[EN-048] Enhancing Wake Vortex Surveillance Capability Using Innovative Fusion Approaches

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Abstract: A new concept for collaboration of wake vortex prediction and measurement is introduced in this paper. This approach has the ability to enhance wake vortex surveillance capability of both airborne and ground wake vortex warning or avoidance systems. Thus, a significant step towards the increase of airport and air space capacity while maintaining or even improving current wake vortex safety could be achieved. Following an overview of the model and sensor components the fusion concept is being described. Implementation examples are given for ease of understanding.

Keywords: Wake Vortex Surveillance, Sensor/Data Fusion, Safety, Capacity

1. INTRODUCTION

Directly following from aerodynamic lift, vorticity is generated by the aircraft, which after complete roll-up evolves into a pair of counter-rotating vortices. These wake vortices can become a serious danger for the succeeding aircraft leading to loss of control. Therefore, to assure that wake turbulence generated by the predecessor has decayed to a level where it does not pose a hazard anymore, the follower aircraft must respect certain separation minima.

Today's wake vortex separations are regulated by strict criteria based on the maximum take off weight of an aircraft that have been set up by ICAO documentation (ICAO Doc 4444 PANS-ATM, [1]) in the 1970s. They have proved sufficiently safe but are also very conservative, as they assume a worst-case scenario (i.e. extremely calm air and no lateral winds). In the consequence, the existing wake vortex regulations often unnecessarily limit capacity. This already poses a significant problem to many major congested airports that operate nearly at their capacity limit today. Despite of the decrease in traffic caused by the economic downturn during the past two years, air traffic is still forecast to increase. For European region, the medium-term forecasts expect a stable growth of 3% per year, meaning that there will be around 22% more IFR flights in 2016 than there were in 2009 (see e.g [2]). Consequently, the challenge to balance available capacity and demand will even increase. However, the required capacity increase brought about by any change of separations or procedures will have to preserve or even to improve the current safety level.

Moreover, for the future concepts of free flight [3] and Trajectory Based Operations (TBO) [4] will become indispensable for the pilot to obtain full awareness of his environment including potentially hazardous vortex traffic. At the moment, no onboard system exists that would provide this information with enough accuracy and reliability.

For the purpose of wake vortex surveillance, two basic approaches are available: the prediction by a mathematic model and the physical detection by a dedicated sensor. Both elements are part of the projected Wake Vortex Warning, Advisory or Avoidance Systems that are objectives of contemporary research. But at the moment, both the prediction and the monitoring functions work independently which means that they do not have the ability to deliver direct mutual support e.g. by correcting each other, thus resulting in necessity of increased safety margins to account for system inaccuracy and uncertainty.

The research results and objectives that will be presented in this paper aim exactly at this point of collaboration of sensor and model. The Institute of Flight Guidance of the Technische Universiaet Braunschweig is currently investigating the close-coupling approach for measurement and prediction in the scope of the EUROCONTROL Research Grant scheme. This fusion concept has been successfully applied in other areas like integrated navigation but its application is new to the domain of wake vortex detection and monitoring.

The obvious advantages of fusion applied in wake vortex surveillance systems are first of all the decreased uncertainty of information about the vortex state. This will in turn reduce the false alarm rate and allow higher performance, resulting in more capacity gain, safer performance as well as better acceptance compared to systems operating with separated prediction and detection functions.

2. FUSION CONCEPT

The approach being currently investigated for the coupling of wake vortex prediction and detection is the use of an observation or estimation filter, the best known realization of which is certainly the Kalman filter as described e.g. in [9]. This approach is widely used amongst others in integrated navigation systems of aircraft, where sensor measurements with complementary error characteristics are fused in order to obtain an optimal solution for the system states. For this purpose, a mathematical model for the system dynamics is required.

The filter generally operates in two – not necessarily alternating – steps: a time update step, where the system state is predicted based on the current state, and a measurement update which is obviously performed when new sensor data are available.

Obviously, the wake vortex modeling and measuring show similarities to the established fusion filter applications. So to transfer the fusion approach to the domain of wake vortex monitoring looks promising.

2.1 Wake Vortex Model

Mathematical models exist that describe and predict wake vortex generation, evolution, transport and decay based on atmospheric and aircraft inputs. The issue of modelling wake vortices is extremely complex, so only some of its general characteristics will be briefly explained here for ease of understanding.

The models coming into focus for operational use with a fused system are the so-called fast-time models that reliably predict vortex characteristics as vortex strength (called circulation) and decay as well as position in faster than real-time. They were developed using theoretical concepts according to the underlying physical principles and calibrated with empirical data. Some of the best known representatives are NASA's Aircraft Vortex Spacing System Prediction Algorithm (APA) [5], UCL's Deterministic Wake Vortex Model (DVM) [6] and finally

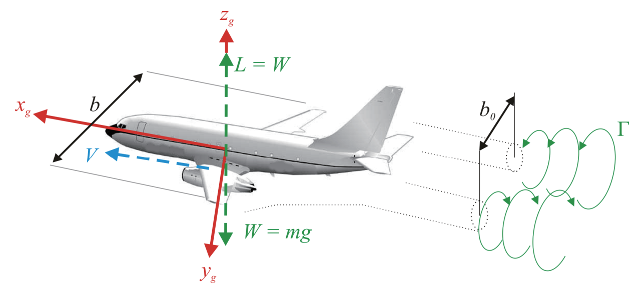

Figure 1 Wake generating aircraft with the respective wake parameters

the model developed by DLR called the Deterministic 2 Phase Wake Vortex Decay and Transport Model (D2P) [7]. DVM and D2P have been further developed to deliver probabilistic predictions to account for the uncertainties of model input. The main model inputs are parameters of the generating aircraft, namely weight, airspeed, wingspan and position, as well as meteorological data (e.g. wind vector over height, turbulence and temperature). Fig. 1 illustrates the aircraft parameters that influence the wake generation.

The accuracy of model predictions is highly dependent on the accuracy of the atmospheric and aircraft specific input. Due to the stochastic nature of the atmospheric environment, uncertainties can not be avoided which makes deterministic predictions quasi impossible. Furthermore, the uncertainties grow in time.Therefore, DVM and D2P have been further developed to deliver probabilistic predictions to account for the uncertainties of model input. For the first implementation of the fusion approach presented in this paper the prediction algorithms of DLR's model have been chosen, as the algorithms are published [7], [8] and allowed a straightforward adaptation to a collaborative prediction and detection system.

The scheme in Fig. 2 illustrates the processes performed by the D2P algorithms: with the parameters of the wake generating aircraft, including the initial position of the wake $\underline{x}_0$, D2P estimates the initial vortex state. The atmospheric conditions, namely wind vector $\underline{v}_w$, temperature T, turbulence parameter eddy dissipation rate ε and air density ρ are provided over height z. The circulation decay and vortex transport algorithms predict the vortex state for any time step t_i.

The maturity of the D2P algorithm has been assessed in several experiments and its ability to predict vortex behavior in an adequate way has been proved. So undoubtedly, its short term predictions deliver a good estimate of the vortex state and are available at very high update rates.

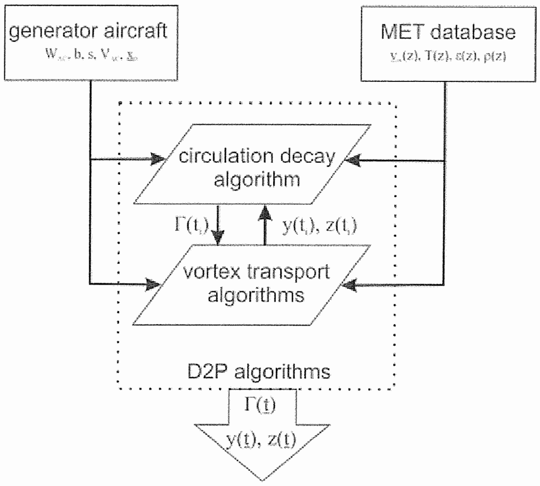

Figure 2 D2P algorithm scheme

2.2 Wake Vortex Sensor

Wake vortex detection (either ground based or for on-board applications) is realized by means of remote sensing technology. Here, especially the RADAR and LIDAR sensors come into focus, both utilizing radio waves to sense movement of the ambient air masses. For the purpose of this paper, exemplary the wake detection by LIDAR should be explained in more detail in order to discuss the fusion issues. Nevertheless, as the application of RADAR technology for the purpose of wake detection becomes available, it should be mentioned that the fusion concept can be adapted to this sensor in a similar way.

The LIDAR system is measuring the line-of-sight velocity of the aerosols in a certain scanning plane. The general principles of scanning and measuring of the backscattered signal are illustrated in Fig. 3. From the velocity distribution the position of the wake vortex is determined e.g. via the slopes of the tangential velocity distribution. Fig. 4 shows the vertical velocity distribution of the left (dashed line) and right (fine solid line) vortex behind an aircraft. Both distributions overlay to the velocity distribution of the vortex pair (solid bold line). There exist several methods to determine the wake vortex circulation from this distribution.

The major advantage of wake vortex monitoring by LIDAR or RADAR lies in the physical turbulence detection which no model can provide. But this achievement comes at high computational burden which means that many processes have to be automated. As the flow field in an operational environment is very complex, this automated process is prone to errors like over- or underestimation or even failure of recognition of mature vortices from the velocity field and suffers in addition of the measurement noise.

As no information is available between single measurements and the update rate is relatively low, even loss of track may occur (which is an even greater problem for onboard LIDAR systems). But in the case of successful wake detection, the system has updated information on vortex state that can be used to decrease its uncertainty.

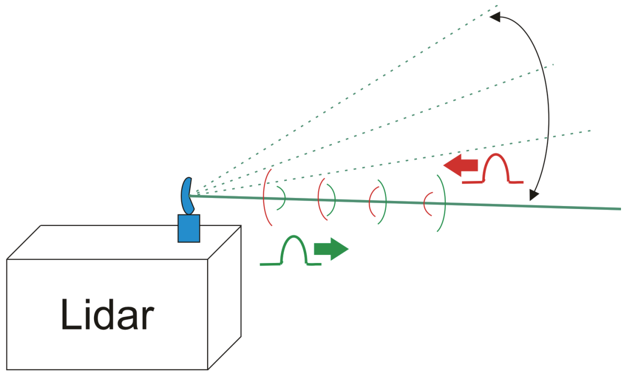

Figure 3 General scanning and measuring principles of LIDAR sensors

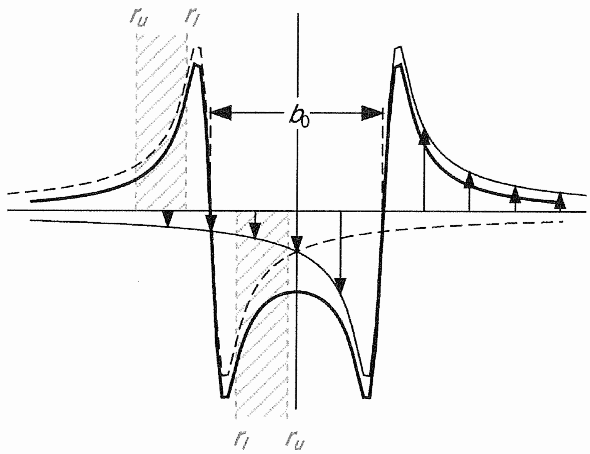

Figure 4 Vertical velocity profile of wake vortex system

2.3 Collaboration of Model and Sensor

Considering the complementary characteristics of wake prediction and vortex detection described above, one can assume that a collaboration between the two would result in a more reliable and accurate solution.

Several methods of coupling models with measurements exist. Some of them will be introduced here with the focus on their performance and possible field of application. They mainly differ in the way how the models are integrated into the fused system and how the measurements are fed to the system.

First one has to differ between error state fusion and full state (or total state) fusion. In an error state approach, the fusion filter is estimating the errors of the model prediction, e.g. in the case of wake vortex tracking the lateral and vertical wake vortex position error and the error in wake vortex strength prediction.

In contrast to the error state approach, a total state system estimates the system states directly. This system would not use a separate prediction module, but would incorporate the prediction model algorithms within the fusion filter propagation step. In the course of this paper the error state approach will be described in more detail.

There are two possible ways to deal with the estimated error states. They can either be used to correct only the output of the model or the sensor in an open-loop setup or they can be fed back to either of the modules, which is then called a closed-loop system.

In the following, two examples of error state systems will be presented to explain the interaction between the system modules.

In an open-loop configuration as presented in Fig. 5, the wake vortex prediction models would be corrected by the estimated errors.

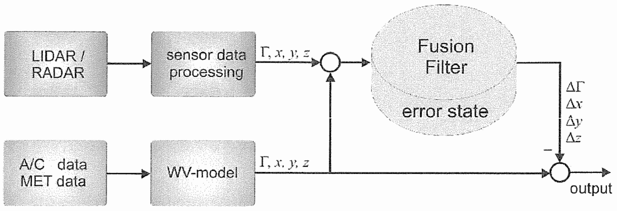

Figure 5 Loose-coupled open-loop error state system

In this way, the sensor processing and the model algorithms remain untouched and the coupling delivers additional fused output. The result of the collaborative system (marked by the superscript $^+$) is generated by correcting the a priori model output (indicated by the superscript $^-$) with the propagated error estimations according to Equ. (1).

$$\begin{aligned} \Gamma^+_{output,k} &= \Gamma^-_{prediction,k} - \Delta\Gamma^+_k \\ y^+_{output,k} &= y^-_{prediction,k} - \Delta y^+_k \\ z^+_{output,k} &= z^-_{prediction,k} - \Delta z^+_k \end{aligned} \tag{1}$$

The advantage is that no changes have to be implied on already existing processes and the modules can readily be used. However, as measurement and prediction will get no feedback on the accuracy of their output, they can not improve their performance. This will lead to a lower benefit than that provided by other fusion setups, but its uncertainty will still be less than the one of a stand-alone prediction because of the measurement update.

In the case that estimated errors are fed back to the prediction or sensor module, the system is operating in closed-loop mode. An example for such a system is presented in Fig. 6, incorporating both feedbacks to the model and to the sensor processing unit.

The model will need an interface to accept corrections in circulation strength and wake vortex position (*ΔΓ, Δx, Δy, Δz*). Also estimated errors in meteorological input (e.g. crosswind errors or errors of initial circulation strength) can be provided by the filter to improve the further forecasts.

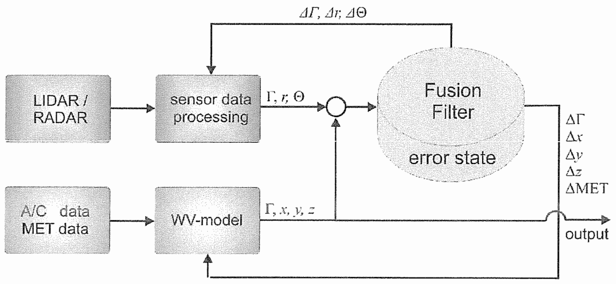

Figure 6 Deep-coupled closed-loop error state system

In order to make this interaction possible, the model will have to allow feedback also between time propagation steps t_i. This means that the computation of every state will have to be discretised. For example, circulation at time step $k+1$ will be calculated according to Eq. (2):

$$\Gamma_{k+1} = \Gamma_k + \dot{\Gamma}_k \cdot dt \tag{2}$$

where Γ_k represents the circulation of the preceding time step and $\dot{\Gamma}_k$ is the decay rate. The same demand applies to position calculations. Here, the algorithms are even more complex, especially when ground effect has to be taken into account. This is usually done by introduction of secondary and tertiary vortices, whose positions and circulations will have to be corrected as well.

The values at the propagation step will then be calculated according to Eq. (3):

$$\begin{aligned} \Gamma^+_{prediction,k} &= \Gamma^-_{prediction,k} - \Delta\Gamma^+_k \\ y^+_{prediciton,k} &= y^-_{prediction,k} - \Delta y^+_k \\ z^+_{prediciton,k} &= z^-_{prediction,k} - \Delta z^+_k \end{aligned} \tag{3}$$

2.3.1 *Results*

The fusion approach described above aims at providing more accurate information on the wake vortex state than the sole prediction or only sensor measurements. In order to investigate this ability, simulations were used (see [10]) where intentionally erroneous meteorological information was provided to the model.

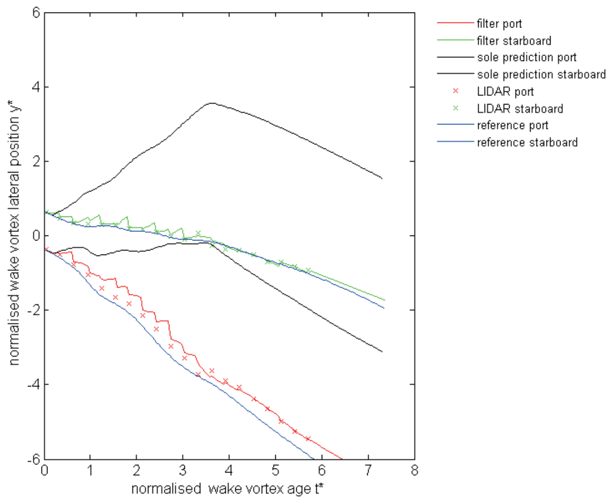

Figure 7 Comparison of fused system and sole prediction for simulated error in crosswind determination [10]

The crosswind that is an essential mechanism for lateral wake transport was charged with a constant offset up to the normalised wake vortex age $t^* = 4$. The effect on model prediction, see Fig. 7, is considerable when compared to the reference trajectory given by the simulation using correct crosswind information. Additionally, measurements of the vortices provided by a LIDAR sensor were simulated that varied around the true position of the vortex.

The fused system, implemented as an error state system, was able to estimate the error in crosswind input using the measurement updates and could provide a more accurate lateral trajectory. Consequently, the uncertainty bounds in order to cover possible wake vortex positions can be decreased compared to sole prediction.

3. APPLICATIONS FOR FUSED WAKE VORTEX SYSTEMS

Fusion systems as the one introduced in this paper can be applied for wake prediction and detection either as ground based implementations for wake monitoring on airport sites or as on-board systems for airborne detection and display of wake vortex traffic. These two possible applications shall be discussed in the following, focusing on the system requirements and the integration in the available infrastructure.

3.1 Airborne Environment

The general problem is depicted in Fig. 8, where the wake vortex generated by the preceding aircraft is being tracked in a certain scanning plane by the follower by use of a dedicated sensor installed on-board of this aircraft.

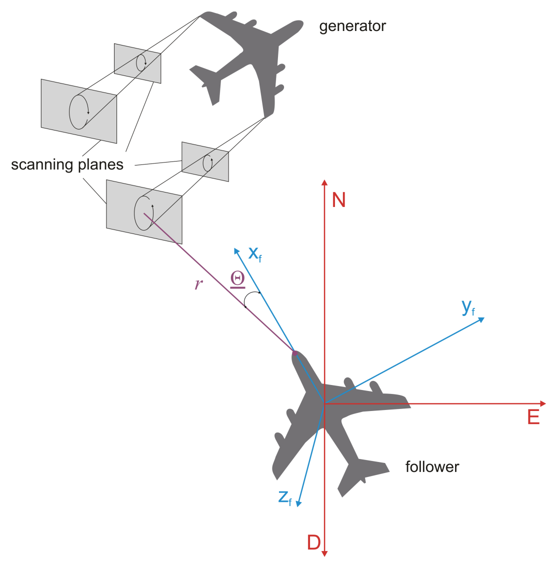

Figure 8 Detecting and tracking wake vortices on-board

The range r and bearing Θ are also available on board and are measured in the body-fixed coordinate system of the follower. The measurement conditions are difficult because of the large search space and potentially unfavorable viewing angle of the sensor. Therefore, detection and tracking by a stand-alone sensor can be difficult and become noisy and infrequent. But the fused system is able to minimize these problems by making use of the wake vortex prediction which describes the tracked object's dynamics and is able to predict its behavior between measurements. Because of this a-priori knowledge, the sensor can be aided in acquisition and tracking of the vortex and thus can work more stable and deliver more accurate information. This information will in turn be used by the system to correct the input parameters of prediction and decrease its uncertainty.

The deep-coupled closed-loop approach as described above is applicable for use with an on-board sensor as it could be linked directly to the sensor control unit and would provide the required information with a high trustworthiness. The performance would increase significantly compared to standard tracking algorithms usually available for such onboard sensors.

The system needs to be integrated into the aircraft's avionic system in order to receive the parameters it requires for wake prediction and detection as shown schematically in Fig. 9.

The output of the system could e.g. contain vortex hazard areas indicating also the remaining circulation intensity level, inflated with a safety factor to account for the remaining uncertainty. This information could be passed on to a Human Machine Interface (HMI) in order to display the no-fly areas to the pilot (comparable to the already existing traffic display used for collision avoidance). Another possibility is to connect the system with the Flight Control System of the aircraft if an automated conflict resolution shall be implemented.

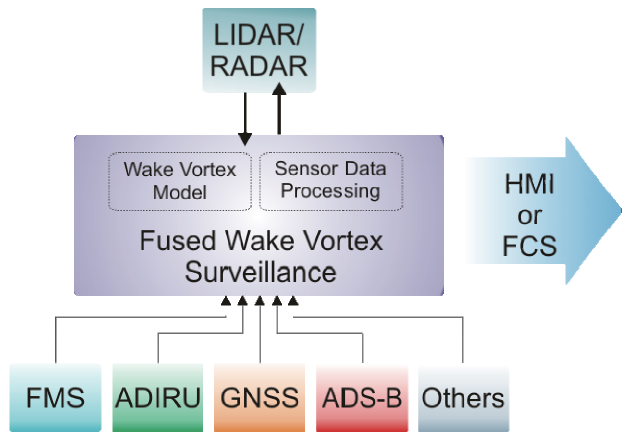

Figure 9 Scheme of possible interfaces with the aircraft avionics

3.2 Airport Environment

The problem of wake vortex surveillance in an airport environment differs from an airborne application in several aspects, such as fixed sensor position, limited monitoring area, larger time horizon and available information sources (as wind and temperature forecasts and in- and outgoing air traffic). Also, an adequate integration into the overall ATC system has to be considered in order to achieve the expected safety and capacity improvements. Many of these aspects have already been subject to contemporary wake vortex research, see e.g. [11]-[13]. Here, only the possible impact of a fused wake vortex surveillance system shall be mentioned to highlight its expected benefits.

The need to verify model predictions via additional detection sensors has already been recognized by the designers of the Wake Vortex Warning and Advisory Systems mentioned above. Yet, in these systems the sensor has been used either for research aims in post process (e.g. to tune the model parameters) or to identify potentially erroneous predictions of the model. They do not give any in situ feedback to the system prediction part that would improve its future forecasts. Neither is it envisioned to provide the monitoring part with a-priori information to facilitate its measurement capabilities.

Here is the essential difference of the novel fusion approach developed by the Institute of Flight Guidance. It aims to provide both available wake forecasts to the sensor part and physical detection information to the model component. Moreover, from the comparison of the complementary information obtained from prediction and measurement, the overall system uncertainty can be optimally estimated and continuously updated. This would result in reduced uncertainties and thus a better availability of the system for operation. Also the false alarm rate could be reduced while the safety level would be maintained.

The open-loop system as presented above comes into focus for airport wake surveillance systems that are already operative and therefore no changes of the existing components are possible. Applied as superimposed layer to compare and improve wake turbulence forecasts it would contribute to increasing availability and integrity of the system. That would allow increasing the operational time of the system and thus possibly leading to augmented tactical capacity.

4. OUTLOOK

This paper presented the general concept of collaboration of wake vortex prediction and detection. One possible implementation using a Kalman filter for error observation was discussed in more detail. It has been discussed that results of the fused system were much more reliable compared to stand alone prediction and the system has the capability to compensate significant errors of the model input (e.g. erroneous cross wind measurement).

The fusion algorithms presented here are still under development and will be constantly improved. For instance, the error propagation model is being refined using more complex error modeling.

For application of the collaborative approach either in an airborne system or in an airport based wake vortex surveillance system some further development steps would be required. The development of interfaces between the fused system and the airborne systems has to be further investigated, e.g. the provision of traffic information available on-board or the adequate presentation of wake vortex hazards to the pilot are subject of research at the Institute of Flight Guidance. For applications on ground, the correct propagation of error behavior of the wake vortex and wind sensors is essential for effective implementation of the fused system. Also the right integration of available wake vortex information into the existing Air Traffic Control system should be further investigated in order to find innovative solutions for improved use of the available capacity.

5. ACKNOWLEDGMENTS

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6. REFERENCES

[1] ICAO Doc 4444 PANS-ATM Fifteenth Edition 2007, Chapter 4, Paragraph 4.9.1.

[2] EUROCONTROL Medium-Term Forecast: IFR Flight Movements 2010-2016, ed. 1.0. EUROCONTROL, February 2010.

[3] RTCA, Final Report of RTCA Task Force 3; Free Flight implementation, RTCA Inc., Washington DC, October 1995.

[4] FAA Federal Aviation Administration, "NextGen Implementation Plan", Appendix B, March 2010.

[5] Robins R, Delisi D., "NWRA AVOSS wake vortex prediction algorithm version 3.1.1", NASA/CR-2002-211746, Hampton, Virginia, National Aeronautics and Space Administration, 2002.

[6] De Visscher I, Winckelmans G, Desenfans O, Lonfils T., "Overview of UCL operational tools for predicting aircraft wake vortex transport and decay: the Deterministic/Probabilistic wake Vortex Models (DVM/PVM) and the WAKE4D platform", Louvain-la-Neuve, Belgium, Universite catholique de Louvain (UCL), 2008.

[7] Holzaepfel F., "Probabilistic two-phase wake vortex decay and transport model", Journal of Aircraft, Vol. 40, (no. 2), American Institute of Aeronautics and Astronautics, 2003, pp. 323-331.

[8] Holzaepfel F., "Probabilistic two-phase aircraft wake vortex model: further development and assessment", Journal of Aircraft, Vol. 43, (no. 3), American Institute of Aeronautics and Astronautics, 2006, pp. 700-708.

[9] Zarchan P, Musoff H., "Fundamentals of Kalman Filtering: A Practical Approach", 2nd Edition, Progress in Astronautics and Aeronautics, Vol. 208, American Institute of Aeronautics and Astronautics, Inc., 2005.

[10] Steen, M., Schoenhals, S., Hecker, P., "Collaboration of wake vortex models and sensors in modern avionics systems", Proc 28th Digital Avionics Systems Conference, Orlando, Florida, paper #136, 2009.

[11] Holzaepfel, F. et al, "The wake vortex prediction and monitoring system WSVBS Part I: Design", in: "The DLR project Wirbelschleppe: detecting, characterizing, controlling, attenuating, understanding, and predicting aircraft wake vortices", DLR research report 2008-15, 2008, pp. 73-88.

[12] Gerz, T. et al, "The wake vortex prediction and monitoring system WSVBS Part II: Performance and ATC integration at Frankfurt airport", in: "The DLR project Wirbelschleppe: detecting, characterizing, controlling, attenuating, understanding, and predicting aircraft wake vortices", DLR research report 2008-15, 2008, pp. 89-106.

[13] van Baren, G., Speijker, L., Frech, M., "Increased arrival capacity through the use of the ATC-Wake separation mode planner", 6th AIAA Aviation Technology, Integration and Operations Conference (ATIO), Wichita, Kansas, American Institute of Aeronautics and Astronautics, 2006.

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