Final Project Report

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Abstract

Project 09.11 dealt with the development of on-board functions for wake turbulence encounter prediction and alleviation, based on air-to-air data exchange and on-board sensors. Two functions, called WEPS-P (Wake Encounter Prevention System - Prediction) and WEPS-C (Wake Encounter Prevention System - Control), were prototyped on different platforms with the aim to define a validated system solution.

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Acronyms

Acronym	Definition
A/C	Aircraft
ADS-B	Automatic Dependent Surveillance - Broadcast
ARP	Aerospace Recommended Practice
ATM	Air Traffic Management
DLR	Deutsches Zentrum für Luft- und Raumfahrt
EDR	Eddy Dissipation Rate
FAA	Federal Aviation Administration
HMI	Human-Machine Interface
HP	Human Performance
LiDAR	Light Detection and Ranging
MOPS	Minimum Operational Performance Specification
OFA	Operational Focus Area
OI	Operational Improvement
OSED	Operational Services and Environment Description
OSMA	Outil de Simulation des Mouvements Avion
RECAT	Recategorization of Wake Turbulence Separations
RTCA	Radio Technical Commission for Aeronautics
SAE	Society of Automotive Engineers
SC	Special Committee
TRL	Technology Readiness Level
WEPS	Wake Encounter Prevention System
WTSG	Wake Turbulence Study Group (*ICAO*)
WVTF	Wake Vortex Task Force (*Eurocontrol*)
WV	Wake Vortex

1 Project Overview

Project 09.11 (including former project 09.30) dealt with on-board systems for wake turbulence encounter alerting and wake turbulence encounter alleviation. Wake turbulence encounters, or wake vortex encounters, are a hazard occurring when an aircraft flies into the flow field created by the wake vortex of another aircraft. This can have various effects which can range from a mild change in aircraft attitude to an impairment or loss of control of the encountering aircraft. The consequences of a wake encounter are a complex function of wake vortex strength, encounter geometry and properties of the encountering aircraft. Wake turbulence encounters can be encountered during all flight phases, even though today specific separation constraints only exist for the approach and departure phase.

Project 09.11 focused on an on-board function for wake awareness and prediction of imminent wake turbulence encounters based on air-to-air data link, called WEPS-P. Project 09.30 focused on a flight control function enabled by new airflow sensors to mitigate strong wake turbulence encounters, called WEPS-C. The goal of the projects was to mature these airborne capabilities to increase safety with respect to severe wake turbulence encounters. The WEPS-P prediction function aims to provide information about surrounding wakes' positions and predict a potential severe wake encounter sufficiently in advance such that a tactical avoidance manoeuvre can be initiated by the flight crew. It is designed to raise flight crew awareness of such situations and to provide the appropriate information to manage them. The WEPS-C function on the other hand aims to provide an improved flight control that reduces the impact of strong wake turbulences should they be encountered by an aircraft.

1.1 Project progress and contribution to the Master Plan

The project methodology consisted in prototyping the solutions on development and validation platforms of increasing maturity. It relied on two pillars:

- Functional development: Prototyping of the WEPS function with all its components, preparation of a simulation and development platform and verification of the function's performance.
- Cockpit integration: Refinement of operational needs with pilots, design of the HMI and integration into cockpit simulator, followed by evaluations to assess the operational concept.

Additionally important external competence was used by sub-contracting DLR, EADS-Innovation Works (now Airbus Innovation Group) as well as the Université Catholique de Louvain (UCL) to provide important contributions.

WEPS-P

Development of the functional side of the WEPS-P wake encounter prediction function was done using a software demonstrator including the important functional elements. An offline simulation platform was developed allowing to run the function with inputs from either flight test or generic traffic simulation. This platform served as the primary tool to develop and refine the functional architecture of the function and it is intended to further use it for any future development activities.

For evaluation of cockpit integration aspects the WEPS-P function was integrated into the cockpit simulation environment of the Airbus research simulator MOSART that was also used within several other WP9 projects.

The WEPS-P function was designed to contribute to Enabler *A/C-30a*. During the project the Technology Readiness Level could be advanced to TRL3. Its maturity is thus still assessed as V1.

WEPS-C

Development of the WEPS-C wake encounter alleviation function followed a similar approach. The primary development and validation tool was the Airbus flight dynamics simulation OSMA which includes the capability to simulate wake turbulence encounters in all six degrees of freedom. Important preliminary validation steps were also performed on a less representative platform owned by DLR, who were tasked with a large part of the development of the function.

The most promising solution approach for a WEPS-C function was assessed using a model of a LiDAR sensor that could be capable to provide the required performance, but which does not yet have sufficient maturity to be integrated on an aircraft today. This and the fact that the proposed solution still has open issues regarding the integration with the existing Fly-By-Wire control laws has led to the decision to suspend the development for the last 1.5 years of the project and instead look for simpler solutions that may bring earlier benefits while waiting for the LiDAR sensor technology to become mature.

In terms of cockpit integration there was no specific activity performed by the project since the function was designed to be transparent to the flight crew without any particular HMI or associated procedures.

The WEPS-C function was designed to contribute to Enabler *A/C-30b*. During the project the Technology Readiness Level could be advanced to TRL2. Its maturity is thus still assessed as V1.

Code	Name	Project contribution	Maturity at project start	Maturity at project end
A/C-30a	On-board prediction of wake turbulences based on aircraft data exchange	Development and validation of an on-board alerting function that can predict imminent wake turbulence encounters, based on information received via air-to-air data exchange. A function demonstrator has been produced and functional architecture options evaluated using an offline fast-time simulation platform. A cockpit HMI has been specified and evaluated in a realistic cockpit simulator with test pilots.	V1 / TRL2	V1 / TRL3
A/C-30b	On-board detection of wake turbulences based on on-board sensor (e.g. LiDAR)	Development and validation of a flight control function making use of on-board LiDAR sensor measurements to mitigate strong wake turbulence encounters. The function was developed on validated flight dynamics simulation platforms using a LiDAR model developed using results from the AWIATOR project [5]. Different options have been evaluated and initial results are available. It is noted that the assumed LiDAR sensors are not yet sufficiently mature today, so activities at the end of the project have been focused on simpler solutions requiring no new sensors.	V1 / TRL1	V1 / TRL2

1.2 Project achievements

WEPS-P

The project started out with a definition of a demonstrator for on-board wake encounter prediction developed during the FP6 FLYSAFE project [6]. Early in the project a flight test opportunity could be used to expose this early version of the function to real wake turbulence encounters in the frame of the Airbus A380 wake vortex flight test campaign in 2010. The data captured during that campaign proved very valuable for the further development and validation of the function. The results are reported in 09.30-D12 [39].

To refine the functional architecture different options for the key elements of the function were developed and evaluated to identify the most appropriate architecture responding to the operational concept. Furthermore a first performance assessment was carried out for this functional architecture to quantify the accuracy of the prediction and expected rate of spurious alerts. The results show that, due to the probabilistic nature of the applied models, a wake encounter prediction by WEPS-P is likely to be correct in about 30 – 40% of alerts in the optimum case, i.e. if all required inputs are available. The unavailability of certain input parameters in today's ADS-B, and consequently the necessity to estimate these, results in a reduction of that percentage. Further simulations [16] showed that under the assumption of optimum input availability, and limited to the cruise flight phase only, an approximate wake encounter alert frequency of $3.5 \cdot 10^{-4}$ per Flight Hour can be expected. Unavailability of some input parameters are likely to result in an increase of that frequency.

The evaluations showed that the most important parameters in that respect are information about the wake-generating aircraft's size and mass, followed by information about the wind at the wake generator's position, either measured directly or via simultaneous transmission of ground- and air-referenced speeds. Detailed results are contained in the Validation & Verification Report 09.11-D31 [27].

The work on the operational concept for the function focused on defining a cockpit HMI and associated concept for use by the flight crew. One major achievement of the project is the integration of the function into the cockpit simulation environment of the Airbus research simulator MOSART and the subsequent evaluation campaign that was conducted with test pilots. This activity allowed to refine the operational concept and functional architecture and evaluate it in a representative simulated environment. The campaign allowed identifying several issues with the proposed concept and HMI. In particular it was seen that the design of the function was not appropriate for the approach and landing phase of flight. On the other hand the general interest of such a function for the en-route phase of flight could be confirmed, although open issues with the proposed HMI remain here as well. These reasons prevented the function from reaching the expected maturity at the end of the project. Results of the campaign are contained in the Validation Report 09.11-D31 [27], and the current operational concept is documented in 09.11-D26 [25].

From a transverse perspective, the project followed the applicable guidance of the Human Performance Assessment Process, the final HP log is accessible in the validation report [27]. As the associated OI Steps have not been addressed by operational projects in SESAR 1, the HP log was not merged with other assessments in the same context. For the reasons already mentioned above, the HP maturity assessment is not detailed at this stage. Further transverse assessments were not considered due to the initial level of maturity of the concept.

The function did not reach a maturity of V3 as initially intended at the start of the project. One of the objectives of the project was to demonstrate benefits in terms of safety that the function could deliver. Considering the operational concept and associated HMI were not validated, this could not be achieved. One reason for that is that it took longer than intended to define the operational concept for the function and an associated functional architecture. The related Enablers were not considered in any operational project until the end of the project, thus not providing any requirements that could be used by the project. The development of the WEPS functions therefore was done using assumptions on the operational concept and requirements made by the project itself, leading to the Operational Concept document produced by P09.11 [25]. The V&V activities showed that these were not fully adequate, but there was no time for another design iteration based on the outcomes of these activities.

WEPS-C

The major part of achievements regarding the WEPS-C function was reached in project 09.30 which was merged with 09.11 in 2014.

A major output of the project is the Preliminary Validation Report [41], which contains the results obtained with a tentative system solution using a LiDAR sensor connected to a flight control function. These results were primarily produced by DLR who were sub-contracted by P09.30. They show that using LiDAR measurements at appropriate measurement points approximately 100 m ahead of the aircraft in a feed-forward control loop could allow reducing the impact on the encountering aircraft's attitude reaction by as much as 80%. The simulation makes assumptions on the performance of a LiDAR sensor which cannot yet be met by sensors that could be installed on an aircraft easily. But they allow to make statements about the requirements on such sensors so that they are useful for a wake encounter alleviation control.

These requirements have been compiled into a separate deliverable 09.30-D11 [38], which is a further main output of the project. It summarizes the performance requirements based on the simulations made so far and with the current assumptions on the functional architecture. It can be useful to sensor manufacturers to orient the development of sensors for such a future application.

The WEPS-C function nevertheless did not reach the maturity initially intended at the start of the project. Reasons for that are, besides the fact that adequate sensors for the LiDAR solution are not yet available, a missing integration of the new wake alleviation function into existing flight control laws and demonstration of robustness and performance under realistic conditions. Furthermore an effective alternative solution not requiring a LiDAR sensor could not be found either. Without these a final statement about a potential separation reduction that such a function would allow cannot be made.

1.3 Project Deliverables

The following table presents the relevant deliverables that have been produced by the project.

Reference	Title	Description
09.11.D08	WEPS-P Preliminary Validation Report	This report contains results produced using a WEPS-P simulation platform that uses realistic traffic and weather data to provide inputs to the WEPS-P function. It contained the core algorithms of the WEPS-P function (Wake Prediction, Conflict Prediction and Severity Estimation). Evaluation aimed at showing how much wake encounter detections by WEPS-P can be expected under certain hypotheses, and how this rate depends on the available capabilities of the airborne data link and the accuracy of the contained information. The results supported the further definition of the operational concept for WEPS-P.
09.11.D26	WEPS Concept of Operations and Requirements	This deliverable contains the operational concept for the WEPS-P and WEPS-C functions as defined at the end of the project. It includes a description of the functions and their intended use in the operational environment. Different use cases are developed which served as input to the validation exercises. From this several operational requirements are derived.
09.11.D30	WEPS-P High-Level Functional Architecture	This document contains the High-level Functional Architecture of the WEPS-P function that was the basis of Validation & Verification activities in project 09.11. It describes the different components of the WEPS-P function. This functional architecture represents the definition of the function at the end of the project.
09.11.D31	WEPS-P Final Validation and Verification Report	This report contains further results of validation and verification activities for the WEPS-P function. Validation was carried out during pilot-in-the-loop simulations in a cockpit research simulator, running the WEPS-P function in several realistic scenarios. It was aimed at validating the operational concept and associated HMI. Verification of the WEPS-P function was done using a fast-time simulation platform to demonstrate the performance of the different components of the function, and that they respond to the requirements of the operational concept.

09.30.D11	LiDAR sensor requirements and technology selections for wake alleviation by flight control	This report describes requirements on forward-looking LiDAR sensors for wake vortex encounter alleviation flight controls. The requirements are based on the results in the preliminary validation report (09.30-D17). By variation of a number of parameters of the LiDAR sensor measurement setup a range of parameters could be determined that enables an effective wake alleviation in simulation. It is aimed to support development of sensors intended for such an application.
09.30.D17	WEPS-C Preliminary Validation Report	This document contains results from an initial validation of the WEPS-C concept for wake encounter alleviation by flight control using on-board LiDAR sensor measurements. The validation was aimed at demonstrating the potential safety benefit of the function with respect to wake vortex encounters by using simulations. The simulation platform uses a 6 degree-of-freedom aircraft simulation representative of an A320 type aircraft, including a wake vortex encounter simulation and further models for the LiDAR sensor, an online wake identification and a wake impact alleviation function.
09.11.D37	WEPS-C High-Level Functional Architecture	This document contains the High-level Functional Architecture of the WEPS-C function that was the basis of Validation & Verification activities in project 09.11. It describes the different components of the WEPS-C function. This functional architecture represents the definition of the function at the end of the project.
09.11.D38	WEPS-C Final Validation and Verification Report	This report contains additional verification results for an optional WEPS-C solution using no new sensors. It complements the results contained in 09.30.D17.

1.4 Contribution to Standardisation

RTCA SC-206 & WV Tiger Team

A group for Wake, ATM & Weather data exchange via ADS-B has been established through RTCA in 2009 as a sub-group of Special Committee 206 (SC-206 "Aeronautical Information and Meteorological Data Link Services"). P09.11 was involved in this subgroup, which issued an Operational Services and Environment Definition (OSED) for "Aircraft Derived Meteorological Data via ADS-B Data Link for Wake Vortex, Air Traffic Management and Weather Applications" in 2012 [7]. This OSED details the requirements for ADS-B transmitted data (ADS-B Out) for the above applications, of which a notion can already be found in the current DO-260B standard, Appendix V [8].

The OSED contains proposals for additional data items to be transmitted, their encoding and transmission rates to enable on-board wake vortex applications while not requiring any important bandwidth and hence safeguarding services based on DO-260B. The document furthermore attempts to define a process for standardisation of on-board Eddy Dissipation Rate (EDR) computations characterising the turbulence level in the atmosphere.

The proposed formats have been reviewed by P09.11 with respect to the requirements for WEPS, and extensive review comments have been sent to the RTCA subgroup during the draft review period in 2011.

In 2014 the RTCA has decided to launch a "Wake Vortex Tiger Team", which was kicked off on May 1st, 2014. The output of the Tiger Team is a White Paper on "Suggested Standards Development Activities to Move Forward with Wake Vortex, Air Traffic Management, and Meteorological Applications" which will be published as DO-360 [9] in order to prepare future evolutions of the ADS-B standard. Several meetings were held during the course of 2014, which were followed by P09.11. Project 09.11 contributed a high-level overview of the WEPS-P function and its associated data link input requirements (for an ideal case) to the White Paper.

The same information was also provided to SESAR project 09.22 (ADS-B Mid and Full Capability – Research) to support the future ADS-B requirements capture done by the project

SAE G10 - Wake Vortex

Following a proposal of International Aero Navigation Systems IANS (Russian Federation) and Astronautics Corporation of America (United States) to start a new working group related to "Human Factors standards for the presentation of Wake Vortex information" in 2012, a first meeting has been held during the Society of Automotive Engineers (SAE) G-10 winter session on Jan. 28-31, 2013. Airbus participated to the meeting and presented its activities on airborne systems for prevention of severe wake vortex encounters, expressing at the same time concerns that it is too early to define recommendations regarding HMI aspects. Hence P09.11 did not propose to actively participate to this group.

Following the session, SAE has decided to start work on an Aerospace Recommended Practices (ARP) for "Airborne Wake Vortex Safety Systems" during 2013, chaired by the Russian IANS company. The document focuses on displays and indications for on-board functions. In its initial draft it collected a lot of different HMI solutions, from several different sources and projects, but without much background material. From P09.11 point of view, at end of 2013 the maturity was not sufficient to propose it as ARP. The draft ARP [10] was proposed for a first ballot in May 2014 and rejected. Several detailed comments have been made on the document by P09.11. Since then no new version has been proposed.

Wake Encounter severity metric (RECAT, WVTF)

In 2013, Eurocontrol has presented for wide European consultation the RECAT-EU proposal, which in essence represents a change in static wake turbulence separations for departure and arrival. Airbus has actively contributed to the consultation process via the European Wake Vortex Task Force (WVTF) and by providing coherent analysis results specifically for Super Heavy leader aircraft. The severity metric used in the associated Safety Case includes a representation of the vortex viscous core and takes into account the vulnerability to a wake encounter of the follower aircraft in the roll axis. P09.11 has reviewed the definition of the severity metric and its applicability to the WEPS function. An implementation of the metric is used within the WEPS-P function demonstrator to determine the severity of a predicted wake encounter.

1.5 Project Conclusion and Recommendations

Regarding WEPS-P the project defined a functional architecture and corresponding operational concept. The maturity of key functional elements could be increased. These were evaluated in dedicated V&V activities. The activities included a first performance assessment of the functional architecture, as well as an evaluation of the operational concept and an associated HMI in a cockpit simulator.

The evaluation of the operational concept for WEPS-P proposed by the project left several open questions. One result of the V&V activities is that the current WEPS-P design does not seem appropriate for the approach and landing phase since the complexity of the environment was not sufficiently taken into account. It may therefore be more promising to link the airborne wake prediction capability with other specific operational concepts such as Assisted Visual Separations in order to advance an on-board wake awareness concept. On the other hand the potential of a wake awareness function during en-route flight was confirmed, especially since today there are no specific wake turbulence separation requirements in that phase. However there are still open issues related to the proposed HMI to be solved, and to progress with this the requirements on the function need to be better known. No association to any en-route concept was made in SESAR 1 so far, the applicable OI steps were only associated to the airport environment.

To further advance with a WEPS-P function, the project thus recommends to:

- Seek synergies with other airborne concepts such as Assisted Visual Separations in order to mature Operational Improvements in the approach phase of flight.
- Seek links to en-route operational concepts and related Operational Improvements, and refine the operational requirements on the function for that phase of flight.

Regarding the WEPS-C function, the project demonstrated that there is a potential for significant alleviation of wake encounter effects when using on-board LiDAR sensor measurements. The proposed solution is however not yet technically mature, both in terms of the flight control application and the sensors needed for it. Due to this the maturity of the operational concept did not present a significant problem to the project.

To advance with a WEPS-C function, the project recommends to further develop the integration of such a function into existing flight control law architectures, and to demonstrate its robustness and non-intrusiveness. This can still be carried out using appropriate models of a LiDAR sensor. It is expected that LiDAR/Laser technology will advance independently in the meantime driven by other applications, such that an integration with an airborne flight control will become easier to achieve in the future. Therefore the focus should be put on maturing the flight control application part.

In terms of the operational concept, to gain any capacity benefits the WEPS-C capability still has to be considered in an appropriate wake turbulence separation concept. In that case, the severity metrics used for quantification of the wake turbulence encounter risk in such a concept must take into account aircraft control capabilities. Currently only an external moment acting on the aircraft is considered in the RECAT concepts. Without a specific operational concept however, the function can still provide safety benefits.

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