4.

![Figure 4](image)

**Figure 4**: Example of danger volume prediction by the ATC-Wake IP. Here, one slice corresponding to one computational gate, for a B737 at 4250 m from the runway and with cross-wind. The danger zone evolution is
here shown from 0 to 48 secs, by step of 6 secs. At time 0, the aircraft passes the gate; its position is indicated by the cross symbol. The ICAO corridor tolerance is shown in dash.

**The wake vortex monitoring system**

Lidars are able to detect and monitor wake vortices in real time (see, e.g., [12,14]). Since Lidar is a fair weather tool (it requires a certain amount of visibility), it may be complemented by Radar techniques to detect wake vortices. Ideally the whole glide path should be monitored for wakes while the focus should be on the wake detection close to the surface where a wake encounter may be most critical. During the two measurement campaigns WakeOP and WakeToul wakes were scanned perpendicular to the flight path in order to characterize the strength and position of the wake [14]. The wake vortex monitoring system acts as a safety net in the ATC-Wake system and is part of the ATC-WAKE Monitoring & Alerting System. The actual wake position is analysed and a warning is issued if a wake is found in the safety corridor of an approaching aircraft.

![Figure 5: Quick lock of a 2µm Lidar. Shown are the line-of-sight velocities in a vertical cross section perpendicular to the flight path. of Lidar scan. The signature of a wake is visible at a height of around 250 m.](image)

There is also the newly developed DOPVOR tool by THALES: it provides air turbulence maps inside a specific sector in azimuth for different elevations (these measurements being then put in the proper coordinates system). The turbulence measurements are deduced from regularized high resolution Doppler analysis of spectrum width based on Poincaré’s metric on reflexion coefficients and Cepstrum metric. So far, DOPVOR has been tested on records database of Doppler I&Q (In Phase and Quadrature) data from DLR’s POLDIRAD, for cases with atmospheric turbulence only. Its testing on the actual detection of wake vortices is expected in the near term.

**The Human Machine Interface (HMI)**

The output of the ATC-Wake Predictor is the Wake Vortex Vector (WVV) of an aircraft in the so-called critical area. This information is presented as an enhancement on a Plan View Display (PVD). The PVD shows, in a God's eye view, the information received from the airport radar's, combined with flight track data (call sign, aircraft type, height, speed etc.). Each controller has a PVD; but the range, labelling and details are dependent on the task of the controller. Because the WVV is only calculated in the critical area (an area close to the glide slope) only changes to the PVD of the Final Approach controller and Tower controller are foreseen. Other guidelines for a new HMI are that the WVV should be presented in an unambiguous way, is easy to understand, will not be used for separation planning, and will not add additional workload. Furthermore, it should draw the attention of a controller in case of an alarming situation (such as a WVV in the critical area). Interviews with air traffic controllers resulted in three different HMI formats. To select the best HMI, a small real-time simulation experiment has been executed on the NARSIM (Tower and Approach) simulators of NLR. The different HMI's and the whole ATC-Wake concept have been integrated and tested in the Schiphol environment. Nine controllers from 5 different countries participated; all have chosen the "Variable Wake Vortex" HMI as the best solution. Figure 6 shows the "Variable Wake Vortex" for the Approach controller. New is the blue coloured vector behind
each aircraft, representing the WVV and varying (using information from the Predictor) along the glide slope. Also a micro-label with the distance to the preceding aircraft is proposed.

![Figure 6: ATC-Wake HMI for Approach controller](image)

In case of an alarm, the colour of the WVV will change to orange and an audio alarm will be raised (see Fig. 7). The selected HMI and ATC-Wake concept have been received very well by the controllers, which certainly support the expected benefits of the concept.

![Figure 7: ATC-Wake alarm for Tower controllers](image)

**Conclusions**

The ATC-Wake Predictor system has here been described. It is a part of the ATC-Wake Integrated Platform. So far, the IP is such that the various data provider systems are emulated and was developed through a VPN based environment and SPINEware technology. Illustrative results of the Predictor system as part of the IP were provided: WV behavior prediction, danger volume prediction and wake vortex vector provided to the controllers. These developments (work flows, tools and their integration) can already be used for simulations. It is expected that they will also serve as the basis for developing a "prototype real-time system" operating at an airport.

It is understood that the implementation of a new ATC system, allowing reduction of separation during landing or take-off phase, will have to ensure the same, or even higher, level of safety as the current flight procedures. New proposed wake vortex safety regulation will have to comply with the Eurocontrol Safety Regulatory Requirements (ESARR 4) to ensure that the new services provided by ATC-Wake meet minimum levels of safety. The ESARR 4 requirements concern the use of a quantitative risk based-approach in ATM when introducing and/or planning changes to the ATM system. Once system changes have been introduced, in the context of “safety monitoring”, it then becomes important to monitor the actual number of wake vortex
encounters. Results from these wake vortex safety monitoring activities at an airport would then be fed back into the ATC-Wake Predictor in order to tailor its use to the airport, and thereby increase the performance and reliability of the ATC-Wake system.

**References**


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