PILOTED SIMULATION RESULTS OF AN ONBOARD WAKE VORTEX DETECTION, WARNING AND AVOIDANCE SYSTEM AND COCKPIT DISPLAY ASPECTS

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Abstract

As part of the European project I-WAKE (Instrumentation systems for on-board WAKE vortex and other hazards detection, warning and avoidance), piloted flight simulations have been performed using an onboard wake vortex Detection, Warning and Avoidance (DWA) system concept including a novel cockpit Human Machine Interface (HMI). This HMI consisted of new information on a Primary Flight Display (PFD), the Navigation Display (ND) and a Vertical Navigation Display (VND). These concepts developed, associated wake alerting flight procedures, experimental set up and main results of the piloted study on a fixed base flight simulator will be addressed.

1 Introduction

The project for Instrumentation systems for on-board WAKE vortex and other hazards detection, warning and avoidance (I-WAKE), was a European project executed from 1st of May 2002 until 30th of April 2005. It was co-funded by the European Commission under the 5th Framework Programme, contract no G4RD-CT-2002-00778. The project was led by Thales Avionics (France). Project partners were AIRBUS Deutschland GmbH, LISA Laser Products, German Aerospace Center DLR, University of Hamburg, Fraunhofer Institute at Jena (all Germany), Université catholique de Louvain (Belgium) and the National Aerospace Laboratory NLR (The Netherlands).

The overall project objective was to improve air transport operational capacity and safety by defining onboard integration of an instrumentation system for remote detection, warning and avoidance of wake vortices and atmospheric hazards like wind shear and Clear Air Turbulence (CAT), see [1].

Section 2 of this paper focuses on the wake vortex part of that onboard Detection, Warning and Avoidance (DWA) system concept. Experimental aspects are part of Section 3. The main results, conclusions and recommendations of the piloted flight simulations executed will be provided in Section 4.

2 Wake Vortex DWA System Concept

2.1 Design Objectives

Eurocontrol Experimental Centre (EEC) indicated that at certain airports, when operating flights under particular weather conditions, an increased number of pilot reported wake encounters took place, even when applying normal aircraft separation rules. The project's design objectives of the Wake Vortex DWA system development were defined as follow:

1. To improve flight safety without negative effects on airspace capacity by giving the pilot additional information.
2. To minimize the probability that an aircraft encounters a wake vortex.

2.2 Wake Vortex DWA System

The novel wake vortex Detection, Warning and Avoidance (DWA) system has been set up for the arrival route and the approach and landing flight phase. The wake vortex part of the full DWA system concept is given in Fig. 1. It has three main elements:

[1] Current affiliation; TU Berlin not a partner in I-WAKE

1. Input data, consisting of all onboard gathered data and of 'other aircraft' data, as received via datalink.
2. The DWA processing logic
3. The associated HMI-part, i.e. the cockpit displayed information and aural alerts.

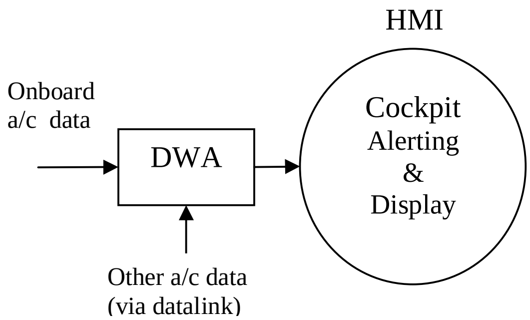


Fig. 1. The Wake Vortex DWA Scheme.

2.2.1 Onboard Input Data

The DWA inputs are either from a special onboard Wake Vortex Model (WVM), see section 2.2.4, or an onboard sensor like the Light Detection and Ranging (LiDAR) device, and from aircraft avionics systems like an Air Data Computer and inertial navigation system. The WVM predicts positions and strengths of the wakes generated by the leading aircraft, at certain position intervals behind the leading aircraft. Data of the leading (and other) aircraft (like 3D-position, heading and speed) are obtained via an ADS-B (Automatic Dependent Surveillance – Broadcast) transceiver.

2.2.2 DWA modes and processing logic

Essentially the pilot can operate the DWA in three different modes:

1. Mode 1 : LiDAR detection mode
2. Mode 2a: Estimation mode (current time)
3. Mode 2b: Prediction mode (future time)

The detection, estimation and prediction modes cannot be used simultaneously. The main characteristics of these three modes are:

- ❖ Mode 1 represents the LiDAR detection of a wake via an onboard sensor device that scans in the horizontal plane within a minimum and maximum detection range along a main axis and a few degrees to the left and right side of this axis that is centered along the aircraft's true heading. In the vertical plane the main scan axis is centered along the aircraft's flight path angle and the LiDAR scans a few degrees up and down. Dimensions see section 3.2.
- ❖ Mode 2a and Mode 2b are both related to real-time onboard simulated wake vortex behavior that include model predictions and as such can provide information beyond the detection range of the LiDAR. The onboard WVM model is able and used to derive the wake characteristics at current or future times. Both the left and right side wake positions (including uncertainty margins) and associated wake strength of the leading aircraft are derived.

In this paper Mode 2a is also referred to as the "estimation" mode and Mode 2b as the "prediction" mode. Mode 2a derives the wake positions and wake strengths at their current locations in space, hence at t'= t1. When the aircraft arrives at t''= t'+ τ at a certain wake position in space the wakes will have moved and will have decayed due to the time evolution. Mode 2b corrects for these aspects and predicts at t' the wake positions and strengths belonging to the future time t''= t1+ τ, so τ seconds ahead of the current time t'. The time-to-encounter the wake (τ) is obtained by dividing the shortest distance to a hazardous wake position by the current True Air Speed (TAS). Mode 2b in essence predicts the wake characteristics when the aircraft would arrive at that particular wake position in space and the HMI continuously presents these future wake characteristics. The outputs of the WVM are transferred to the DWA's wake alerting and cockpit HMI presentation module.

2.2.3 DWA Wake alerting logic

Various (past) projects have studied the impact of wake vortices on aircraft. Examples are WAVENC, S-Wake, Far-Wake, etc., see [2]. Roll control ratio, rolling moment coefficient values, (max) roll rate, vertical acceleration, bank angle loss with height excursion, maximum bank angle, and even combinations of these and other aircraft parameters have all been researched. At the time no real reliable and applicable onboard wake alerting measure existed as known to the authors. But one of the key indicators of a potential wake threat to an aircraft is the wake intensity, see [2]. The other main parameters that will determine a safe wake encounter are:

(i) the time-to-encounter a severe wake part

(ii) the relative position of a severe wake part to the ownship.

Therefore, in addition to the wake intensity, the wake threat has been defined in terms of position-based and time-based parameters. In a first step, and based on a project-internal exploration, wakes should trigger an alert when the (local) vortex intensity at the ownship's centre of gravity (c.g.) position was equal to or exceeded 200 m^2/s.

The DWA's alerting logic related to the wake vortex threat consists of a strategic and a tactical alerting function.

A) Strategic alerting function

Strategic alerting for wakes is performed by enhancing the crew's situational awareness via presenting wakes on the Navigation Display and Vertical Navigation Display. Only wakes that are considered potentially dangerous, i.e. above the wake severity threshold are presented and only when these hazardous wake parts are also within the so-called display volume to filter out any operationally non-relevant wakes. In case a limited, small part of the predicted full wake was meeting these two criteria, the full wake was assumed to be dangerous and presented all the way up to the leading aircraft, at least for DWA Modes 2a and 2b. For DWA Mode 1 only the detected wake part inside the display volume can be presented.

B) Tactical alerting function

The tactical wake alerting consisted of presenting alert information on the PFD and by generation of aural alerts inside the cockpit, conform flight deck alerting guidelines, see [3]. The tactical alerting is based on two types of requirements:

i. Position-based wake alerting requirements

The critical wake area around the aircraft has been defined by a sphere with a radius of 40 meters around the aircraft's c.g. This radius includes the wingspan of the ownship equipped with the DWA system. Any hazardous wake part within this sphere should directly generate a wake vortex WARNING alert state.

ii. Time-based wake alerting requirements

In addition to position-based rules, the DWA system shall provide time-based alerts as well. It shall issue a:

- CAUTION for hazardous wakes encountered within 30 to 15 seconds
- WARNING for hazardous wakes encountered within 15 to 0 seconds

These two requirements were handled per DWA mode in a different fashion:

For Mode 1 the time-based criteria were translated into distance-based criteria. Around the aircraft's c.g. an alerting volume was set up. To set the forward alerting distances of the caution and warning parts, the current aircraft true airspeed (TAS) is multiplied by the above given alert time values. Based on pilot prototyping sessions appropriate lateral and vertical alert distances were developed. To reduce the effects of nuisance alerts, this volume was furthermore made to bend into the horizontal wind direction using a 10 seconds moving average over the onboard obtained current wind values. The volume, as centered on the aircraft's velocity vector was tilted slightly upwards (X_i =3 deg) to account for the natural downward movement of the wakes, such that for level flights, the wakes coming from above the ownship are anticipated. On a 3-degrees ILS approach, wakes will generally descend further down, so away from the ownship, and will move out of this special volume.

For Mode 2a the wake positions are model-derived and -next to the critical sphere implication- the wake alerting is based on the provided time-to-encounter criteria. To assure a low level of nuisance alerts, the logic not only checks the nearest wake position for these encounter times, but also whether the relative distance between aircraft and wake is actually reducing. This way, wake threats that are within the defined encounter time limits, but moving away from the aircraft, will not trigger a wake alert. Furthermore, a position-based, dedicated alerting volume was overlaying (=filtering out) those wakes that meet the encounter time criteria but which are operationally not relevant.

Like Mode 1, this dedicated alerting volume was enhanced with the wind anticipation logic and the wake induced velocity-tilting aspect.

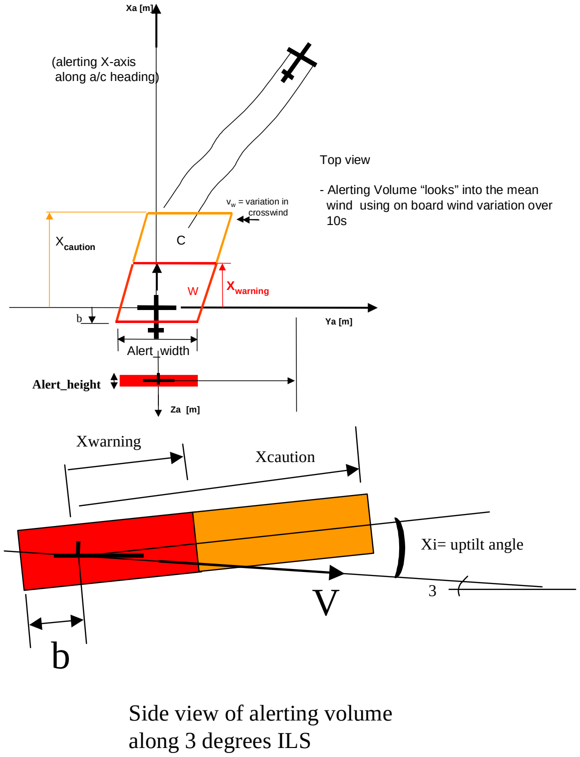


Fig. 2. DWA alerting volume for Mode 2a.

For Mode 2b, a similar alerting logic was applied as in Mode 2a. However instead of the wake positions at current time, those at future times were used. The inherent prediction of time and position allowed leaving out the two special features to anticipate the wakes.
The generated wake alerts were filtered and were made visible on the cockpit displays for a minimum duration of three seconds. All wake vortex alerts were inhibited at and below 20 ft Above Ground Level (AGL).

2.2.4 Wake Vortex Model (WVM)

The onboard wake vortex model (WVM) was developed by UCL to simulate realistic wake vortex behavior in the three dimensional space and in real time. This 3D-model uses multiple 2D-simulations, achieved by the Vortex Forecast System (VFS). This VFS is the core module of the WVM and was previously developed by G. Winckelmans and other international partners, see [4]. It is continuously improved by research conducted at UCL. The VFS is an operational wake vortex predictor based on the Method of Discrete Vortices (MDV) and it predicts the wake vortex evolution faster than real time. The VFS is composed of two major parts:

- The Near Wake model, which represents the wake vortex just after being generated by the aircraft.
- The Far Wake model, which predicts the time evolution of the vortex location and strength, as well as the velocity field in real time.

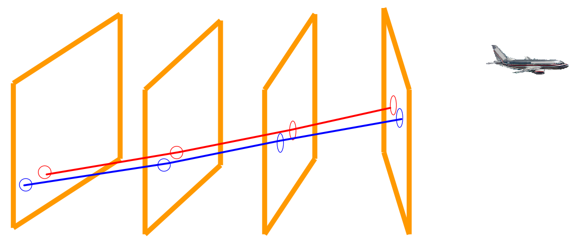


Fig. 3. WVM wake characterization inside gates (3D view).

Both left and right wakes are simulated and use is made of a total of N=48 wake gates (or segments), separated by a 5 seconds time interval over a 240 seconds period wake evolution time. Fig. 3 and 4 show a qualitative approach of this wake simulation.

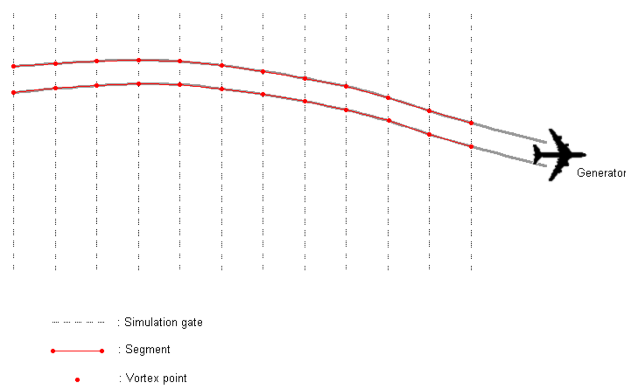


Fig. 4. WVM wake characterization in segments (top view).

Based on the selected DWA mode, the WVM provides the wake positions and wake strengths. The WVM model was also responsible for the inherent LiDAR model simulation, and it was coupled to the weather scenarios since the wake evolution behavior strongly depends upon weather parameters.

For a pilot to trust the information generated by any alert system, the alerts must be sufficiently reliable. No model is able to simulate wake vortex behavior perfectly. It is thus important to consider uncertainties on the wake vortex characteristics calculated by the model. Uncertainties were included on the wake vortex positions but not on the vortices circulation.

The outcome of all onboard DWA and WVM processes is in essence an internal ‘assessment’ whether the wake positions and wake strength form a real threat to the aircraft that has to be indicated to the crew somehow.

2.2.5 Wake Vortex related Cockpit HMI Development Process

The new HMI was integrated into standard display formats and used in conjunction with the DWA mode of operation. The HMI was developed using a classical design approach. The new foreseen HMI aspects were first presented and discussed with engineers and pilots, using simple sketches. Secondly a dynamic presentation was set up with simple animation means. Subsequently these new ideas were implemented into existing cockpit HMI software via NLRs’ display design tool Vincent [5]. Desktop simulations followed and were commented on by engineering pilots. In a next step a simulation was set up on the GESIMO fixed based flight simulator at NLR, nowadays named APERO that for the first time incorporated the WVM model dynamics coupled to the DWA and associated HMI. Multiple sessions were flown with a test pilot. Based on his comments the various prototypes were improved. A lot of the required (and the undesired) display dynamics were revealed. It provided useful information for improving the DWA’s alerting logic. Finally an even more realistic testing was performed on NLR’s full motion based flight simulator GRACE (=Generic Research Aircraft Cockpit Environment), checking on human factor issues like the influence of display h/w arrangements inside the cockpit, visibility of the new information inside a dark or a light cockpit, aural alerting aspects, display and alerting system controls and the effect of simulator motion aspects (like turbulence) on the new presented display information. An aircraft-wake interaction model was not implemented to simulate the actual aircraft response to the wake encounters. Various sessions were flown with a test pilot and remaining s/w issues were solved before the final HMI, WVM and DWA specification and software versions were issued. All these models were integrated into the Airbus development flight simulator THOR in Hamburg, Germany.

2.2.6 Wake Vortex related Cockpit HMI

Wake vortex related new display features were developed for the Primary Flight Display (PFD), the Navigation Display (ND) and the Vertical Navigation Display (VND). These features are presented next.

<u>PFD</u>

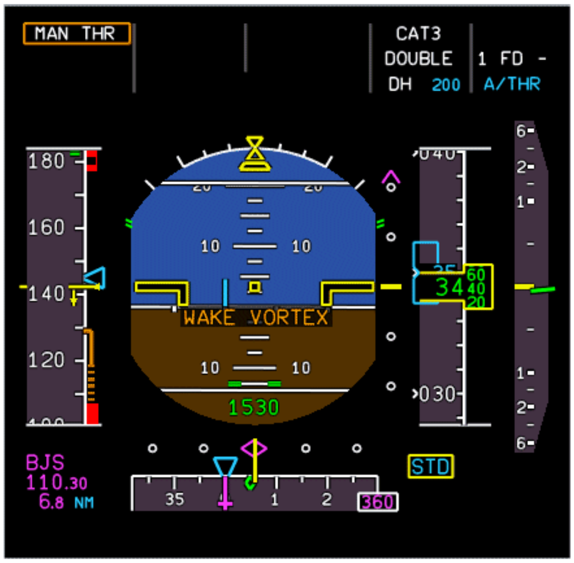
A standard display format was used for the PFD, onto which four new presentation features were added, consisting of:

1. Alert labels

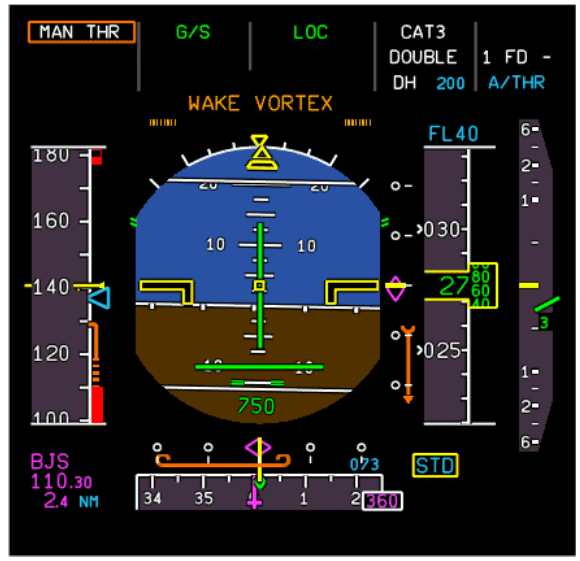
Depending on the DWA’s wake alert state, either a caution or a warning label will be presented using the label text “WAKE VORTEX” in amber respectively red. The red label is boxed. The PFD alert labels may be positioned either in the centre part, see Fig. 5 or just below the FMA, see Fig. 6.

2. Time-To-Encounter (TTE) presentation

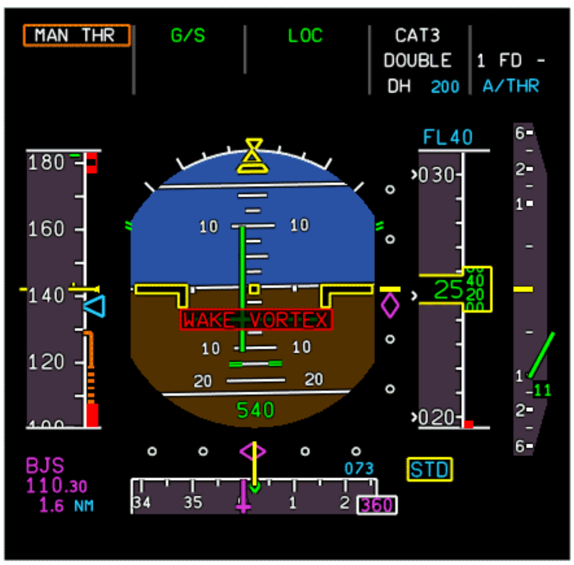
In the black area just below the Flight Mode Annunciation (FMA), a left and right moving bar presentation may appear when the wake vortex caution or warning state is active, see Fig. 6. The bar aims to give a better tactical threat awareness by indicating if the nearest hazardous wake is approaching or moving away. It starts to appear in the amber color when the wake threat is less than 30 but more than 15 seconds away. During the warning state when the threat is less than 15 seconds away, the bar is colored red. The bar is presented in a chequered way and never filled with a solid color to avoid any kind of false horizon cueing. The TTE-presentation by a numerical value between the two horizontal TTE bars was discarded.



a) Caution label

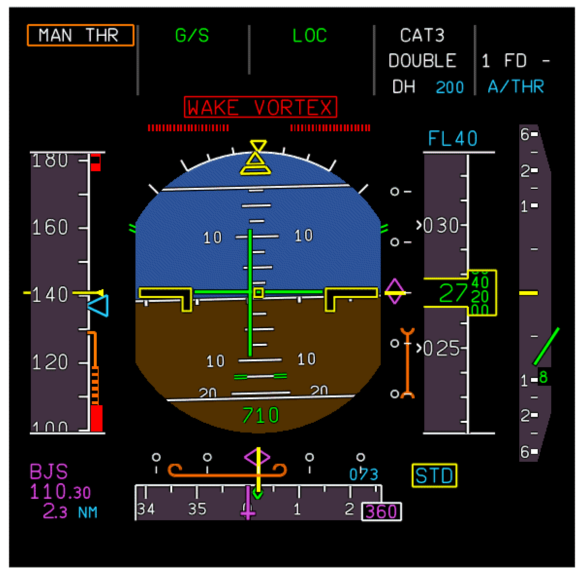


a) Caution level



b) Warning label

Fig. 5. PFD with caution and warning alert labels



b) Warning level

Fig. 6. PFD with alert labels, TTE bar and VPI

3. Vortex Position Indication (VPI)

The VPI is another tactical cueing, intended to be of special use during the approach flight phase. The VPI provides position information of the nearest hazardous wakes relative to the own aircraft. Its distance-based scales are positioned next to the ILS GlideSlope (G/S) and below the Localizer (LOC) scales, see Fig. 6. A full scale width relates to 800 ft, for both the horizontal and vertical scales, hence one tick is 200 ft. Note that the ILS-scales represent an angular format. Once activated, the color of the VPI-symbols remain orange always, independent of the wake alerting state. The horizontal wake symbol moves along the horizontal scale. It indicates the nearest left and right horizontal wake positions. A solid bar connects these outer symbol points, indicating the difference in horizontal distance. Similarly the nearest vertical wake positions are indicated on the vertical VPI-scale. The nearest wake positions move independently, hence the connecting bars of the horizontal and vertical wake position symbols may vary in length. For off-scale and hazardous wakes, orange arrow head indications (like > or <) are used on the appearing side.

ND and VND

Figures 7 and 8 show the ND-related wake vortex presentation formats. The three new ND and VND symbology aspects are given by:

1. Wake vortex position symbol

Whenever a wake vortex is within the display volume, a special filter to suppress presentation of those wake operationally considered being non-relevant, and above the hazardous threshold, the ND and VND will both present the wake positions via orange circles with a constant radius (see Fig. 7). Left and right wakes are presented independently. For the DWA Modes 2a and 2b all relevant hazardous wakes up to the wake generator aircraft are shown. Note that Mode 2b uses the future time.

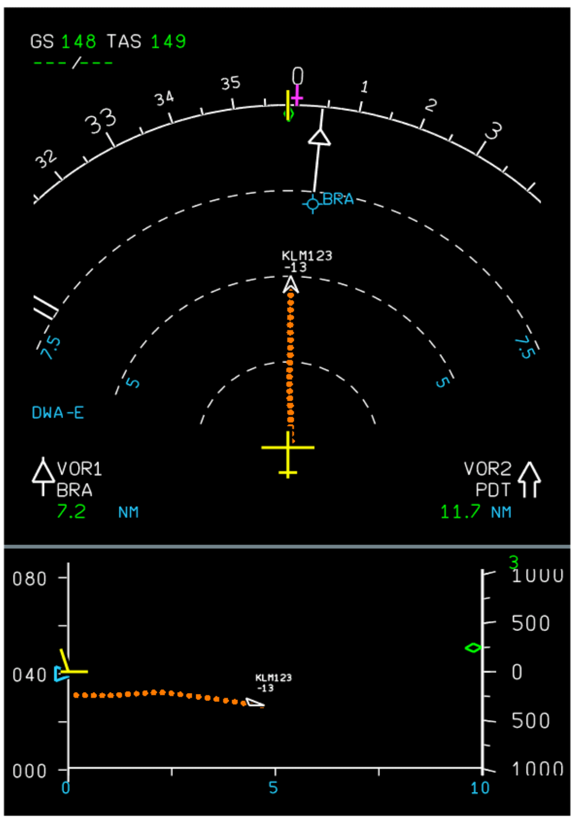
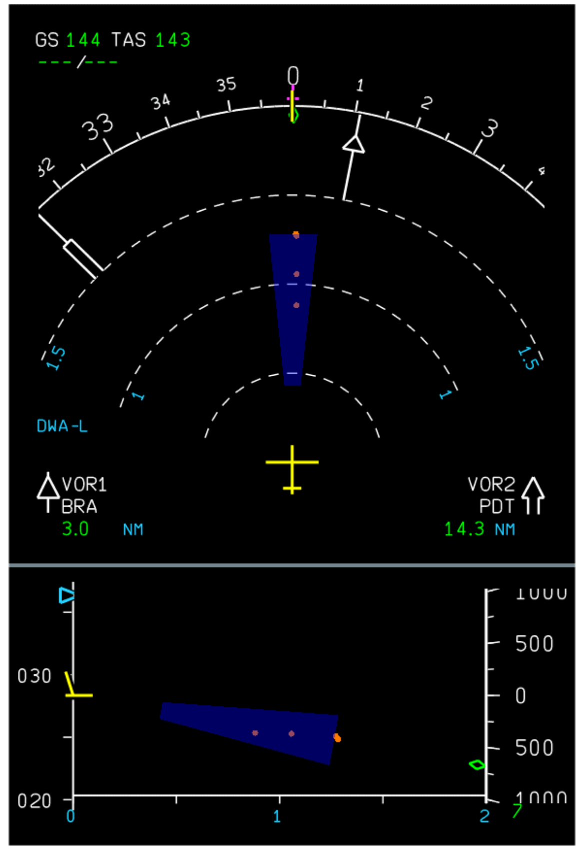


Fig. 7. ND and VND with wake vortex position symbology (DWA-Mode 2a and Mode 2b)

However, for DWA Mode 1, only the detected wake elements are presented, see Fig. 8, which shows the special ND-range zoom option the pilot could use. It also visualizes the LiDAR detection volume in blue. Likewise other system volumes could be visualized. However these special display features were not available to the pilots in the experiments, but only to engineers for debugging purposes.



DWA Mode-1 (Zoom option)

Fig. 8. LiDAR detected wake presentation and detection volume (in blue), ND zoom option

2. DWA mode indication

The selectable DWA-modes were presented in the lower left corner of the ND (in blue). These were given by:

"DWA-L" for the DWA Mode 1 (LiDAR)
"DWA-E" for the DWA Mode 2a (Estimation)
"DWA-P" for the DWA Mode 2b (Prediction)

3. Traffic presentation

For other traffic presentation a chevron type of symbol is used, see Fig. 7. This indicates that traffic information like altitude, position, speed (TAS), heading and vertical speed of the leading aircraft was provided via the ADS-B in datalink It also presented the flight identification And it distinguishes the wake generator aircraft from waypoints and Traffic Collision Avoidance System (TCAS) symbols.

3 Experimental Aspects

3.1 Experiment Objectives

The high-level objectives of section 2.1 were more detailed and translated into a few new experimental objectives:

1. Feasibility and Ergonomic validation

To validate that the Wake Vortex DWA system concept is feasible with particular technical improvements.

To validate the new cockpit displays (HMI aspects) and alerting functions from an ergonomic point of view and to get feedback on the usefulness of the information given by the Wake Vortex DWA system.

2. Encounter probability

To find indications that the encounter probability can be reduced.

Flight Phase	Caution Alert	Warning Alert
before ILS intercept	Check display info & apply speed reduction; Monitor effect	Quickly check displays & immediately climb or descend 100-200 ft, proceed with approach
high in the approach (H>1000 ft AGL)	Quickly check display info; Select final APPR CONFIG & apply fast speed reductions; When alert remains adjust flight path within acceptable limits	Perform Go-around
low in the approach (H<1000 ft AGL)	Quickly check display info and reduce speed 10-15 kts to minimum acceptable	Perform Go-around

3. Flight Procedures

To define, investigate and propose new, adequate flight procedures that fulfill operational requirements. See table below for the wake procedures set up for the experiment.

3.2 Experimental set up

The initial experiment matrix was based on six pilots, i.e. two groups of three each, to compare effects of standard versus reduced aircraft separations. Eventually only three pilots could participate hence the experimental scope had to be reduced and the final experimental design comprised four factors: (1) DWA-settings, (2) HMI-settings,(3) Pilots, (4) airports and weather cases. With DWA (4 levels) x HMI (3-levels), 12 runs per pilot were set up. The various weather\airport cases were nested under these 12 runs. The levels of the four experiment factors are provided next.

DWA-settings (4 levels): Mode 1, splitted into two parts (Lidar1 and Lidar2), Mode 2a and Mode 2b. Lidar1 uses a standard LiDAR system and alerting volume settings, while Lidar2 applies enhanced system and enlarged alerting volume settings. See Table below.

Mode	Alerting Volume (Forward [m], Alert_width [m], Alert_height [m])	Rmin \ Rmax [m]	Horizontal \ Vertical Field of View [deg]
Lidar1	VTAS*240s, 80 m, 40m	800 \ 2375	12 \ 3
Lidar2	VTAS*240s, 80 m, 80 m	300 \ 2375	24 \ 6

HMI-settings (3 levels):
- HMI-1: PFD wake vortex label in the centre, but no additional wake info on ND and VND
- HMI-2: PFD wake vortex label below FMA, and the ND & VND presented orange wake position circles.
- HMI-3: PFD wake vortex label and Time-To-Encounter bar below FMA + Vortex Position Indication (VPI), and the ND & VND presented orange wake position circles. See Fig. 5 to 8.

The eight DWA and HMI combinations applied in the experiment were:

DWA-Mode	1	2a	2b
HMI			
HMI-1	X	X	X
HMI-2	X	X	X
HMI-3	-	X	X

Pilots (3 levels): P1, P2 and P3.

The nested airport-weather combinations used were:

pilot P1: A2-W7 ; A2-W9
pilot P2: A2-W7 ; A2-W9 ; A3-W6
pilot P3: A2-W7 ; A2-W9

in which A2 is the ILS/DME approach to Madrid-Barajas (LEMD) runway 36R and A3 the ILS/DME approach to Toulouse (LFBO) runway 32R. Weather cases W6, W7 and W9 were mainly crosswinds, with different altitude and shearing patterns. To gather reference data, autopilot (AP) runs were performed as well.

3.2 Experiment Execution and Subjects

In May and June 2004 a piloted assessment of the DWA concept was held at the Airbus development flight simulator THOR. Three professional, male pilots participated, all in one-day sessions. The pilots acted as a single pilot, assisted by a flight simulator engineer. The pilots had an age of 26, 43 and 48 years respectively. The flight experience differed from being a First Officer (1x) to being a Captain (2x). The logged flight hrs varied between the minimum of 470 hrs to 13000 hrs (with an average of 6257 hrs and a median of 5300 hrs). Only pilot P3 had experienced many real-life wake vortex encounters.

3.3 Pilot Task

During the flight simulator experiment, the pilots performed flights inside the TMA of the flight areas of Madrid-Barajas airport and Toulouse-Blagnac airport. The pilot's primary task was to safely fly a part of the arrival, perform an ILS intercept, approach and land the aircraft, using normal operational safety standards. For the DWA wake vortex alerting related new flight procedures were set up. The aircraft type flown using an autopilot (AP) was a medium-weight twin-engined aircraft. The pilots were asked to verbally indicate when they would initiate a Go-Around based on the alert/situation, but no to execute it and proceed with the approach and land the aircraft.

The wakes were produced by a leading, heavy category aircraft. Inside Madrid airport's TMA, the potential wake encounter would occur at relative high altitude just before the intermediate descent. For Toulouse operations the potential wake encounter area was at low altitude around 500 ft AGL and 150 ft AGL.

In both cases, the wake generating (lead) aircraft would fly an ILS intercept course with a constant speed of 145 KIAS, in full approach configuration. A minimum ICAO[2] separation of 5 NM at the runway threshold was applied.

The pilots were first briefed and had to fill in a pilot intake questionnaire before trials. After every flight made a run questionnaire, and after all runs were performed, a debriefing questionnaire was filled in. Furthermore some objective flight data was measured. The information provided was collected and used to derive the results of the study.

4 Results and Conclusions

4.1 Results

DWA and HMI

The pilot appreciation for the three DWA modes is expressed in Fig. 9 below. This indicates a slight pilot preference for Mode-2A.

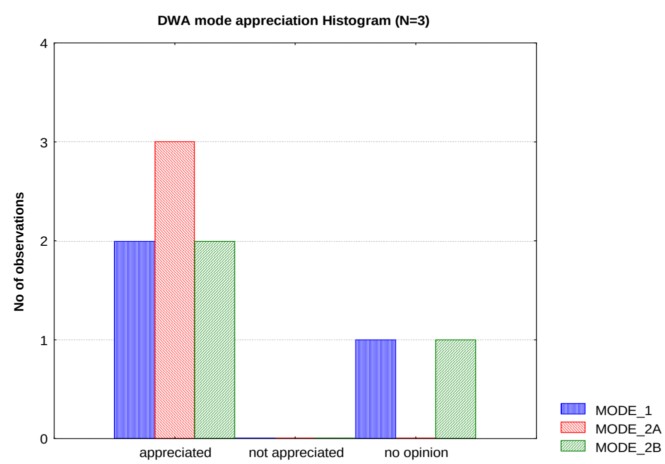


Fig. 9. DWA mode appreciation.

When asked for the usefulness of a particular DWA mode, all modes were at least considered to be 'useful' or 'very useful' by the pilots.

However the DWA sometimes directly issued a warning without a caution first. This was disliked by all pilots. The DWA should always provide lead information. Essentially this was

[2] ICAO= International Civil Aviation Organization

traced back to be a conceptual issue and the DWA's alerting volume should be improved on this aspect. In other cases the time between a caution and warning alert was considered to be too short. However, this was mostly a wake physics related aspect. Especially when flying on the ILS the wakes are sometimes residing very close (below and near) to the ownship.
Fig.10 shows results when only rating the HMI (independent of the DWA-mode). A small pilot preference occurred for HMI-3 (having all display features) over HMI-2, but this was conditional. More detailed analysis of the pilot comments showed that all three pilots preferred HMI-2 + VPI on PFD, or HMI-3 without the TTE-bars. Hence the VPI was appreciated but the TTE bars were disliked.

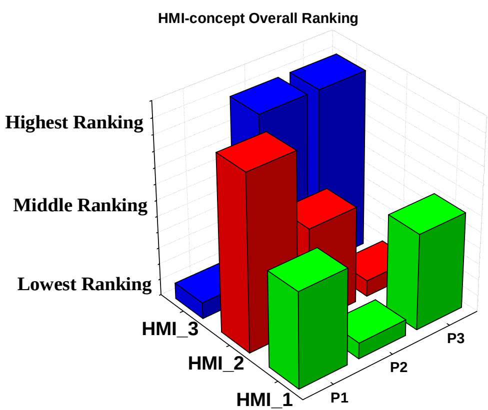


Fig. 10. HMI-concept overall ranking.

The different meaning of the VPI- and ILS scales did not provide any pilot confusion. The PFD alert labels were all found acceptable. No preference for top or centre alert label positioning was coming out of the study. But VPI and wake alert label color harmonization should be aimed for. When looking at the ratings of the combination of DWA mode and HMI no conclusive result was found, neither between modes nor between HMI-types, although HMI-1 (PFD only) was certainly not found the best.

The orange wake vortex symbols on the ND were found acceptable. The only suggestions given were:
- to color it white for non-threatening situations and amber/orange for threatening positions.
- to add a pilot control for on/off switching of wake symbols.
The ND range zoom option was liked but the wake presented accuracy was questioned.
Potential clutter issues remained unclear since the ND did not contain all the data as present during a normal approach (no FMS route info was available). There was no PFD versus ND incompatibility issue raised.

Results related to the following ergonomic attributes:
<u>Efficiency</u>
All pilots felt that with the new DWA+HMI logic they achieved a better level of decision making during the ILS approaches. "Currently the wakes are invisible but with this new system we can see where they are". When using the presented wake vortex information, the new system gave all pilots a significant benefit of induced safety by allowing them to anticipate the actions during the conduct of flight.
<u>Learning and Memory</u>
Not all pilots found the DWA system modes easy to understand when it was explained during the pilot briefing, but in the flight simulator they found it really simple to use. Also the new HMI aspects were easily understood from the briefing by the pilots.
<u>Satisfaction</u>
The pilots were asked to state their level of agreement and essentiality on the following:
“The DWA system is able to perform all things that I feel necessary to cope with wake encounter during the approach phase”.
The table below shows the result.

Pilot	**Pilot Level of Agreement**	**Level of Essentiality**
P1	Neutral	Very essential
P2	I agree	Very essential
P3	I agree	Very essential

Wake vortex avoidance flight procedure(s)
The operational usefulness was asked for when:
A) <u>before ILS intercept</u>
Two pilots considered it “Useful” for wake avoidance, and one was “Neutral” stating that more exposure was needed. The wake alert based speed reductions were mostly not applied

by pilots, path adjustments were preferred in this flight phase; ATC implications were referred to (i.e. less flow efficiency).

B) <u>high in the approach</u>

All pilots rated a ‘‘Neutral’’, but their comments indicated this procedure was not really found ok. Pilots did not like to fly above the ILS\GS (path adjustment), for either caution or warning alert. According to them this gives a (too) high descend rate lower in the approach, which could trigger ground prox. (GPWS) alerts easily.

C) <u>low in the approach</u>

One pilot found the procedure ‘‘Useful’’, but only for a go-around decision. Two pilots did not find this procedure useful for wake avoidance.

Speed reductions were sometimes applied for caution alerts, but the results remained inconclusive. However the DWA system was found useful for Go-Around decision making.

Additional pilot comments made were:

- I am not sure whether a Warning high up in the approach is essential. Above 1000 ft AGL, such a wake alert is not regarded critical.
- Sometimes a warning was almost directly followed by a caution this interferes with the flight procedure.
- Maybe I could fly up 1 dot high in the approach, but I need to be stabilized below 1000ft AGL, so can not do much any more at low altitudes.
- Flying 1 dot high [above GS] is difficult and not allowed today due to safety reasons (high descend rates low in the approach, destabilized)

Maybe only use a warning (no caution) at low altitudes to trigger a valid go-around.

- Maybe only use a caution to trigger awareness only

Encounter probability aspects

Subjective results indicated that it was too difficult for a pilot to visually judge via ND or PFD (VPI) whether the DWA wake alerts were right or wrong. All pilots referred to the lack of an aircraft response to a wake disturbance when flying through the wakes as the wake-a/c interaction model was not implemented.

Objective results: The measured\recorded data was looked at in more detail to determine the closeness of the wakes to the aircraft.

See Fig. 11 and 12 below.

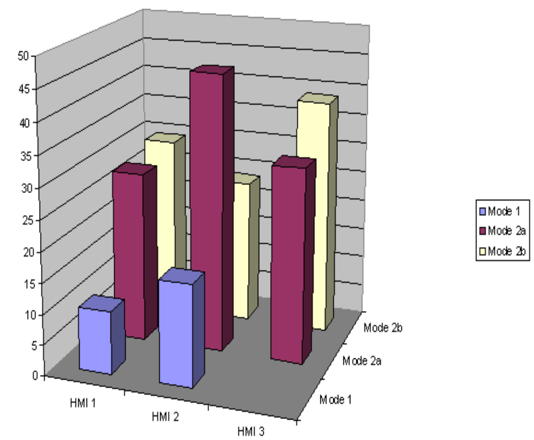


Fig. 11. Minimum wake to aircraft distance [m] per DWA mode and per HMI-concept.

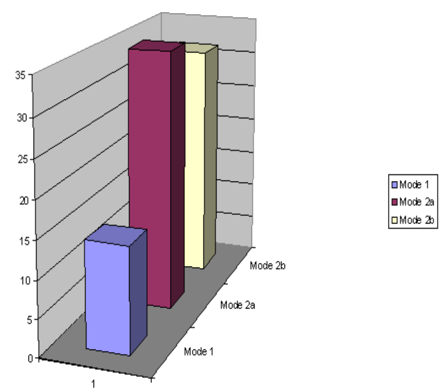


Fig. 12. Minimum wake to aircraft distance [m] per DWA mode (over all HMI concepts).

The larger the distance values the better, since further separated from the hazardous wake. The only clear noticeable effect found was related to the factor ‘DWA modes’, see Fig 12. The factor ‘HMI concepts’ did not matters so much, see Fig. 11. With DWA Mode 1 smaller distances were encountered than with the other two modes. This only gives a first indication that DWA Modes 2a and 2b may be somewhat safer than Mode 1. More studies into this aspect will be required as nothing valid can be derived on encounter probabilities.

The following conclusions are limited to the investigated flight phases only, the flight simulator set up used, and are based on an assessment performed by merely three pilots, providing statistically insignificant results.

4.2 Conclusions

The overall conclusion that was drawn, see [1] is that the DWA system and the associated wake vortex HMI has been proven feasible and is easy to use by the pilots.

The DWA and HMI ergonomics were found adequate and acceptable. All three different DWA modes were at least found useful and not difficult to handle, with a slight ergonomic related preference to DWA Mode 2a. DWA Modes 2a and 2b resulted into a larger wake encounter distance and hence potential smaller encounter probability than Mode 1. The HMI type had no real significant influence on the encounter aspects, but there are small indications that the addition of wake position information to the HMI may have a positive effect on safety. The DWA alerting logic based on alerting volumes worked as expected: it only alerted for really dangerous situations, but it should be improved on details.

The display concept that the pilots favored was neither HMI concept 2 or 3, but a mix of both: the presentation of wake vortex alert labels and vortex position information (VPI) on the PFD combined with a wake vortex presentation on the horizontal and vertical navigation display (i.e. on ND and VSD).

The pilot workload does not increase and situation awareness is improved with the display of new wake vortex presentation.

The DWA-mode that came out overall best was Mode 2. No significant difference between Mode 2a and Mode 2b was found, although DWA Mode 2a had a slight pilot preference.

A first effort was made to investigate the DWA alert-related flight procedures. From the few results obtained it has been concluded that providing a wake warning high in the approach is most likely not necessary, a caution might be sufficient. However, low in the approach the usefulness of a caution type of alert becomes disputable. A warning type of alert, coupled to a go-around is most likely the only useful option. More investigation towards these alerts and procedural aspects will be needed, in which also more different wake patterns will have to be used.

4.3 Recommendations

To increase operational realism, more complex, dynamic scenarios should be set up, that is: using more dense traffic near the airport, inside the TMA, in wake favorable weather and low visibility conditions. Also, the real life system aspects essential for certification (reliability, integrity) and accuracy of the wake vortex model data should be further investigated. On a standard three degrees approach a wake vortex can be relatively close to a landing aircraft while being non-hazardous. To timely notify for a hazardous wake will leave less alerting time margins than expected. Therefore the position and time based alerting criteria should be critically studied again. Although the first development steps for such a new safety system have proven to be difficult it provides a good basis for further improvements.

4.4 References

[1] I-WAKE consortium, *I-WAKE Final Publishable Report*, Ref. IWAKE-5-D-RE-THAV-055, 2005.

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[3] Society of Automotive Engineers, *Flight Deck Alerting System (FAS),* SAE Standard, Aerospace Recommended Practice ARP-4102/4, Revision A, Issued July 1988.

[4] W. Jackson, M. Yaras, J. Harvey, G. Winckelmans, G. Fournier and A. Belotserkovsky, *Wake Vortex Prediction – An Overview , Phase 6 and Project Final Report* prepared for Transportation Development Centre and Transport Canada, TP 13629E, March 2001.

[5] R.P.M. Verhoeven and A.J.C. de Reus, *Prototyping interactive cockpit applications*, NLR Technical Publication TP-2005-066, Feb. 2005.