A SIMPLIFIED HAZARD AREA PREDICTION (SHAPE) MODEL FOR WAKE VORTEX ENCOUNTER AVOIDANCE

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Abstract

This paper gives details from offline simulations, full-flight simulator studies and the preparation of a flight test experiment using the In-Flight Simulation capability of DLR's (German Aerospace Center) test aircraft ATTAS (Advanced Technologies Testing Aircraft) to validate safe boundaries around a wake vortex for encounter avoidance. The so developed hazard zone is an element in the Wake Vortex Prediction and Observation System which is under development in the frame of the DLR "Wake Vortex II" project to reduce aircraft approach separation and to improve flight safety.

*In any case the separation distance of approaching aircraft has to be determined in such a way that the approach corridor is free of hazardous vortex flows for the trailing aircraft. The question to be answered is what is the meaning of "hazard free"? The presented approach for solving this fundamental problem follows the idea that it is possible to define an area around a wake vortex outside which the vortex flow is definitely not hazardous to an aircraft. The reason for this "inverse" definition is the fact that a clear criterion of what is hazardous is difficult to set up (especially if a pilot is in the loop). The so defined boundaries of the hazard zone can easily be determined by the developed **S**implified **H**azard **A**rea **Pre**diction (SHAPe) Model. It allows the computation of hazard zone dimensions for any aircraft pairing (real or non existing aircraft). This potential of a universal application is based on the parameterization of the relevant aircraft wake vortex characteristics which are fitted by simple functions.*

List of Symbols and Abbreviations

a/c	aircraft
ATTAS	Advanced Technologies Testing Aircraft System
b	wing span
cg	center of gravity
DoF	degrees of freedom
DLR	German Aerospace Center
IFS	in-flight simulation
IMC	instrumental meteorological conditions
MTOW	maximum take-off weight
NLR	National Aerospace Laboratory
P2P	probabilistic two phase model
RCR	roll control ratio (= ξ^*)
t	time co-ordinate
SHA	simplified hazard area
SHAPe	simplified hazard area prediction
v	lateral velocity component
V	airspeed (no index), velocity
VMC	visual meteorological conditions
w	vertical velocity component
ZFB	Zentrum für Flugsimulation Berlin
Γ	circulation
η	elevator deflection
ξ	aileron deflection
ζ	rudder deflection
Δ	difference
Φ	bank angle
Θ	pitch angle
ψ	azimuth

indices

g	geodetic
K	kinetic (refers to flight path)
max	maximum
nom	nominal
W	wind
WV	wake vortex
WVL	wake vortex line
*	denotes normalized parameters

1 Introduction

The well known phenomenon of wake vortices behind a lift producing wing can adversely affect flight safety if encountered by trailing aircraft. The strength of the vortices increases with the weight of the vortex generating a/c. Therefore, weight dependent separation distances have been established for approach and landing to avoid dangerous wake vortex encounters. These proven separation distances have to be investigated to discover possible margins which could be used to solve the current and future capacity problems at airports. This demand forms the need for more flexible separation procedures taking into account the actual weather situation and the parameters of the individual a/c pairing. Within this scope a Wake Vortex Prediction and Observation System is under development in the frame of the DLR “Wake Vortex II” project to reduce aircraft approach separation and to improve flight safety [1].

2 Safety and Hazard

In any case the separation distance of approaching aircraft has to be determined in such a way that the approach corridor is free of hazardous vortex flows for the trailing a/c. The question to be answered is what is the meaning of “hazard free”? For solving this fundamental problem two different methodologies are applicable. One approach can be to define the constraints for which an encounter becomes hazardous. The difficulty of this procedure is the great variety of possible encounter situations and the numerous parameters of influence:

- Encounter Scenario
  - state of the a/c
  - orientation of flight path and wake vortex (encounter angles)
  - relative positions of wake vortex lines
  - encounter altitude
- Aircraft Pairing
  - vortex generator (a/c dimension, vortex strength, shape of velocity distribution)
  - follower (mass, a/c dimension, airspeed, aerodynamics, cg, control power)
- Meteorological Conditions
  - wind (e.g. cross wind, wind shear)
  - atmospheric turbulence
  - VMC, IMC (ceiling, visibility)
- Aircraft Control
  - individual pilot behavior (skill)
  - performance of automatic controllers

The list above claims not to be complete. But it underlines the difficulties (especially if a pilot is in the loop) to set up a clear criterion of what is hazardous (in terms of constraints leading unquestionably into an unsafe situation) as many attempts illustrate.

Approaching the problem from a safety point of view leads to the idea that it is possible to define an area around a wake vortex <u>outside</u> which the vortex flow is definitely not hazardous to an aircraft. This does not imply that any encounter (slight penetration) of the so defined Hazard Zone must result in a threatening situation. But the area outside the Hazard Zone has to be an absolute Safety Zone.

Following this approach it is necessary to identify safe boundaries around a wake vortex defining this Hazard Zone. The today policy to avoid hazardous situations is formulated by the obligation that “no vortex should be encountered by intention [2]”. But what means “no vortex encounter”. A qualitative statement can easily be made: the more distant the encountering a/c flies away from the vortex cores, the less are the noticeable effects of an encounter. From this declaration at least the following two conditions for a “no vortex encounter” situation can be derived:

- no vortex <u>core</u> encounter
- the a/c behaviour should be not abnormal compared to a flight in normal atmospheric disturbances (natural gusts and turbulence)

The latter statement is the more demanding one which has to be regarded for the development of safe boundaries around a Hazard Area.

3 Simplified Hazard Area (SHA)

For parallel-like encounters the aircraft’s roll response is the dominating motion. The worst case occurs when the wake vortex is parallel to the approach path and the following a/c is permanently exposed to the vortex flow field in a quasi stationary flight. The effect on roll within a wake vortex flow field then can be calculated using the required control power normalized by the maximum available control power of the encountering a/c expressed in terms of aileron deflection [3]. The wake vortex induced roll moment can be compensated if equation (1) applies.

$$x^{*} = \left| x / x_{\max} \right| < 1 \qquad (1)$$

Areas of various roll control demands can be defined by this normalized aileron deflection x^{*} which is equal to the roll control ration (RCR) known from other publications. Thus, x^{*} (respectively RCR) is a suitable measure to quantify the effect of a wake vortex flow field on an aircraft. Fig. 1 illustrates the flow field behind a generic vortex generating a/c (MTOW=79 to) in terms of normalized aileron deflection ξ^{*} for a light aircraft (MTOW=4.35 to). Different colored regions represent different levels of required normalized aileron deflections.

The complex shape of the areas for a specific nominal x^{*}_{nom} can be conservatively approximated by a simple rectangle which covers the respective region (Fig. 1). SHA includes the closer regions around the vortex lines. As a result, for small values of x^{*}_{nom} all other encounter parameters of interest (e.g. roll acceleration, angle of attack and load factor, lateral acceleration) are covered and remain within acceptable limits in terms of a/c controllability (which will be shown later). So if the term encounter is used in this paper the respective situation has to be understood to be rather a passing by than a hit of a vortex. The dimension of this SHA depends on the amount of x^{*}_{nom} which is tolerable without any adverse effect on safety. The appropriate value has to be established and validated for a reliable sizing of the SHA.

4 Validation of Safe SHA Boundaries

The validation of safe boundaries for SHA has been planned to be performed in 3 steps with increasing level of reality.

4.1 Numerical Offline Simulations

The numerical offline simulation is the nowadays universal state-of-the-art analysis tool. The reliability of the simulation results depends on the quality of the applied models. The choice of models was based on the rule “as complex as necessary but as simple as possible”. Nevertheless, great store was set by realistic modeling.

4.1.1 Modeling and Validation

A complex simulation system [3] was developed including the main modules:

- Vortex Generating Aircraft
  (→ flow field of a wake vortex)
- Encountering Aircraft
  (→ 6 DoF simulation and wake vortex/ aerodynamic interaction model)
- Encounter Control
  (→ ILS model and autopilot / autothrottle)

While the basic simulation system is based on standard modules and models particular effort was dedicated to include the special effect of wake vortices. In the frame of the S-Wake project [4] sponsored by the European Commission real wake vortex encounter flight experiments were executed to gather a valuable high quality data base from real flight tests. For the flight tests DLR’s **A**dvanced **T**echnologies **T**esting **A**ircraft **S**ystem VFW614/ATTAS was used as vortex generator. The encountering aircraft were the NLR’s Cessna Citation and the Dornier Do128 test aircraft of the University of Braunschweig [Fig. 2]. The latter is ideally suited for in-situ wake vortex measurements since it has 4 different stations with flow probes (nose boom, wing tips, fin). The collected data base was used to validate different approaches of wake vortex flow field and aerodynamic interaction models by means of parameter identification and flight path reconstruction techniques [5, 6]. At the end of this process reliable models for wake vortex encounter simulation were available.

Fig. 3 shows the comparison between simulation and flight test results of the Do128 encountering the wake vortex of ATTAS [5]. The black curves give the a/c response measured during the encounter from real fight tests. The red curves represent the output from the numerical simulation. Especially the roll and vertical axes illustrate the very good fit due to the high quality of the simulation system.

4.1.2 Simulation Results

Accepting that the rectangular SHA has to be avoided the worst case situation for an aircraft is a flight along its boundaries. Numerous offline simulations have been performed using the developed simulation tool. As an example the automatic controlled flight along the upper boundary of an SHA belonging to $\xi^*_{nom} = 0.3$ is illustrated in Fig. 4. The wake vortex lines are positioned in such a way that the nominal ILS flight path passes exactly the upper boundary of SHA with an encounter azimuth angle of $\Delta\psi_{WVL} = 5°$ between approach path and vortex lines. The respective time histories of the aircraft response are given in Fig. 5.

The SHA vanishes if the flow field produces only aileron deflection demands below the acceptable threshold of $\xi^* < \xi^*_{nom} = 0.3$ (due to the vortex decay). When the SHA no longer exists even a flight through the vortex core is no more a problem. From the simulations the following main conclusions were drawn:

- As expected the encounter situations down the left and right vertical boundary show mirror symmetry. Flights along the upper and lower boundary have to be differentiated.
- Since flight path deviations from the nominal flight path occur the actual normalized aileron deflection ξ^* respectively RCR during the wake vortex flow penetration can become slightly higher than the nominal value for which the SHA is designed. Nevertheless, the normalized aileron deflection is a well suited measure for hazard avoidance.
- For automatic control (AP/AT) a normalized aileron deflection of $\xi^*_{nom} = 0.3$ seems to provide safe margins to hazardous situations in terms of flight state and path deviations.

4.2 Flight Simulator Study

4.2.1 The Full Flight Simulator

For the next step of validation of the SHA boundaries manual flown wake vortex encounters were conducted in a simulator study using a full flight simulator. This simulator (see Fig. 6) is operated by the “Zentrum für Flugsimulation Berlin” (ZFB). It is used for airline pilot training as well as for scientific research of the University of Berlin. For the latter application a special simulation computer (Scientific Research Facility, SFR) can be connected to the simulator. On this simulation computer flight mechanics models are available representing different aircraft. The SFR generates the data to control the moving cockpit. The cockpit itself can be chosen to represent an A330 or A340 heavy transport type aircraft.

On the simulator described above the flight mechanics model of a small twin engine turboprop a/c similar to a Do228 (MTOW= 5.4 t, see Fig. 7) was implemented. It is essential to note that the dynamics of a commuter a/c have been controlled from a large transport a/c cockpit. The most important difference is the control of the roll and pitch axes via side-stick in the simulator, while the real Do228 a/c is controlled by a conventional control column and wheel. The pilots with a Do228 type rating stated that the real a/c is easier to handle than the simulator due to the described mismatch. Therefore, it can be assumed that the results coming from the simulator experiments were not overoptimistic at all. Consequently, the derived safe boundaries of the SHA can be considered to be conservative.

4.2.2 Experiment Design and Pilot Task

For the encounter investigation the standard situation of a 3° ILS approach was chosen. The initial conditions were defined at a distance of 6nm to the threshold, the a/c was established on the nominal path of the ILS. The gear was up and the flaps were in approach configuration. The reported wind was 15 kt coming 30° from the left. During the approach the a/c was exposed to different levels of turbulence in the range between no and light turbulence. The visibility in VMC was 50km. Additionally encounters in CAT I conditions with a decision height of DH = 222ft were investigated. The IMC was defined having a visibility of 4km and a ceiling from 450ft down to 225ft. Different encounter scenarios were defined by the parameters

- max nominal normalized aileron deflection resp. RCR (ξ^*_{nom} = RCR_{nom} = 0.3, 0.25, 0.2)
- flights along upper, lower, left, and right boundaries of SHA
- encounter angles
(vertical: 3° , horizontal: 0° / ±5° / ±10°)
- encounter altitude
(3m < H < 250m)

The pilots' task was to track the ILS signal to perform the approach and landing. They had to follow the common crew procedures (call outs) and to establish the aircraft's landing configuration (flaps, gear down). An approach sequence was completed after touch down and roll-out or in case of a go-around when a safe climb phase was established.

After each single run the pilots had to make their ratings on controllability, pilot demand, aircraft excursions, and over all hazard. The rating scales are based on [7] with some modifications (see Fig. 8). E.g., only four levels of ratings are established. It was known from other experiments that the pilots were unhappy with more levels of gradations for which they found it really difficult to differentiate smaller nuances. For the determination of acceptable SHA boundaries the subjective pilot ratings using Fig. 8 have to be better than 4.

4.2.3 Man-in-the-Loop Simulation Results

With the above experimental setup 3 simulator campaigns were executed with a total of 82 approaches carried out by 3 different pilots (see Tab. 1). Two of the pilots have a type rating for the a/c implemented on the simulator and one pilot was still a beginner. The respective data analysis is still going on but first results are available [8].

During the simulator experiments manifold parameters were recorded including pilot inputs, a/c states and trajectory. For the objective analysis of numerical data recorded the limits between acceptable and unacceptable encounter situations (see Tab.2) were derived carefully based on information from different sources [9, 10, 11, 12, 13].

Pilot	License	Flight Hours	Do228 Rating
A	CPL-IFR	300	no
B	ATPL	6500	yes
C	ATPL	4000	yes

Tab. 1. Experimental Pilots

parameter	acceptable limits
glide slope dev.	-0.5 DOT = ΔGS = 1 DOT
localizer dev.	ΔLOC = ±1 DOT
bank angle dev.	$\Delta\Phi$ = ±20°
indicated airspeed	-5 kt = ΔVIAS = +15 kt
descent speed	dz_g/dt = 1000 ft/min
roll rate dev.	Δp = ±15°/s
load factor	0.6 = n_z = 1.6

Tab. 2. Limits for Acceptable Conditions

Similar to the off-line simulations the complete SHA border (upper, lower, left, and right boundaries) was a matter of investigation. And again the wake vortex is parallel to the horizontal plane.

A typical example from [8] for an approach with a max nominal ξ^*_{nom} =RCR_{nom} = 0.2 shows Fig. 9. These are the results of a flight along the right border of the SHA. The encounter position is indicated by a red line. It takes place in IMC at a height of 78m. The effect of the vortex flow is not significant compared to other flight path deviations occurring during this approach. The main effect can be observed in the roll-axis but the max bank angle does not exceed $|\Phi|<10°$. The pilot roll input is about 25% of the max available roll control power. So the design value of RCR_{nom} = 0.2 is exceeded which was already observed from the off-line simulations. The numerical analysis shows only very small penetration of the limits defined in Tab. 2. The pilot ratings coming from Fig. 8 are 2 for all categories. Thus, the a/c behavior during encounter can be considered to be acceptable.

Fig. 10 shows the average ratings of the pilot for the investigated RCRs. The min and max ratings for each category are indicated by margins (black lines). It can be seen that for ξ^*_{nom} = RCR = 0.2 the average of each rating is 2 or even better. But the more important message is that no ratings worse than 3 occur. This implies that all encounters were at least acceptable. The numerical analysis of the flights shows only extremely rare situations of very slight penetration of the limits defined in Tab. 2 and only for negligible periods. From the simulator results the following main conclusions can be drawn [14]:

- The roll control inputs applied by the pilots can become higher than the reference value for the SHA design case. Nevertheless, the normalized aileron deflection/RCR is a well suited measure for hazard avoidance.
- For manual control a max nominal normalized aileron deflection of $\xi^*_{nom} = 0.2$ seems to provide acceptable wake vortex encounters covering all the other encounter parameters of interest (e.g. roll acceleration, angle of attack and load factor, vertical speed and lateral acceleration) which stay in between acceptable limits.

4.3 In-Flight Simulation

The final validation of the SHA boundaries will be done using the most realistic simulation tool which is the In-Flight Simulation. The IFS is DLR's standard method to investigate pilot-in-the-loop behavior in real flight conditions [15]. DLR's full fly-by-wire/light testbed ATTAS is especially designed for this application.

The principle of the IFS is roughly sketched in Fig. 11. The complete simulation system to be simulated in real flight (a/c model to be simulated, aerodynamic interaction model, wake vortex model) has to be implemented on the computers onboard the host aircraft ATTAS. The experimental pilot sitting on the left cockpit side of ATTAS is flying the simulated a/c using his real controls. These inputs are fed into the onboard computers stimulating the model a/c which reacts on his inputs and on the effects coming from the virtual wake vortex flow. The resulting model a/c states are fed into the model following control system. The model following controller calculates the control surface deflections of the host a/c which are necessary to make the host a/c behave like the simulated a/c. So the flight states of the host a/c experienced by the experimental pilot are in coincidence with the flight states of the simulated a/c.

That the concept described above can be applied to wake vortex encounter experiments has already been successfully demonstrated [16]. The flight tests for the validation of the SHA boundaries are currently in preparation. The first tests will be executed end of this year.

5 The SHAPe Concept

The dimension of the SHA can be calculated for each a/c pairing as described in chapter 3 if the tolerable ξ^*_{nom} is known. But there are different levels of abstraction for the prediction of these dimensions. For this prediction the **S**implified **H**azard **A**rea **Pre**diction (SHAPe) Model has been developed.

5.1 Levels of Abstraction

SHAPe has 2 levels of abstraction for the vortex generating a/c and 3 levels for the encountering a/c (see Fig. 12) [17].

- Vortex Generating A/C
  - The 1st level (highest quality) uses data of the real a/c (wing span, and relevant data for circulation calculation)
  - For the 2nd (lowest) level the information needed are derived from parameterized a/c data (see Fig. 13) using the MTOW of the respective a/c
- Encountering A/C
  - The 1st level (highest quality) uses the comprehensive data sets of aerodynamics and geometry of the actual a/c
  - For the 2nd (lower) level only the wing aerodynamics and geometry of the real a/c is considered (no effects of fuselage or tail are taken into account)
  - For the 3rd (lowest) level the information needed for are derived from parameterized data (see Fig. 13) using the MTOW of the respective a/c

For the parameterization all information from existing a/c available to the author has been used. Then the a/c data relevant for wake vortex encounters have been correlated with the MTOW (Fig. 13). Fitting curves have been approximated which allow the determination of wake vortex relevant parameters only knowing the MTOW. Due to the uncertainty of this method only the fits representing the worst case situation have to be used for the SHA calculation.

As an example: for the determination of the initial circulation of a vortex generating a/c with a specific MTOW the red curve of the respective diagram in Fig. 13 has to be used. This will produce the max possible circulation for the respective MTOW. If we are looking for the max available roll control power $C_l(\xi_{max})$ of an encountering a/c having a specific MTOW, the min amount of this parameter coming from the respective diagrams in Fig. 13 has to be chosen to consider the worst case situation. The required value is specified by the red curve.

If the above described generic approach using the parameterized a/c data is applied the resulting dimensions of the SHA are always bigger (see Fig. 14) than using actual data of specific a/c pairings. So this approach can be considered to be conservative for the prediction of SHA. The parameterized approach has the advantage that any generic a/c (being in line with existing aircraft) can be treated using SHAPe.

5.2 Computation Process

All levels of abstraction of SHAPe can be used to calculate the SHA dimensions as sketched in Fig. 12 to perform an on-line process. Another possibility offers the pre-calculation of SHA dimensions and their storage in multi dimensional tables (see Fig. 15). This can be done for specific real a/c pairings (if respective data are available) as well as using the parameterized approach for any generic a/c pairing. For the determination of the SHA the actual (time dependent) circulation Γ of the vortex generating a/c must be known. Respective models are available, e.g. ref. [18].

6 Dynamic Separation Distances

The SHAPe model is an important element in DLR's Wake Vortex Prediction and Observation System. Its application is sketched in Fig. 16 which shows the cross section of an ILS approach. The vortex generating aircraft shows some flight path deviations forming the elliptical approach corridor where the generation of wake vortices can be assumed. The ellipse can be conservatively simplified by a rectangle. DLR's Probabilistic Two Phase Wake Vortex development and decay model (P2P) [18] then predicts an area of probable vortex locations after a period Δt. It is assumed that no vortex will leave this P2P area. At the corners of this area the hazard zone computed by SHAPe is superimposed. The envelope around the individual hazard zones is the overall hazard zone which is not allowed to be penetrated. For the determination of safe separation distances for an individual aircraft pairing the period Δt of two consecutive a/c has to be determined in such a way that no overlapping of approach corridor and over all hazard zone exists. This calculation is done at gates along the approach path (Fig. 17).

In Fig, 16 it is assumed that SHA always covers a vortex pair. This is not the case if the 2 vortices of a wake split and move separately. Investigations show that SHAPe can also work with hazard areas of a single vortex without any changes of the presented methodology [19].

7 Summary and Conclusion

The presented approach to solve the fundamental problem of the definition of a "hazard free" area follows the idea that it is much easier to define an area around a wake vortex outside which the vortex flow is definitely not hazardous to an aircraft rather than looking for encounter boundaries and constraints leading unquestionably into a hazardous situation. The reason for this "inverse" definition is the fact that a clear criterion of what is hazardous to an aircraft is difficult to set up (especially if a pilot is in the loop) as many attempts illustrate.

For not too close vortex fly-bys the threat can easily be assessed by the required control power expressed in terms of normalized aileron deflection $\xi^* = |\xi/\xi_{max}|$ also known as RCR. A certain fraction of this expression is identified to present a safe limit in terms of wake vortex encounter depth. An rectangular Simplified Hazard Area is defined covering this region around a wake vortex. From offline simulations and from simulator experiments it was found that for automatic approaches nominal values of ξ^*_{nom} = 0.3 and for manual approaches ξ^*_{nom} = 0.2 seem to provide safe encounter conditions. The latter value will finally be validated by real flight experiments using DLR's In-Flight Simulator ATTAS.

The SHA dimensions can easily be determined by the Simplified Hazard Area Prediction (SHAPe) Model. It allows the computation of hazard zone for any aircraft pairing (real or non existing aircraft). This potential of a universal application is based on the parameterization of the relevant aircraft wake vortex characteristics which are fitted by functions.

The SHAPe model is a important element in DLR's Wake Vortex Prediction and Observation System. Using the wake vortex development and decay output of DLR's P2P model SHAPe can determine safe separation distances by predicting the conditions when no longer an overlapping of approach corridor and over all hazard zone exists.

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9 Figures and Tables

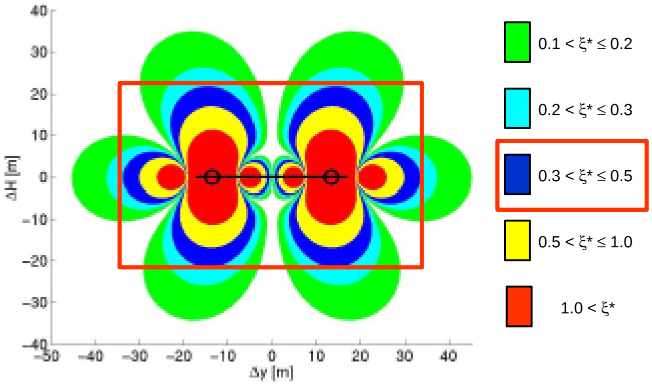


Fig. 1. Required Aileron Deflection in a Wake Vortex and Simplified Hazard Area

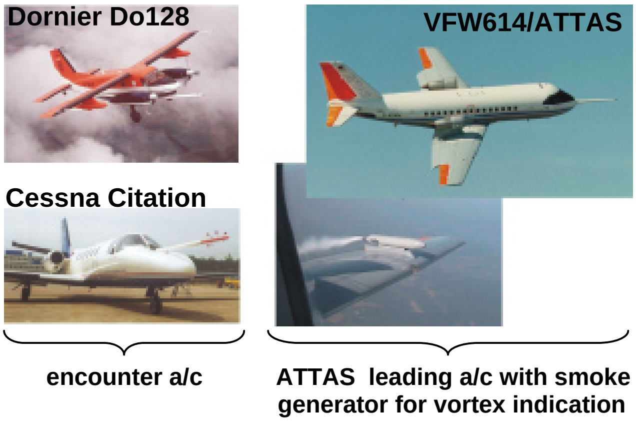


Fig. 2. Test Aircraft for Wake Vortex Encounter Flight Experiments

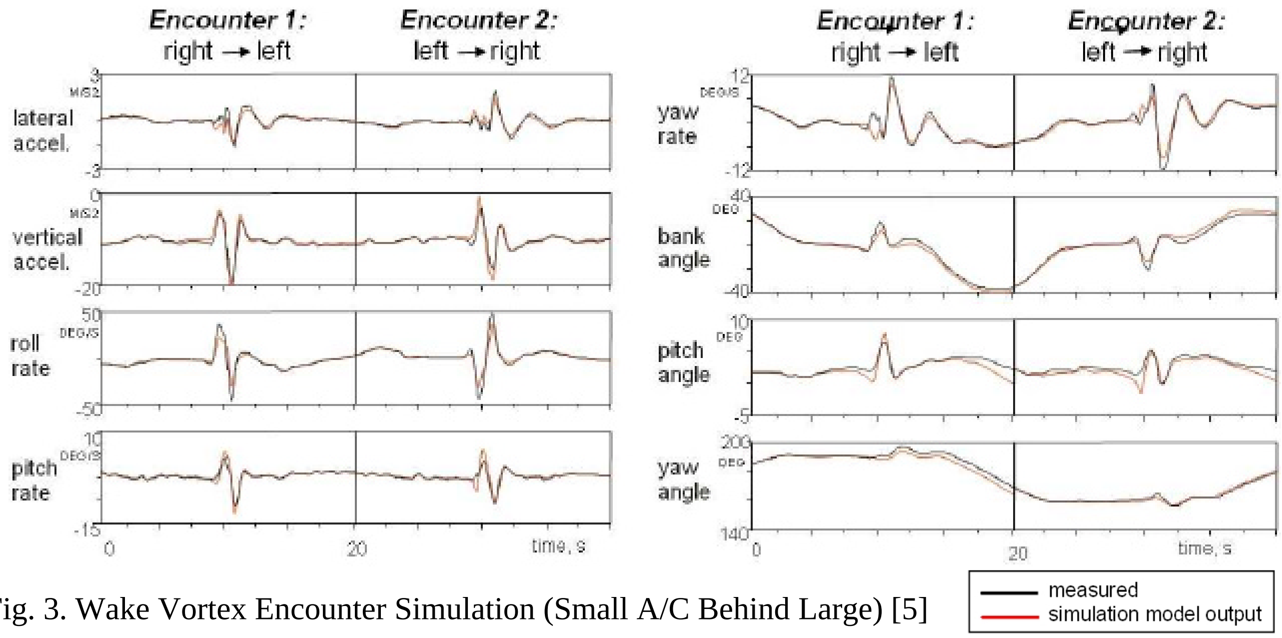
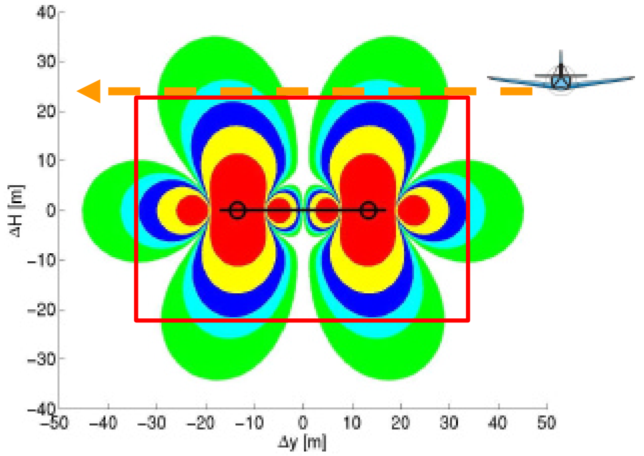


Fig. 3. Wake Vortex Encounter Simulation (Small A/C Behind Large) [5]



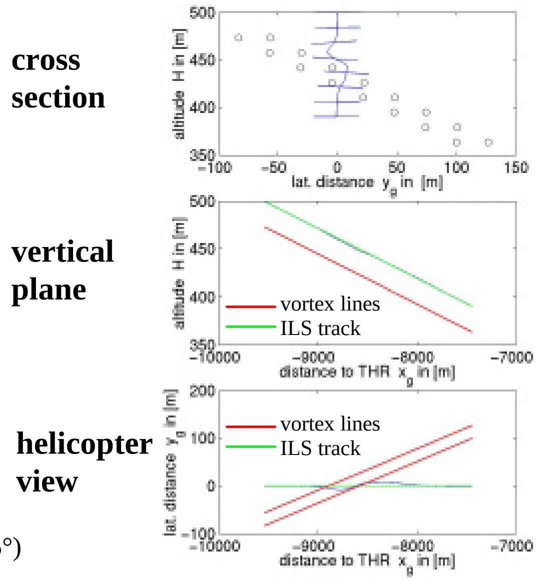


Fig. 4. Flight Along the Upper Boundary of the Simplified Hazard Area ($\xi^*_{nom} = 0.3$)
(flight path angle $\gamma = -3°$, encounter azimuth $\Delta\psi_{WVL} = 5°$)

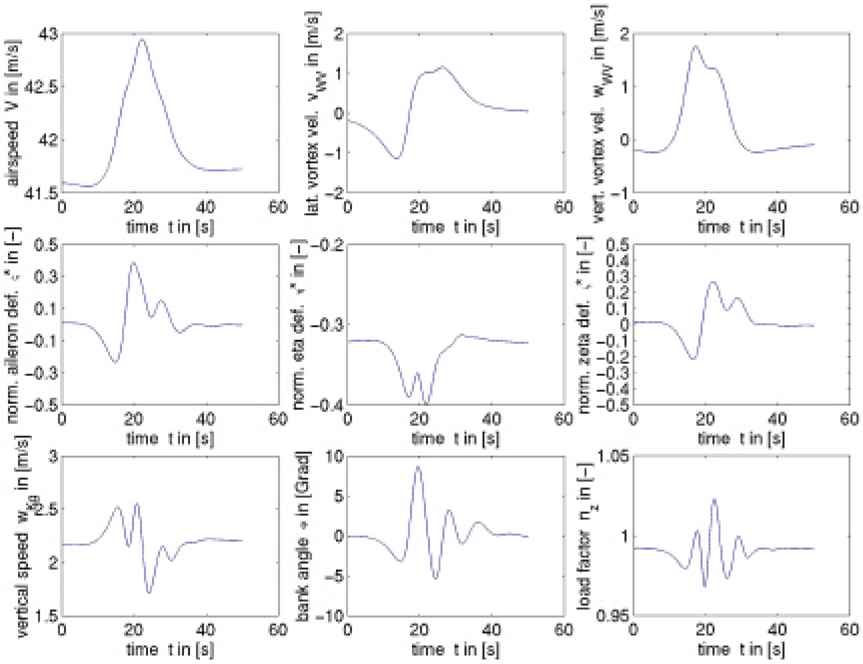


Fig. 5. Time Histories of a Flight Along the Upper Boundary of the Simplified Hazard Area ($\xi^*_{nom} = 0.3$)

Fig. 6. ZFB Full Flight Simulator

Fig. 7. Do228 Aircraft (MTOW=5.4t)

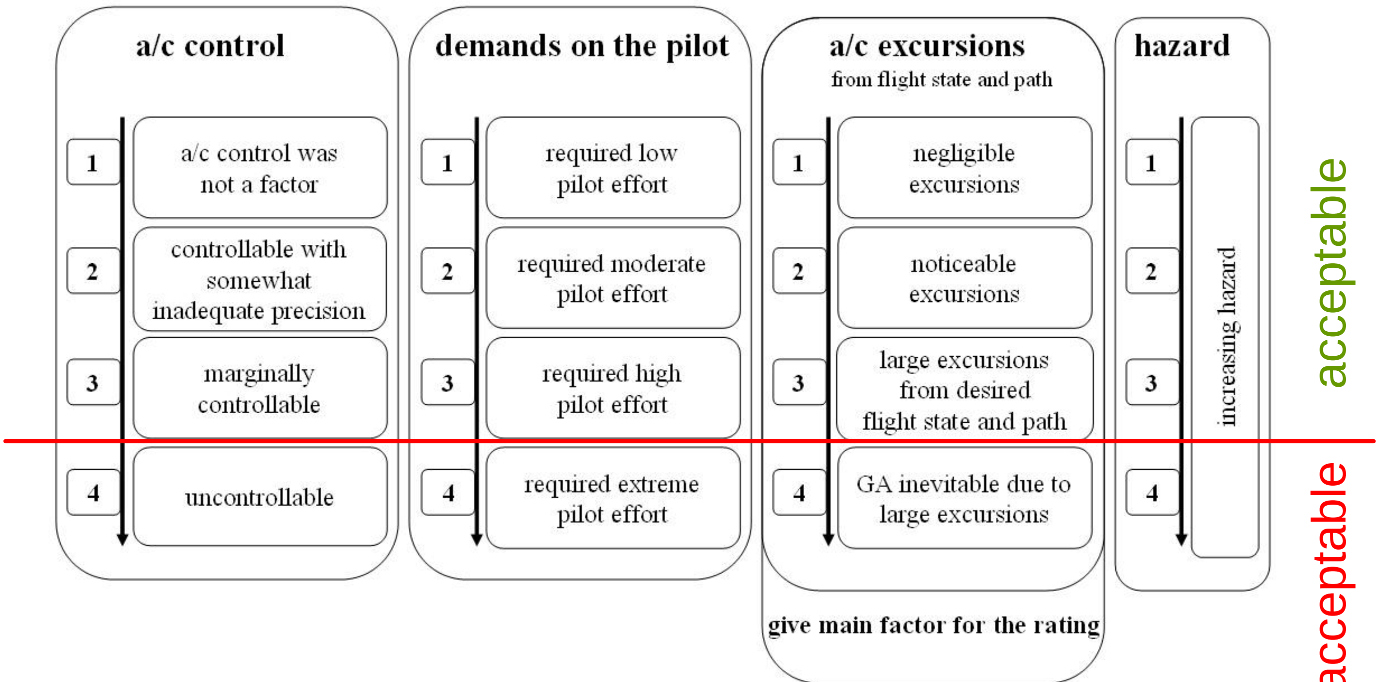


Fig. 8. Pilot Rating Scales

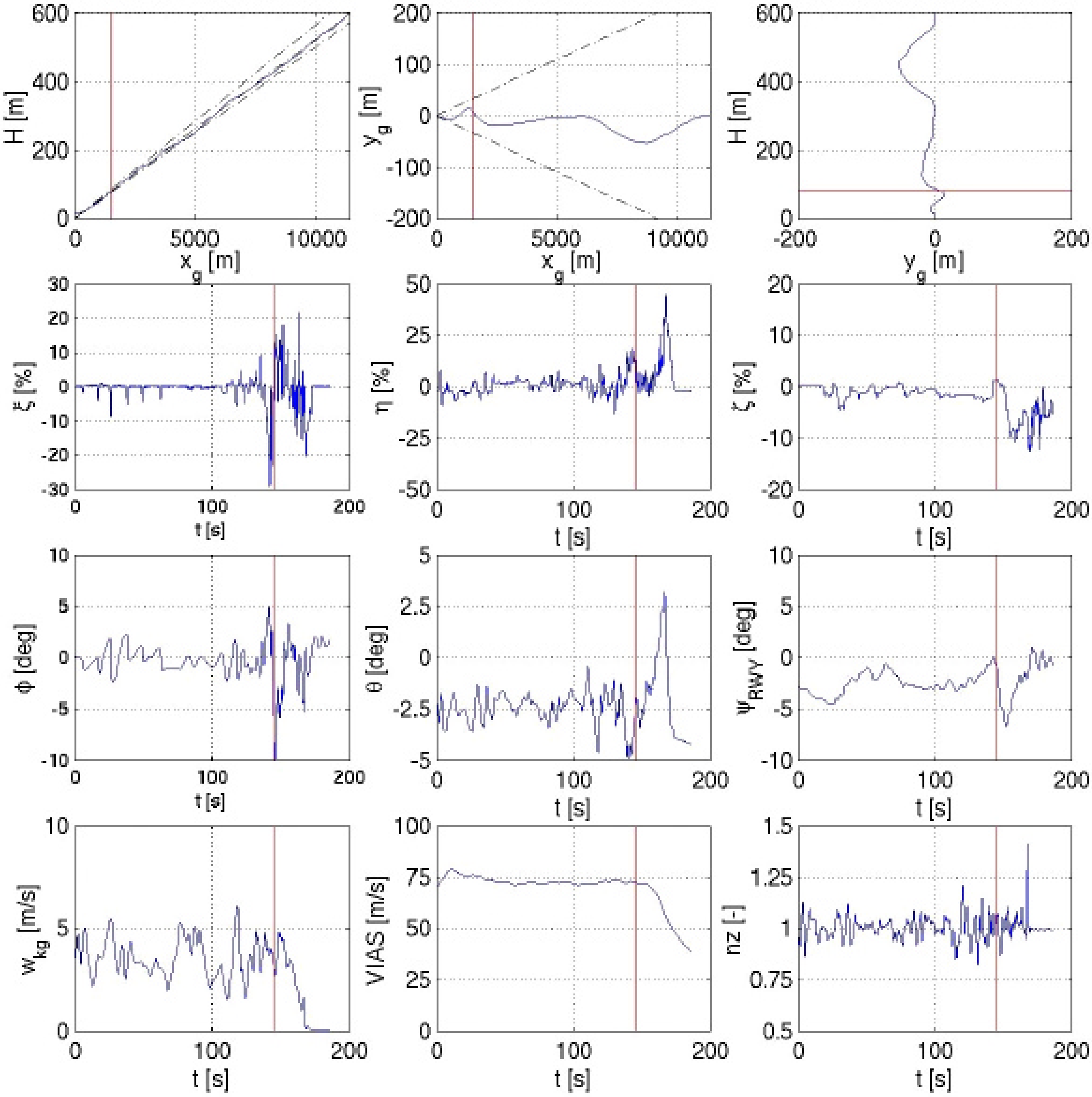


Fig.9. Trajectory and Time Histories of a Vortex Encounter ($\xi^{*}_{nom} = 0.2$) from Simulator Experiment

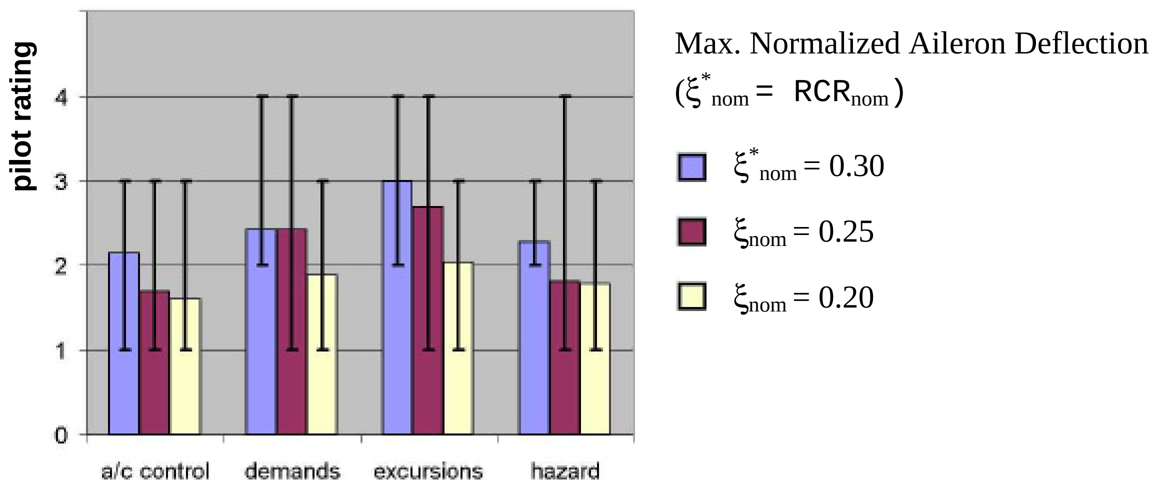


Fig.10. Pilot Ratings of Wake Vortex Encounters with Different Strength

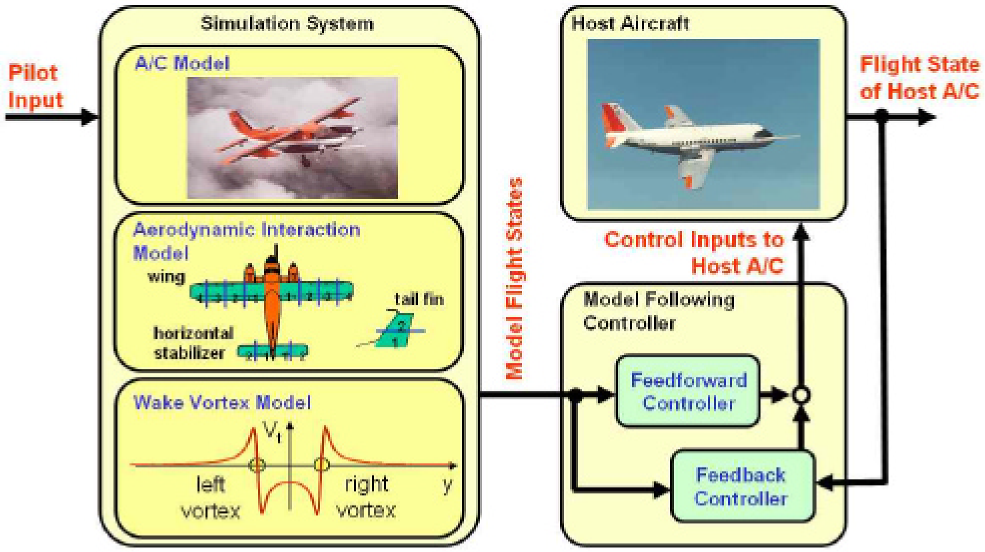


Fig.11. Principle of the In-Flight Simulation for Wake Vortex Encounter Experiments

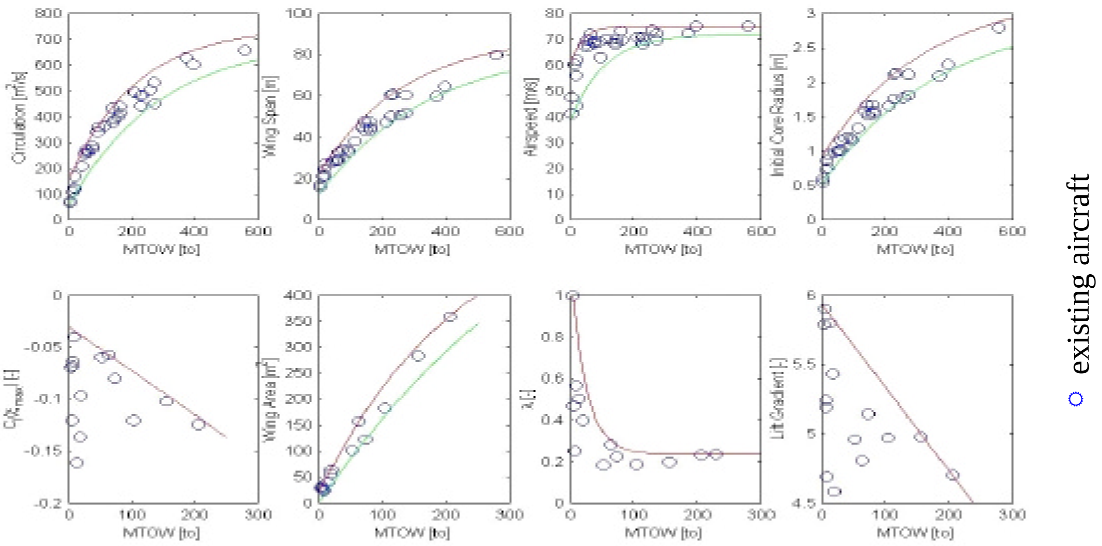


Fig.13. Parameterization of Aircraft Data as a Function of MTOW

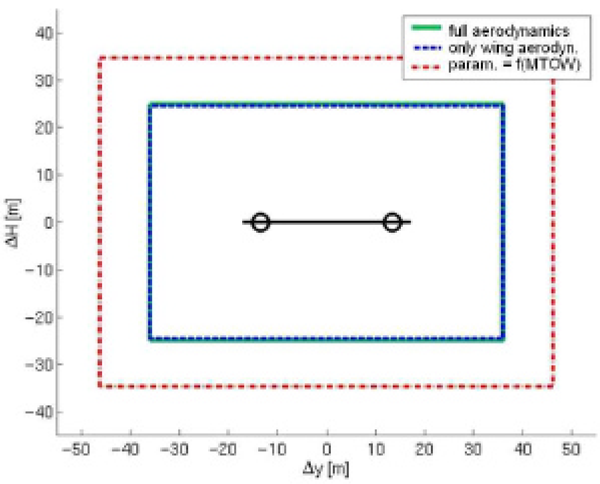


Fig.14. Comparison of Computed SHA Dimensions

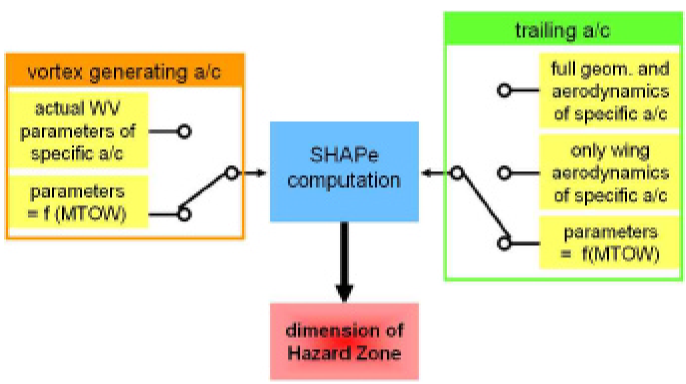


Fig.12. Levels of Abstraction of the **S**implified **H**azard **A**rea **Pre**diction (SHAPe) Model

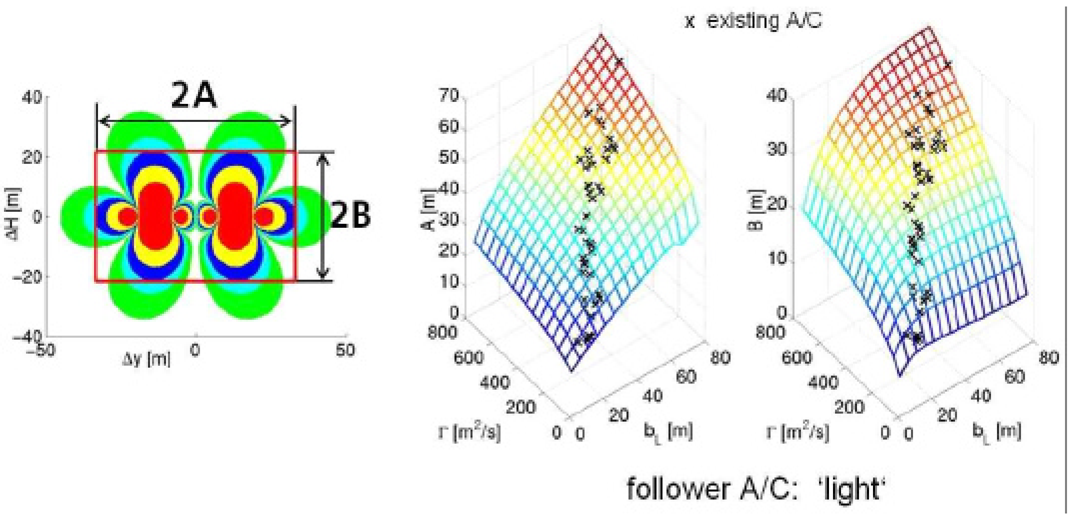


Fig.15. Application of the SHAPe Concept for the Generation of Dynamic Separation Distances

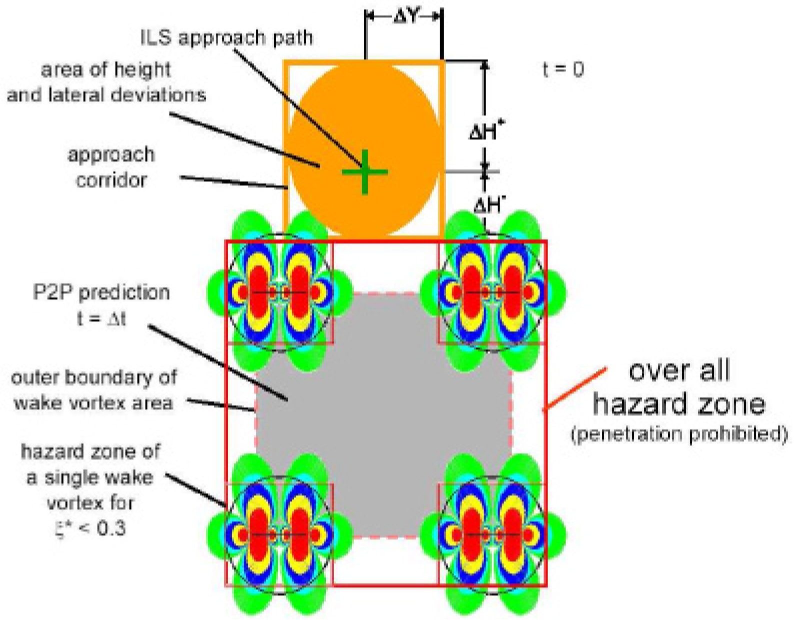


Fig.16. Application of the SHAPe Concept for the Generation of Dynamic Separation Distances

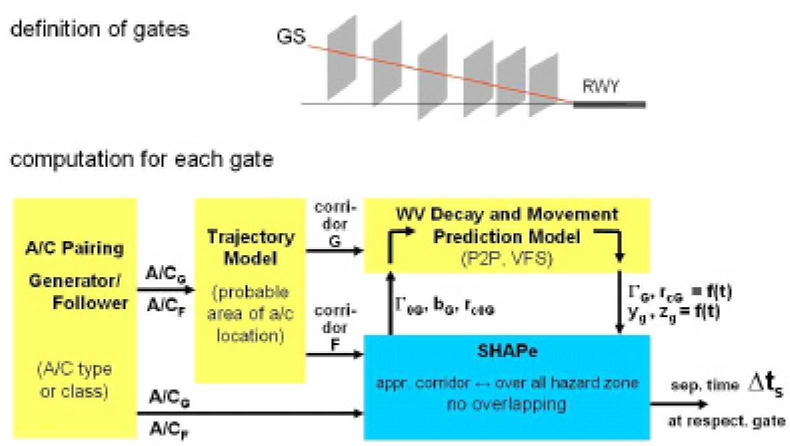


Fig.17. Integration of SHAPe in DLR's Prediction and Observation System