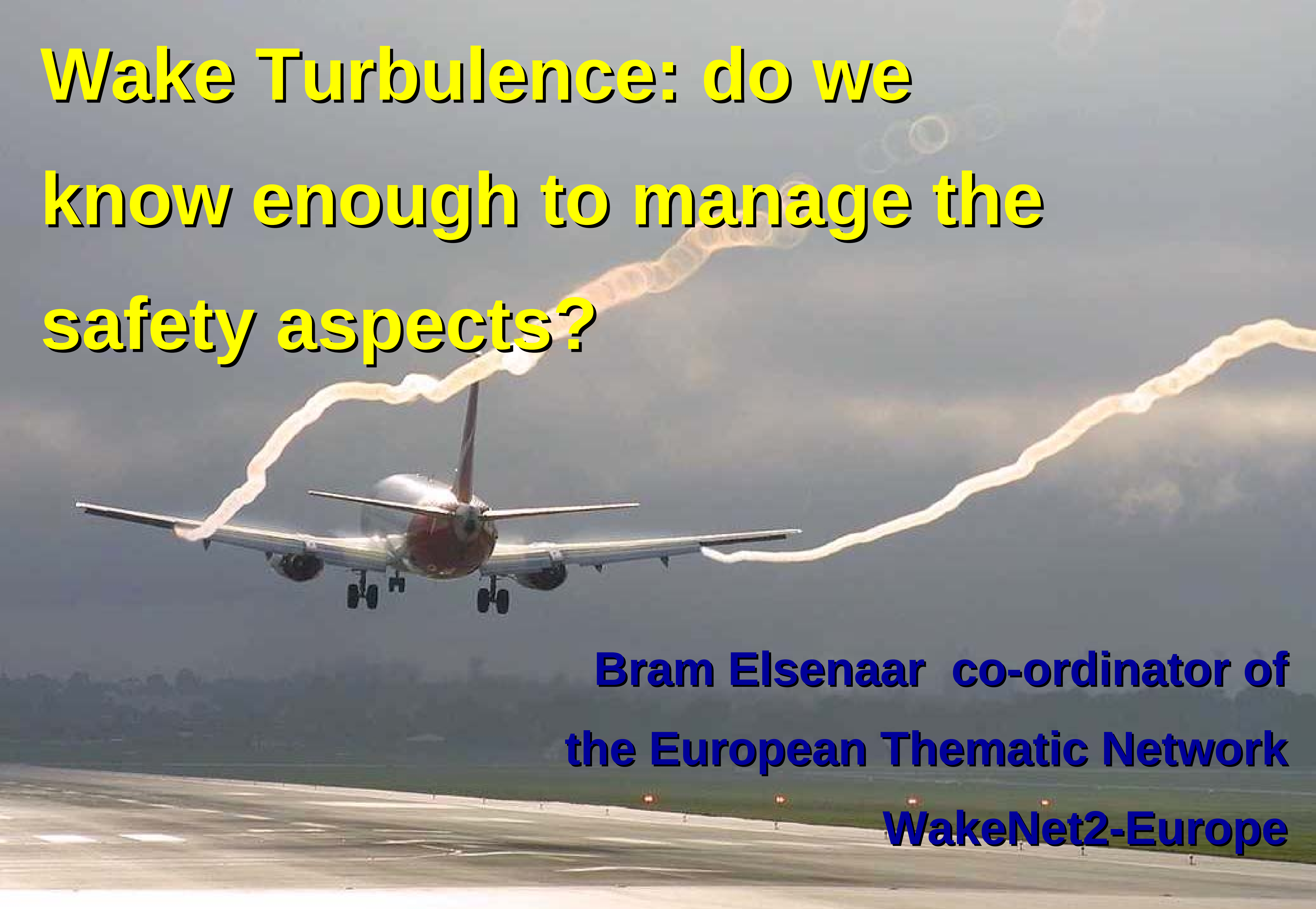
Wake Turbulence: do we know enough to manage the safety aspects?

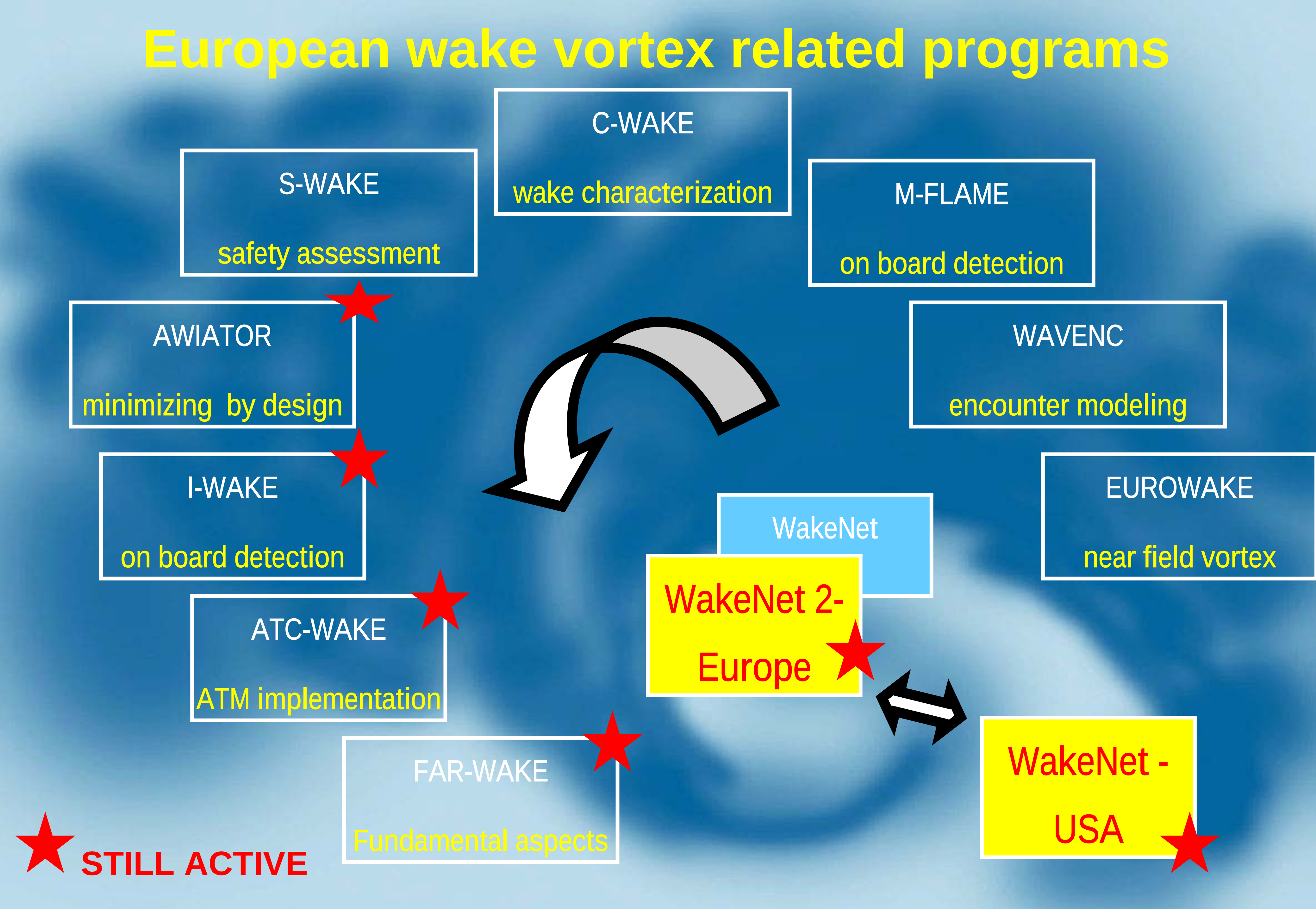


Bram Elsenaar co-ordinator of the European Thematic Network WakeNet2-Europe

Outline

- **Introduction and background**
- **Present ruling, possible changes and benefits**
- **How to assess wake vortex safety ?**
  - Wake characterisation
  - Weather predictability
  - Encounter modelling
  - Probabilistic safety assessment
  - Monitoring rule change

Introduction and background


European wake vortex related programs
C-WAKE
wake characterization
S-WAKE
safety assessment
M-FLAME
on board detection
AWIATOR
minimizing by design
WAVENC
encounter modeling
I-WAKE
on board detection
EUROWAKE
near field vortex
WakeNet
WakeNet 2-Europe
ATC-WAKE
ATM implementation
WakeNet - USA
FAR-WAKE
Fundamental aspects
STILL ACTIVE

What's the problem?

- **Flying aircraft generate a wake of two counter rotating vortices (like horizontal 'tornado's')**
  – their initial strength depends roughly on the lift and wing span
  – they are transported by the wind
  – they normally descent but may stall or rebound for specific atmospheric conditions and near the ground
  – they decay due to atmospheric turbulence but persist for long time in quiet weather
- **When a following aircraft enters a wake, it may result in a severe upset (bank-angle, sink rate)**
- **Hence ICAO has made rules that prescribe the minimum separation distances**
- **These rules put a limit to airport capacity**

Present ruling, possible changes and benefits

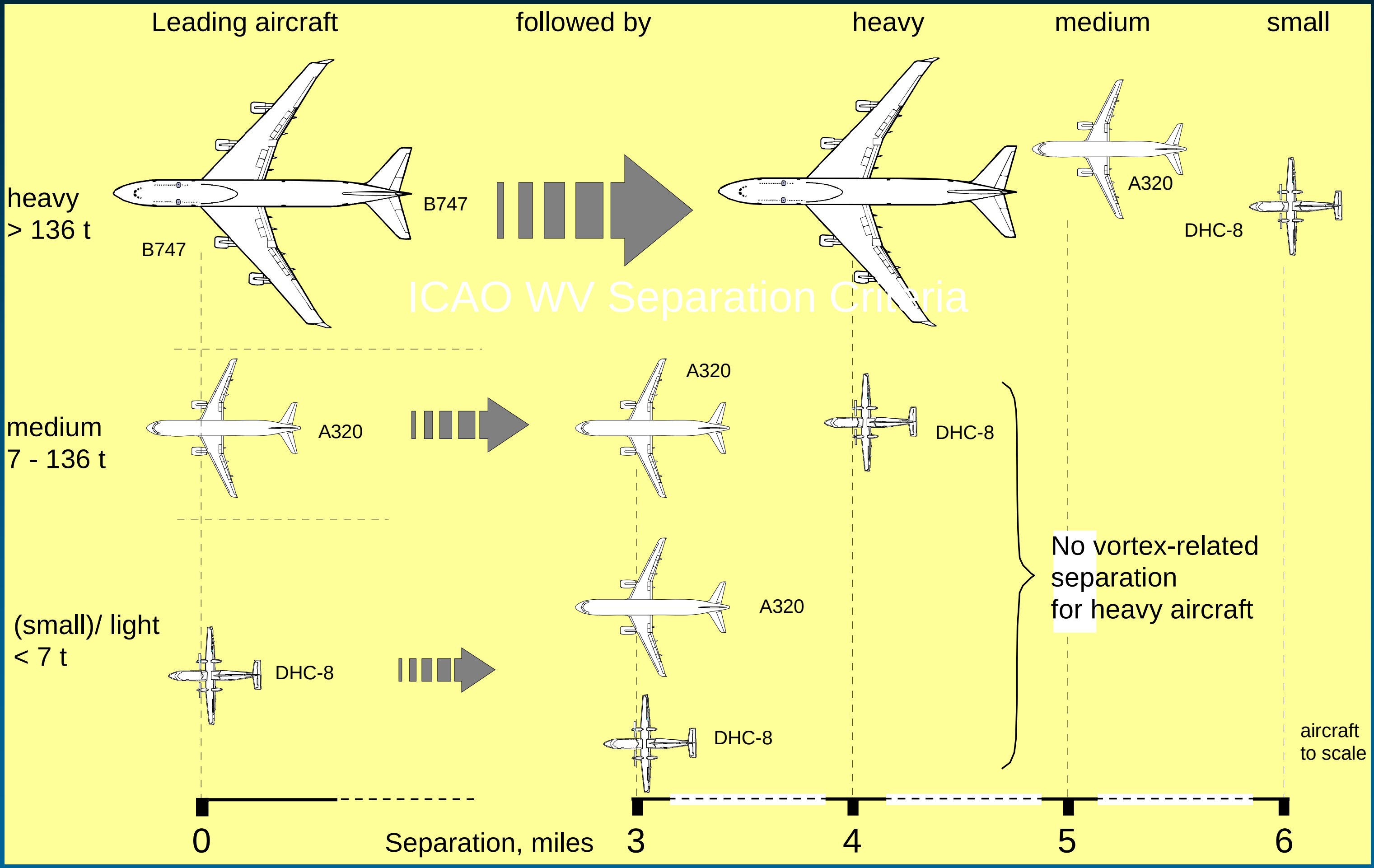
Present (ICAO) ruling (simplified)

- **For VFR conditions separation is determined by the pilot / air traffic controller with the ‘runway occupancy time’ (ROT) as a minimum**

- **For IFR conditions separation distances (in excess of the radar separation of 2.5 nm) are prescribed by the ATC controller applying rules based on aircraft weight categories for leading and follower aircraft**

- **Closely spaced parallel runways (CSPR) are treated as a single runway for separation distances when the runways are less than 2500 ft apart**

ICAO 's weight class dependend separation criteria

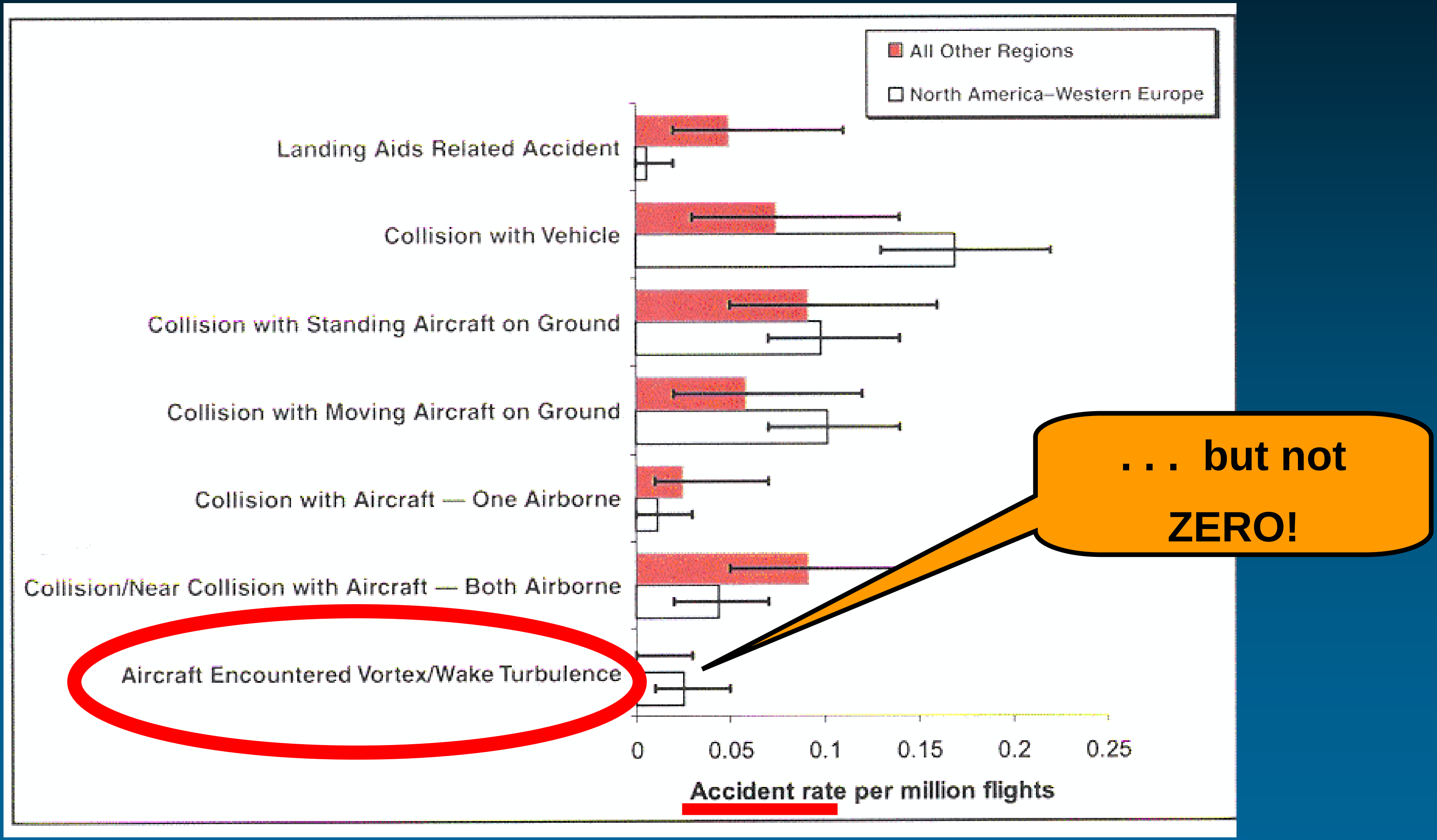


Wake turbulence as loss-of-control factor: many reported incidents. . . .

(Boeing: in Aviation Week, August 2002)

. . . but wake turbulence is very rarely the cause of accidents

***(ATM related accident rate's from NLR** Aviation Safety Data Base)*



Experience with the present (ICAO or national) separation rules

- **There are regular incident reports of wake vortex encounters, mostly non-hazardous**
- **There are very few wake vortex induced accidents and they occur almost exclusively for VFR conditions**
- **Occasionally incident reports are filed for encounters beyond the 'safe separation distances' e.g. for very quiet weather conditions with a weak tail wind**

Present separation distances are safe, possibly too conservative but not always; weather conditions are critical !

Considering a change in the current practice

- **Would it be possible to reduce separation distances (by rule change, depending on the weather conditions), while still maintaining the present level of safety?**

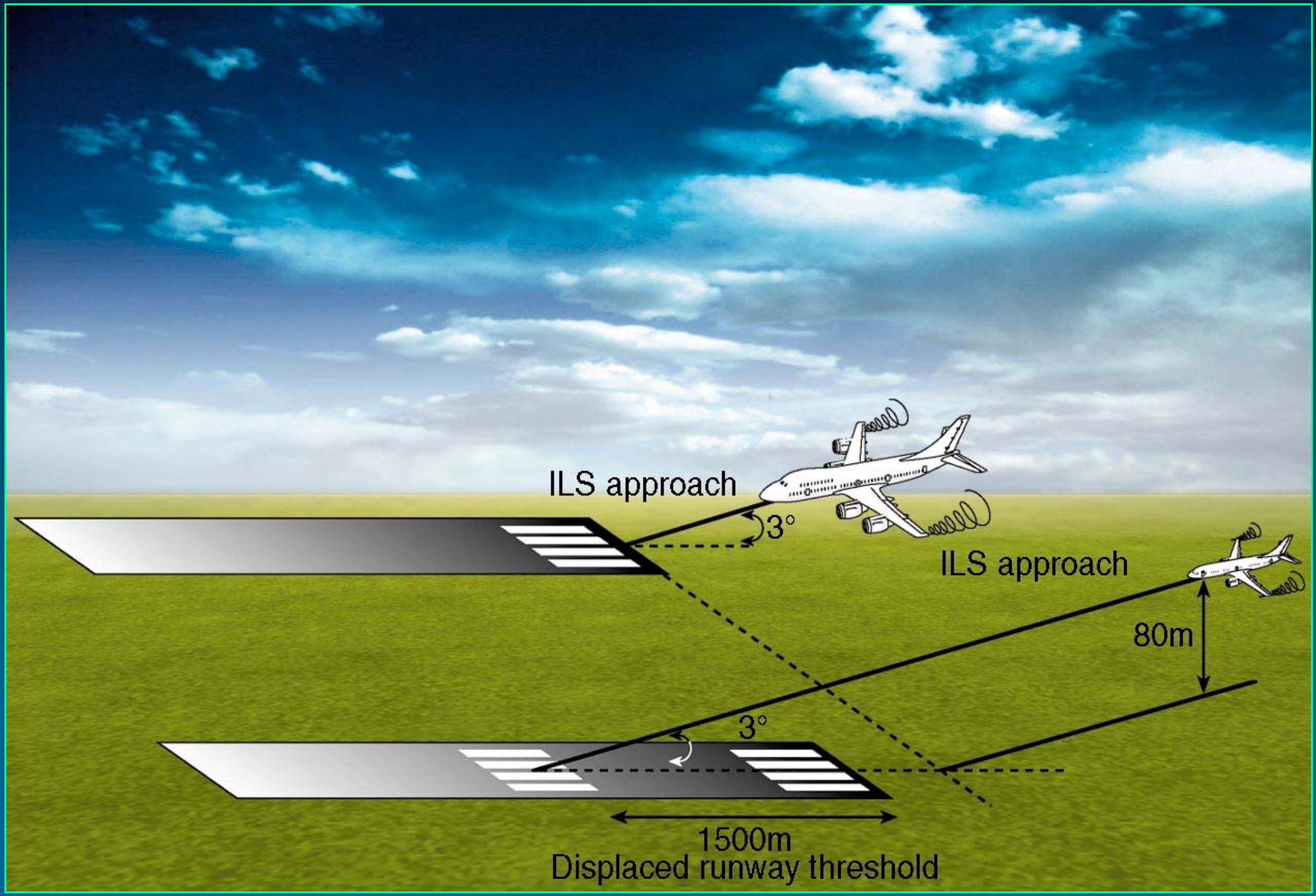
- **Possible benefits are two-fold:**
  - tactical:
    reducing delays (whenever they occur) when the weather allows reduced separation distances
  - strategic:
    increasing the declared airport capacity (number of slots / hour)

From simple to complex changes

- **Examples of 'simple' (rule) changes**
  – reduce the 2500 ft limit for closely space parallel runways to e.g. 1000 ft for smaller aircraft
  – apply a time based instead of a distance based separation criterion

- **Examples of more complex changes:**
  – weather dependent departures (using weather now-casting)
  – make the separation distances for closely spaced parallel runways dependent on the magnitude and direction of the cross-wind
  – make the single runway separation distances dependent on weather conditions ('dynamic spacing')

Example (1): Wake turbulence mitigation for closely spaced parallel runway's with displaced threshold's as applied at Frankfort Airport (HALS/DTOP)



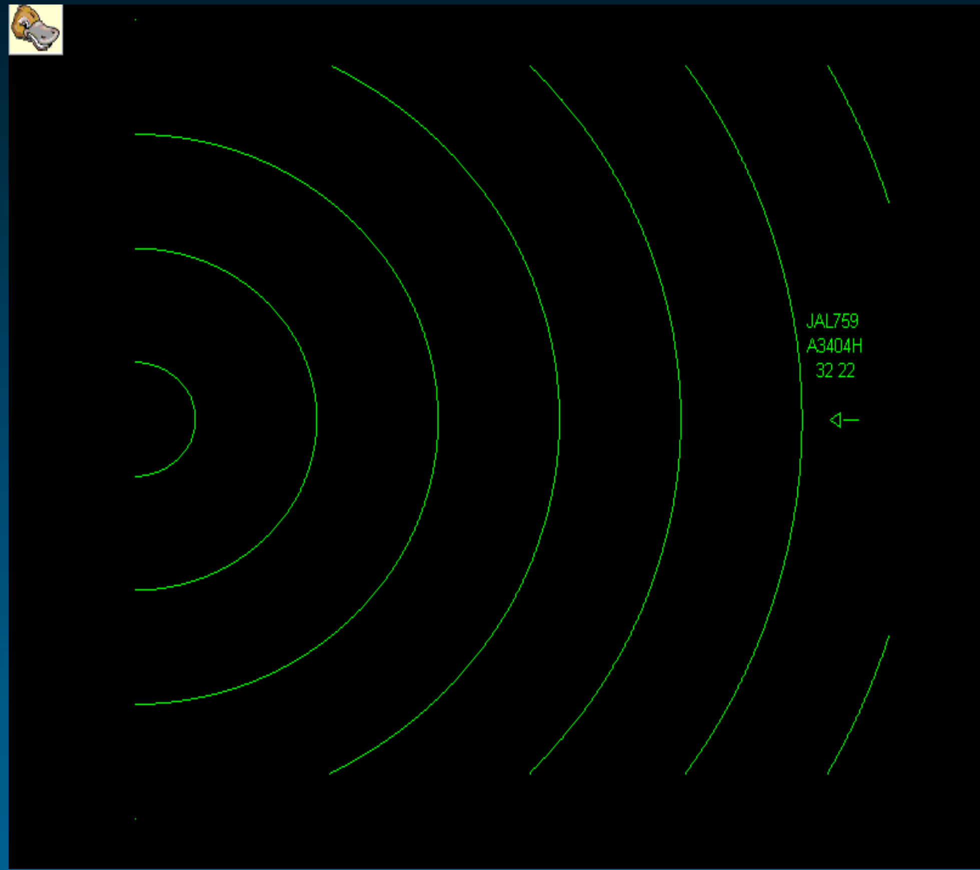
Example (2): 2 Modes of Operation (ICAO / ATC-Wake) depending on weather

(from European ATC-wake program)

Brussels – 25 L / 25 R

17:10 – 14:30	ATC WAKE	Arrivals : 2.5 NM Departures : 90 s
14:30 – 11:50	ICAO	
11:50 – 08:20	ATC WAKE	Arrivals : 2.8 NM Departures : 100 s
08:20 –	ICAO	

07:29 | Mode transition at 07:40



HMI for the Approach Controller
Wake Vortex Vector on Radar Display

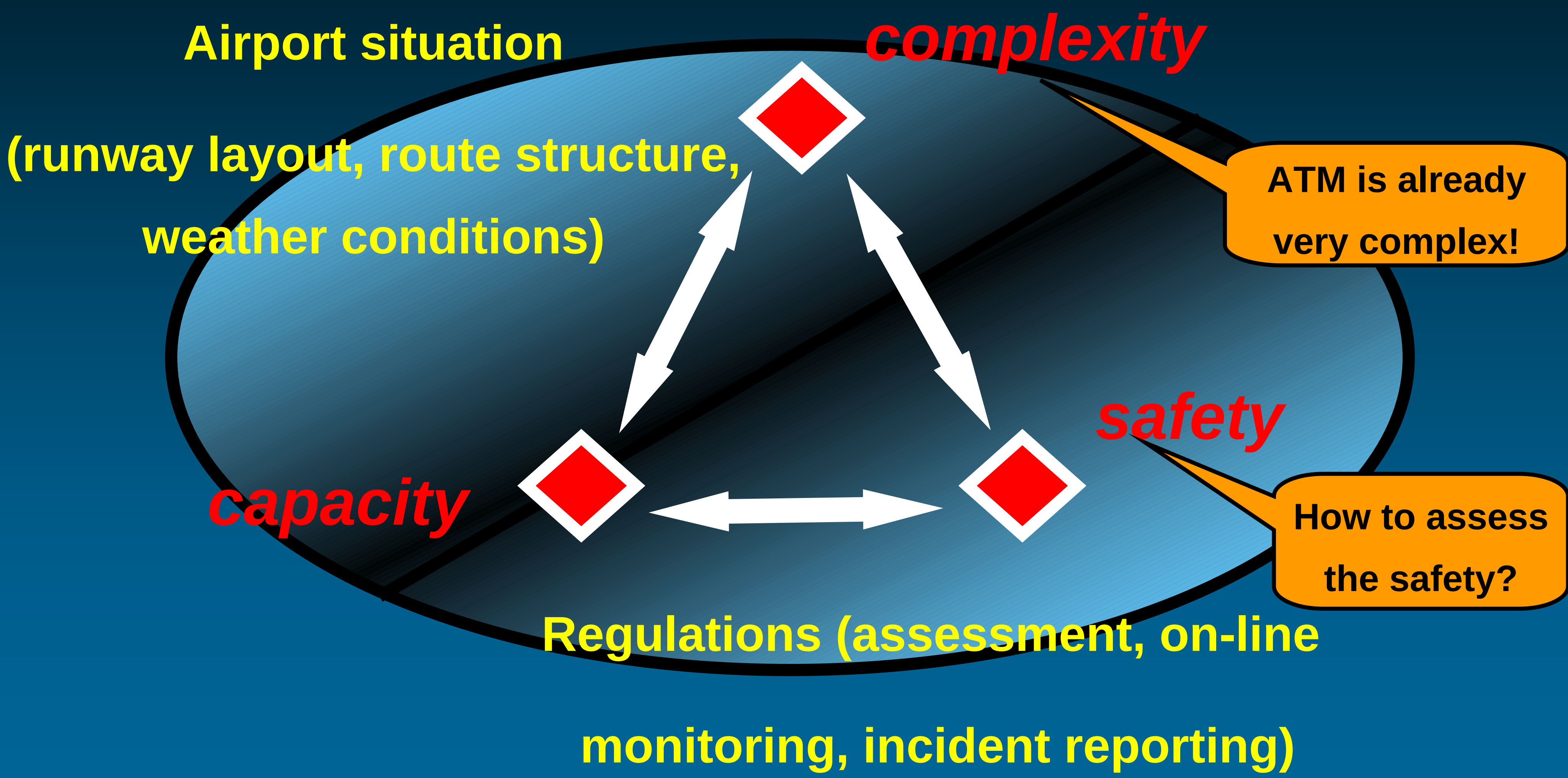
Benefits: some numbers

- **EU estimates: Air Traffic delays cost 62 € per minute ;**
  total costs in 2002 : 700 M€ - 1000 M€
  (from EUROCONTROL Performance Review Report 6)

- **NASA study on Dallas/FortWorth airport (independent runways) indicates 8% capacity increase for weather dependent Wake Vortex Warning System**

- **US Business Case Study indicates very favourable cost / benefit ratio’s for Wake Vortex Advisory Systems (WVAS) in CSPR situations (sometimes as high as order of 100)**

If the benefits are so large, why hasn't it been introduced?



How to assess wake vortex safety ?

Safety framework

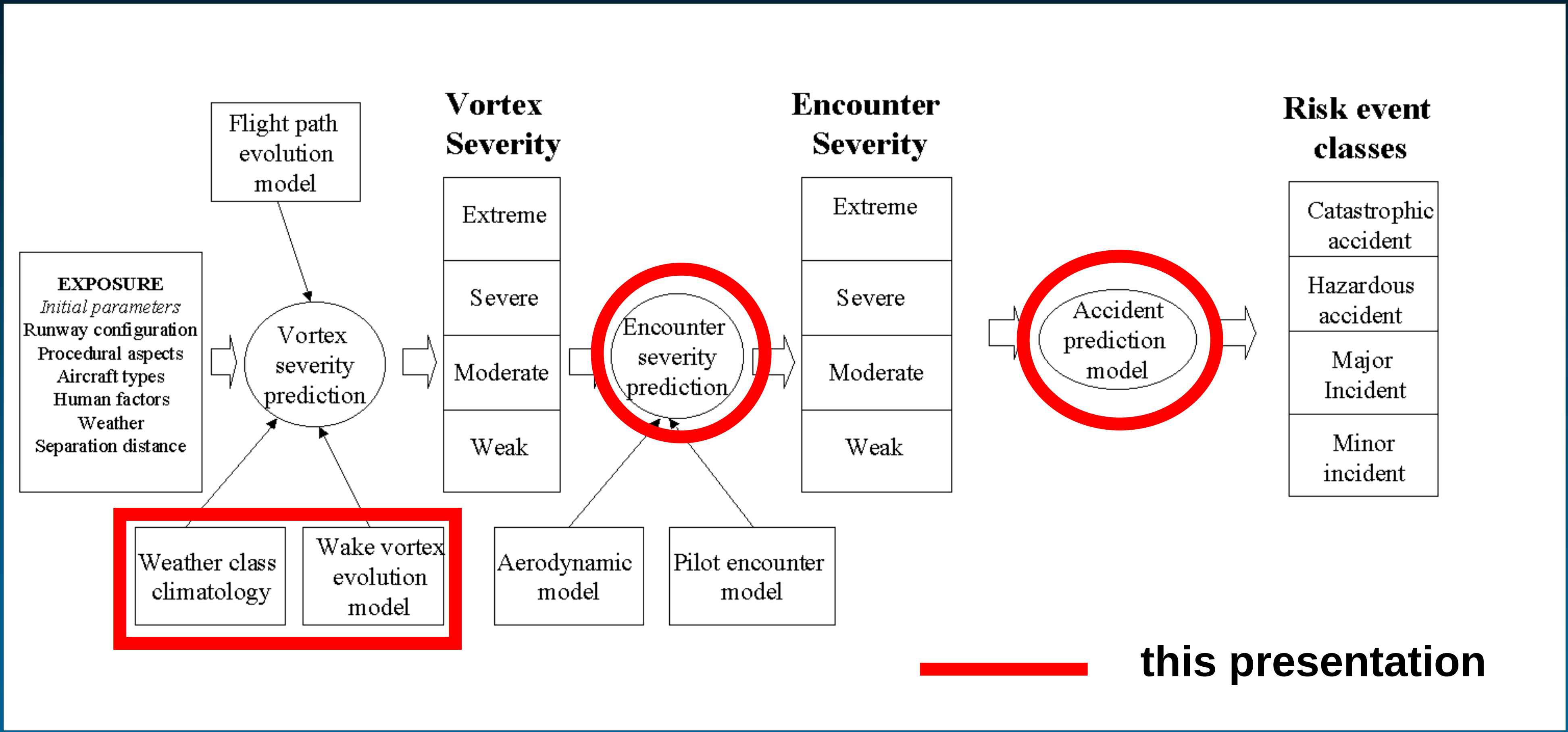
- **In Europe ESARR4 sets requirements for safety assessment ('targeted level of safety' approach)**
- **wake encounters are very rare events, strongly weather dependent: a probabilistic safety assessment is required**
- **in European research programs building blocks for such a safety assessment are developed and being refined e.g.**
  - wake vortex characterisation including weather effects
  - research to define criteria for severe and non-sever encounters
- **for validation of risk assessment methodologies incident reporting is essential**

Probabilistic wake and encounter modelling
(S-Wake, NLR)

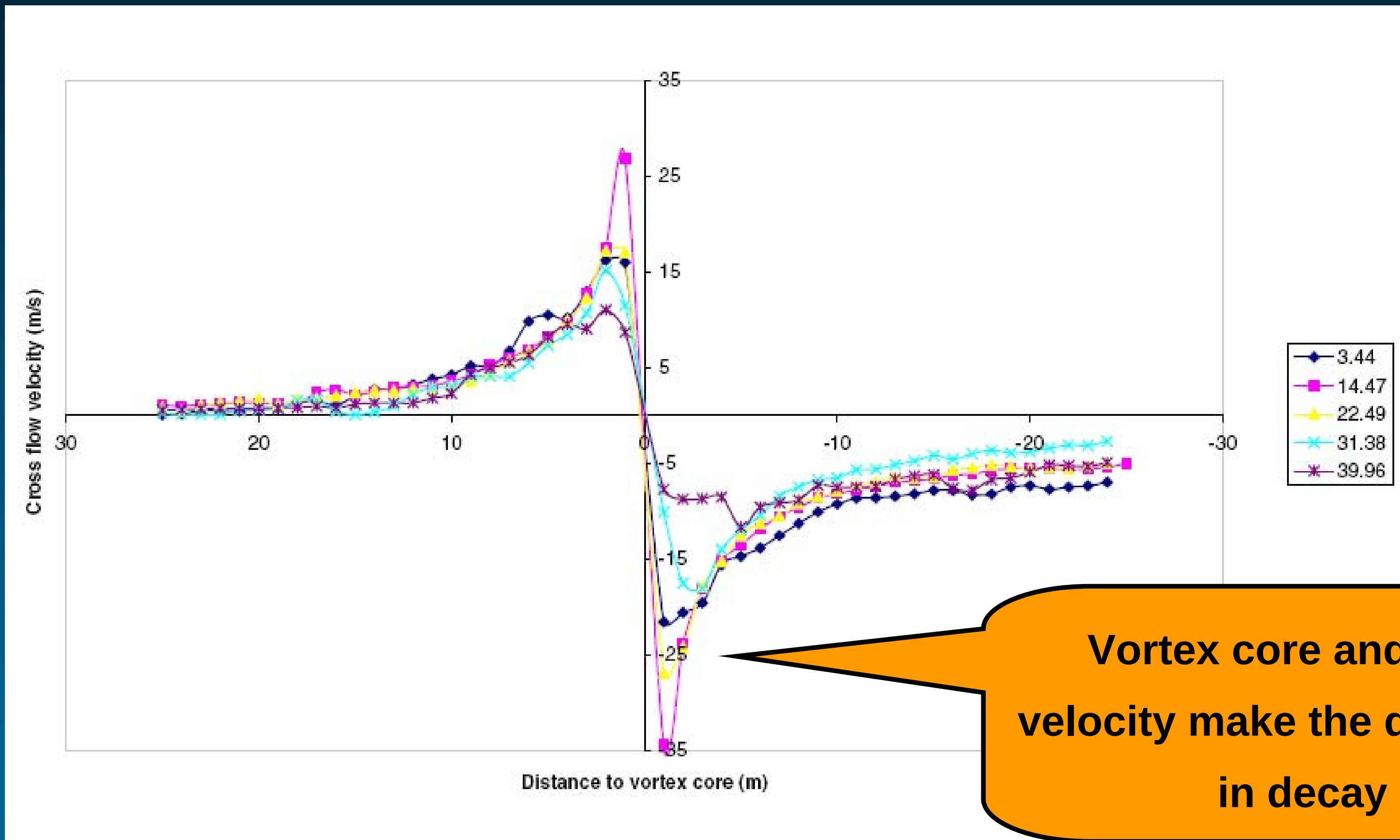
- **A probabilistic risk assessment model for wake turbulence:**
  – tries to model the real world as truthful as possible
  – compares A/C response resulting from an encounter in the frame work of an ‘encounter severity classification’
  – calculates the probability of a (catastrophic, hazardous, major, minor) accident / incident in the frame work of a ‘risk event classification’
  – to be compared with a Target Level of Safety (TLS)

- **Rigor mathematical techniques are required to handle the problem (to calculate for 10^{-9} TLS values)**

Scheme Risk Assessment Methodology



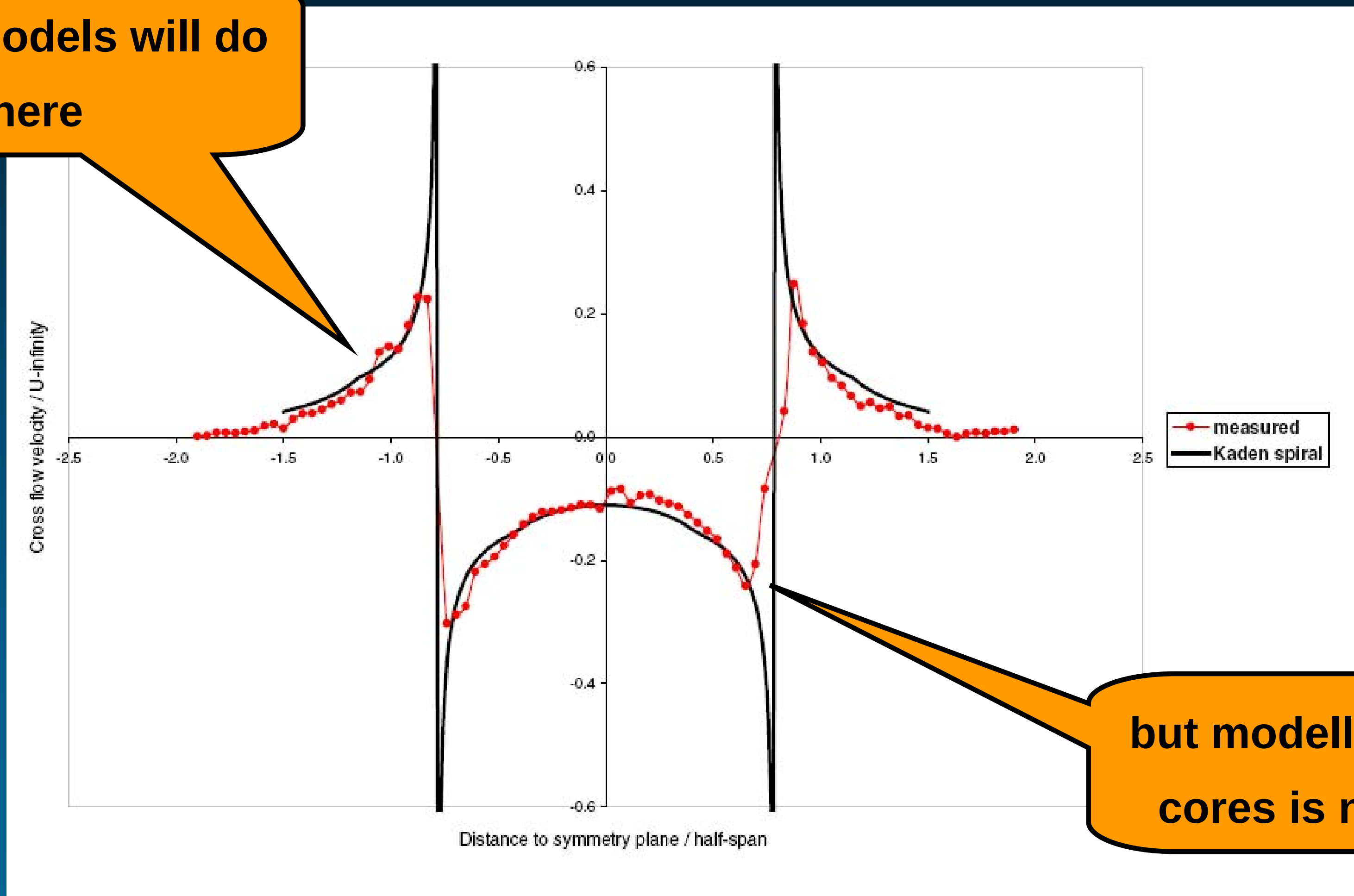
Typical cross flow velocities in a wake vortex (MEMPHIS Case 1107, AIRBUS 300)



Vortex core and peak velocity make the difference in decay

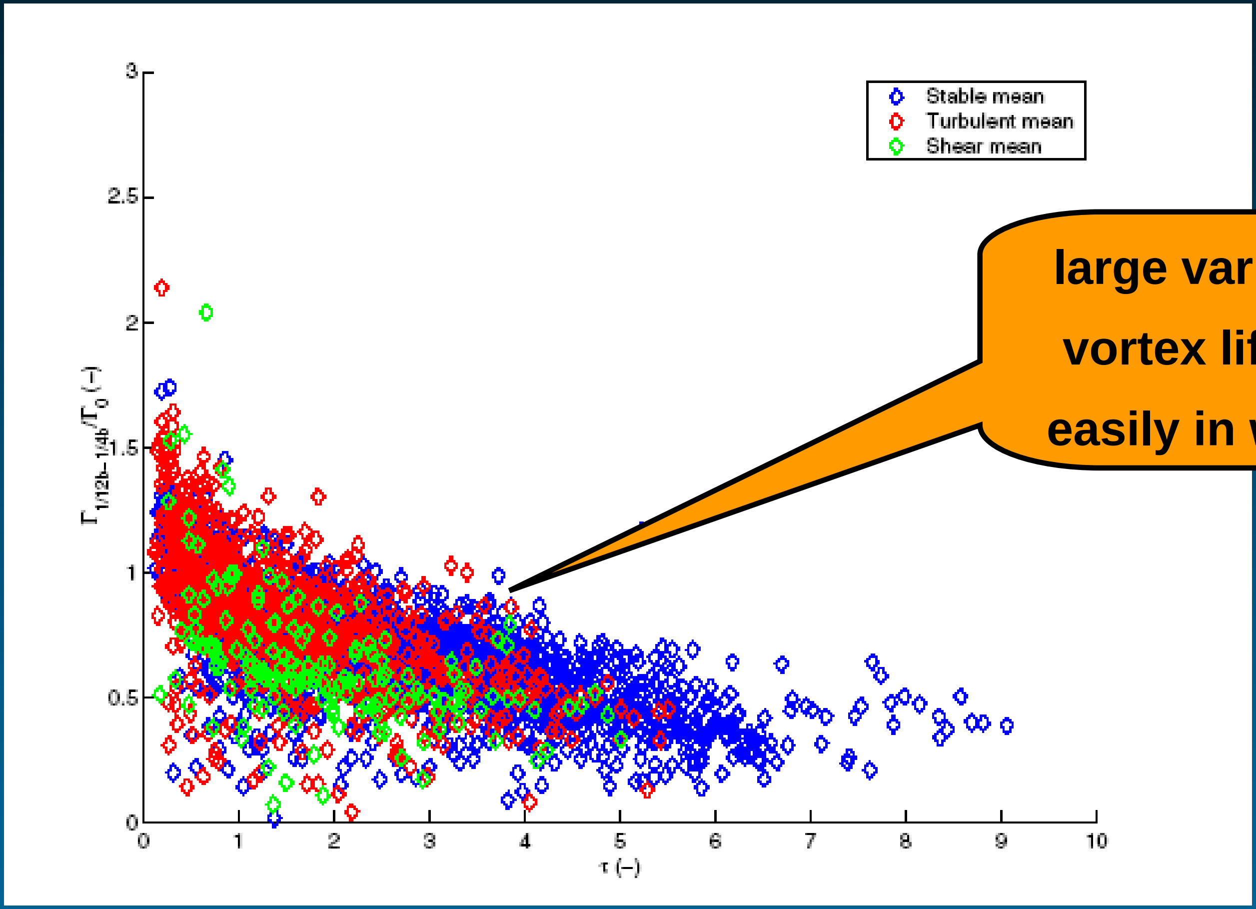
Simple approximation with Kaden Vortex solely based on aircraft characteristics (same case as before; analysis by Elsenaar)

Simple models will do here



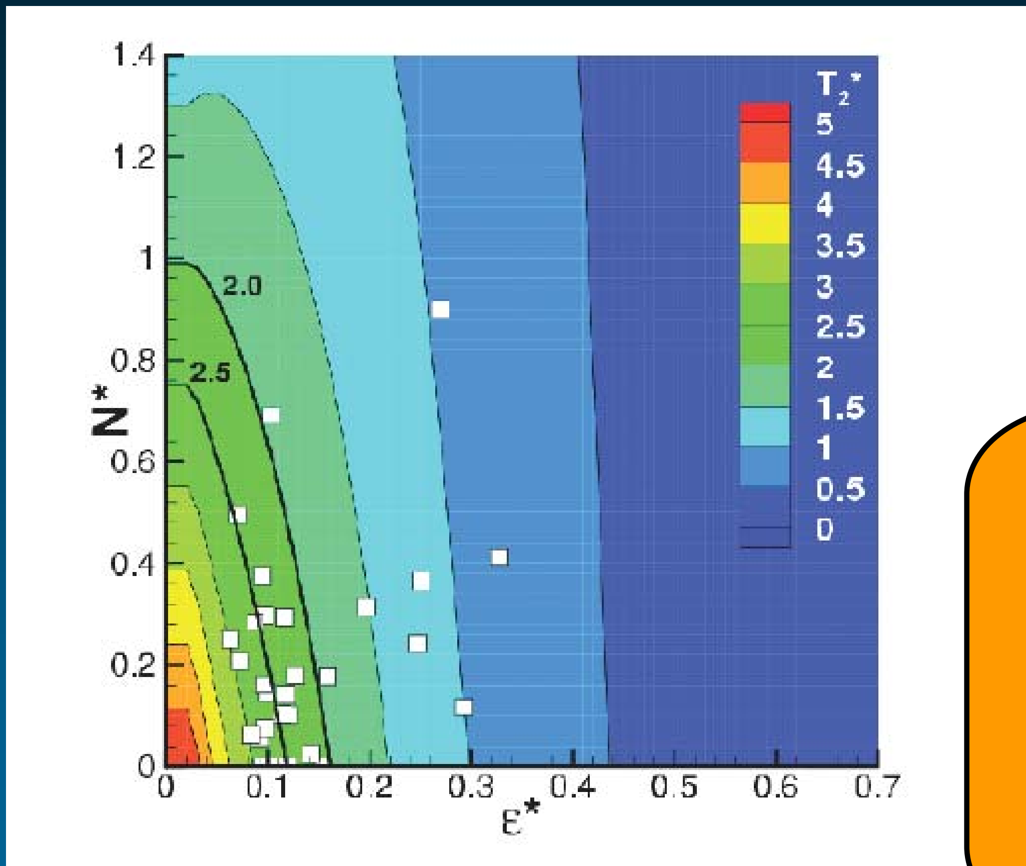
but modelling vortex cores is not trivial

Wake Vortex decay and life time for stable, turbulent and shear weather conditions (Memphis data, based on S-Wake analysis)



large variations in decay, vortex life times don't fit easily in weather classes!

Vortex life time: a function of Eddy dissipation rate and thermal stratification (results from LES calculations, DLR)

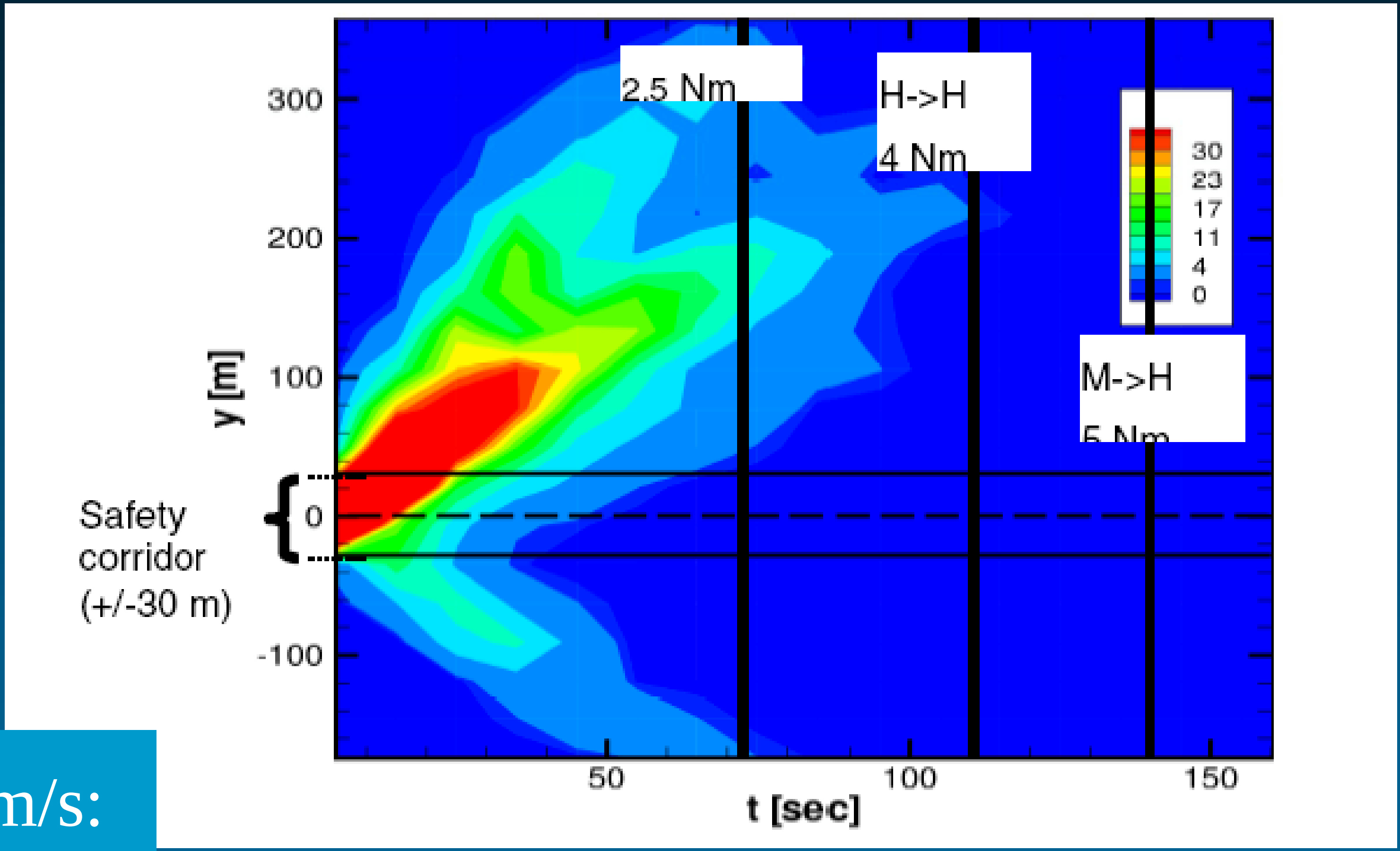


. . . there are more parameters than Eddy Dissipation rate ε like:

Windshear S

Thermal stratification N

Frequency distributions (in %) of lateral transport of vortices due to crosswind (Analysis of the Memphis data for vortices out of ground effect by DLR)

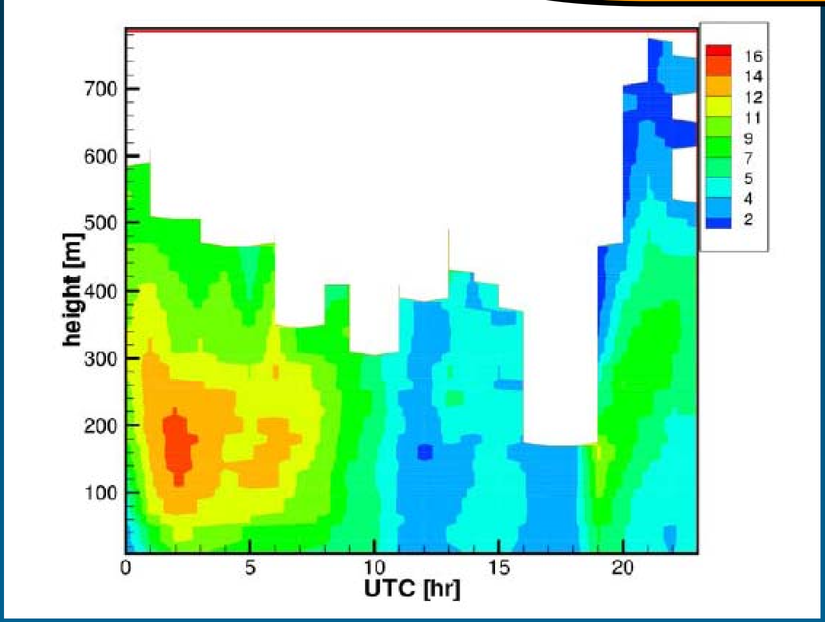


cross wind > 2 m/s:

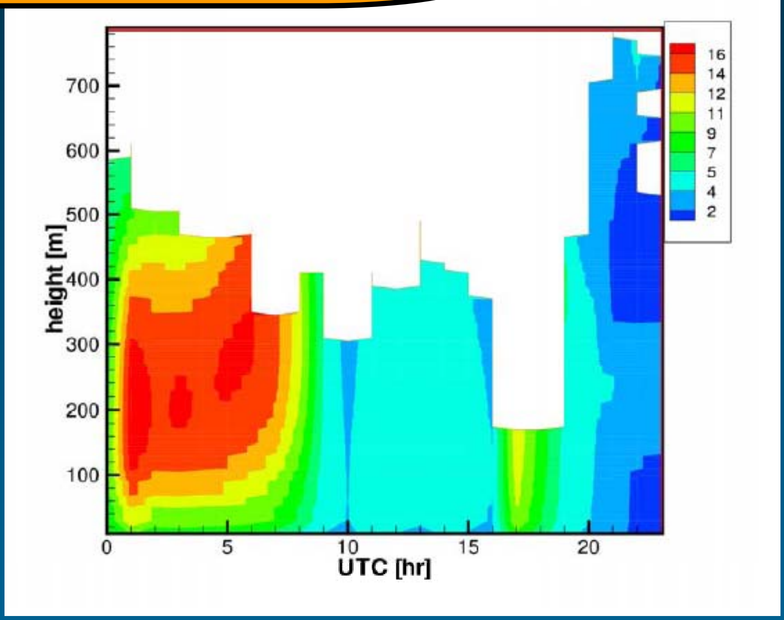
252 cases

Diurnal evolution of the wind speed profile on Tarbes Airport during WakeTOUL campaign (courtesy of DLR)

Good enough ? A difference of a few m/sec in cross wind might matter !



measured

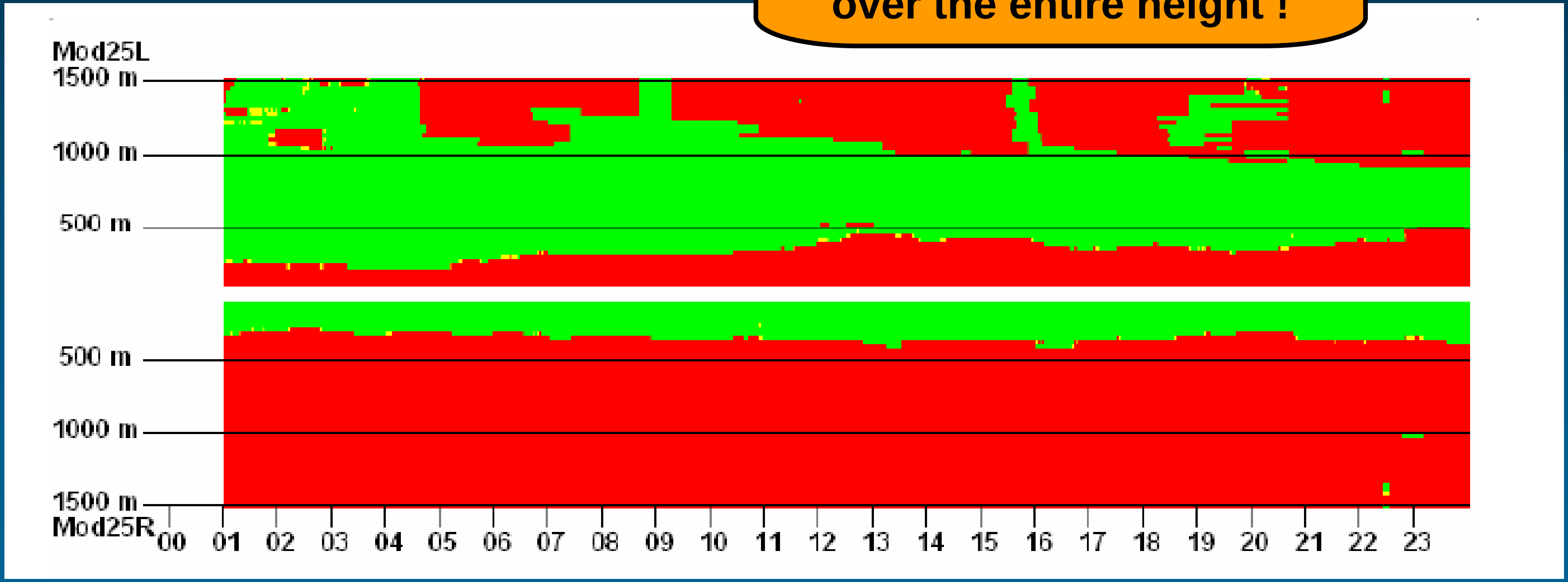


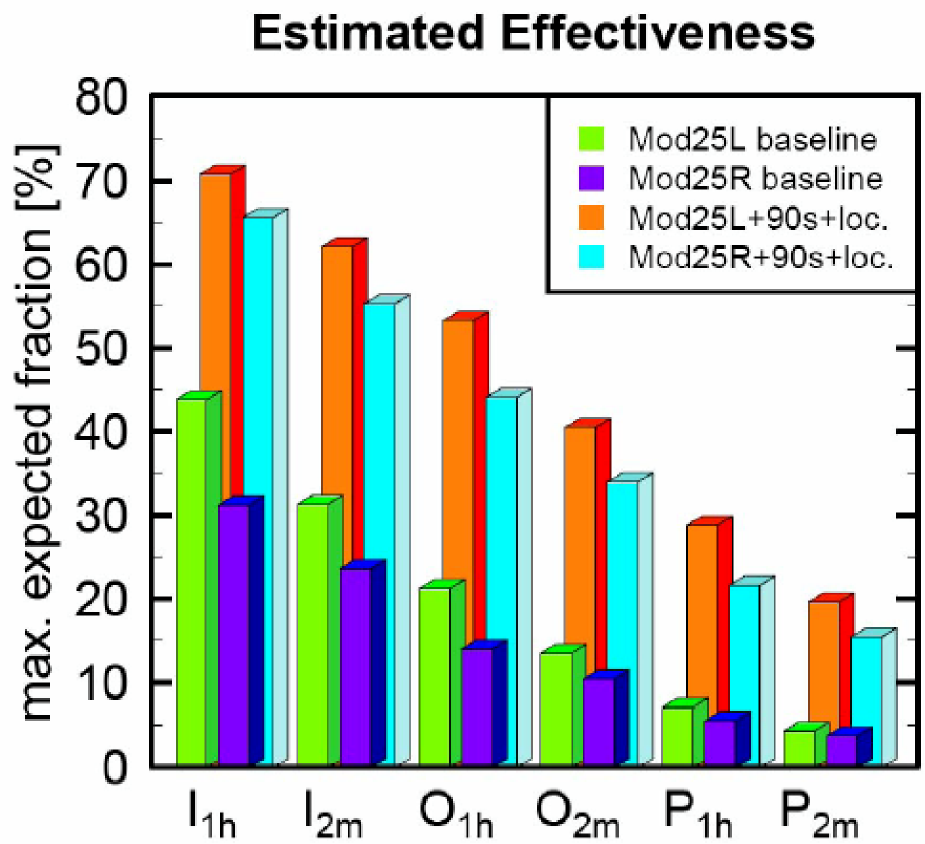
predicted

color code in m/s

Example of actually observed safe and non-safe conditions as function of altitude over 24 hours (Frankfurt study; Konopka, DFS)

. . . in this case never safe over the entire height !



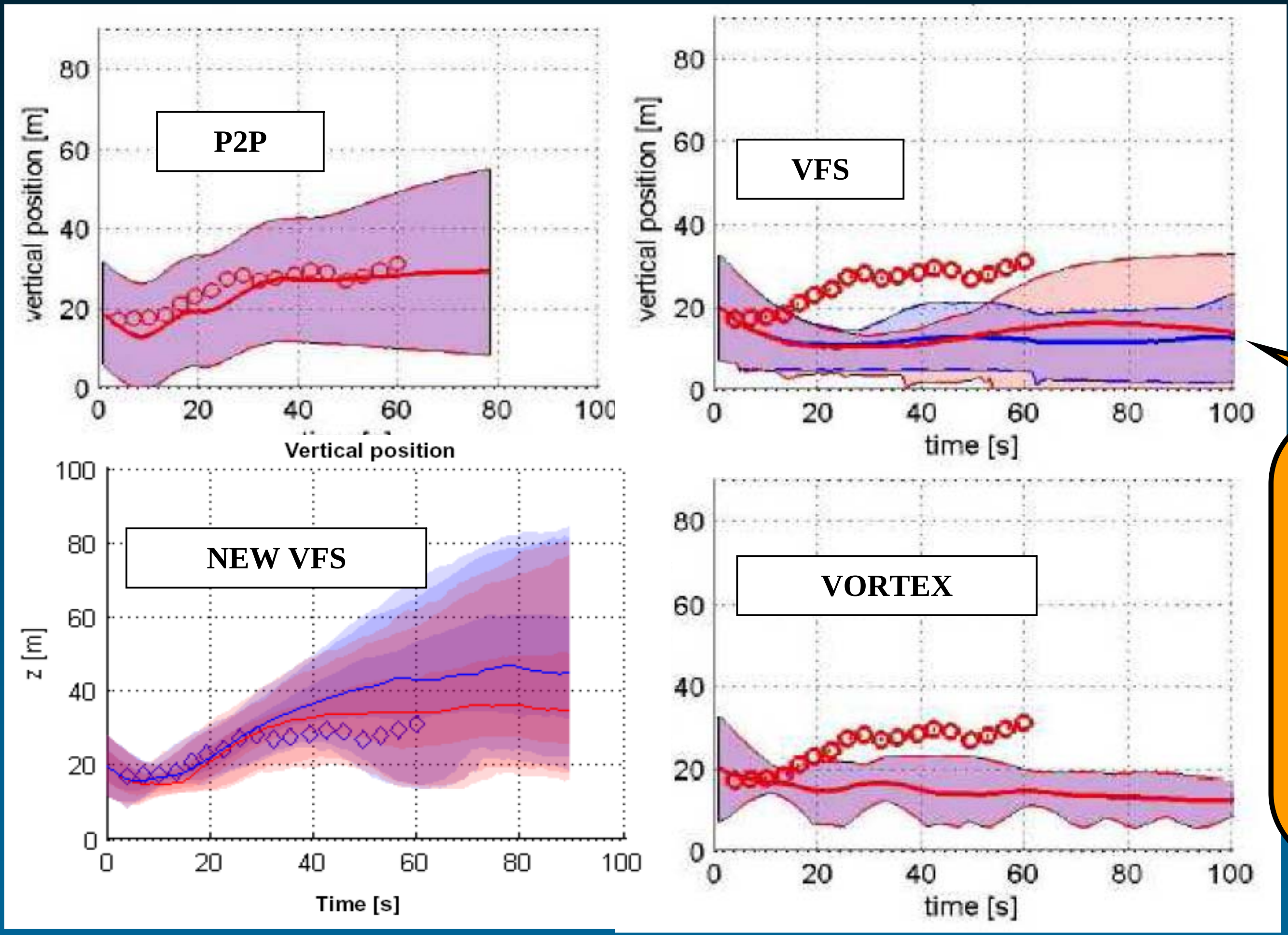


Label	Wake Transport Based on
I_{1h}	actual measured 1 hour averaged wind
I_{2m}	actual measured 2 minute averaged wind
O_{1h}	an optimistic forecast of the 1 hour averaged wind
O_{2m}	an optimistic forecast of the 2 minute averaged wind
P_{1h}	a more pessimistic forecast of the 1 hour averaged wind
P_{2m}	a more pessimistic forecast of the 2 minute averaged wind

Effectiveness of prediction of safe weather conditions (Frankfurt study by Konopka, DFS)

. . . for Frankfurt the benefit is small: too conservative . . . ?

Comparison of prediction methods for wakes in ground effect: MEMPHIS case 1518, weak winds, stratification (from WN-USA / WN2-Europe Ground Effect Workshop)



. . . better modelling of wakes in ground effect might help but needs more validation !

Accurate atmospheric measurements are essential: WTR – Wind Temperature Radar as installed at FraPort

Manufacturer: Scintec AG, Tübingen, Germany

Combination of Doppler-Radar for clear air measurements and Radio Acoustic Sound System (RASS) for measurements in bad weather

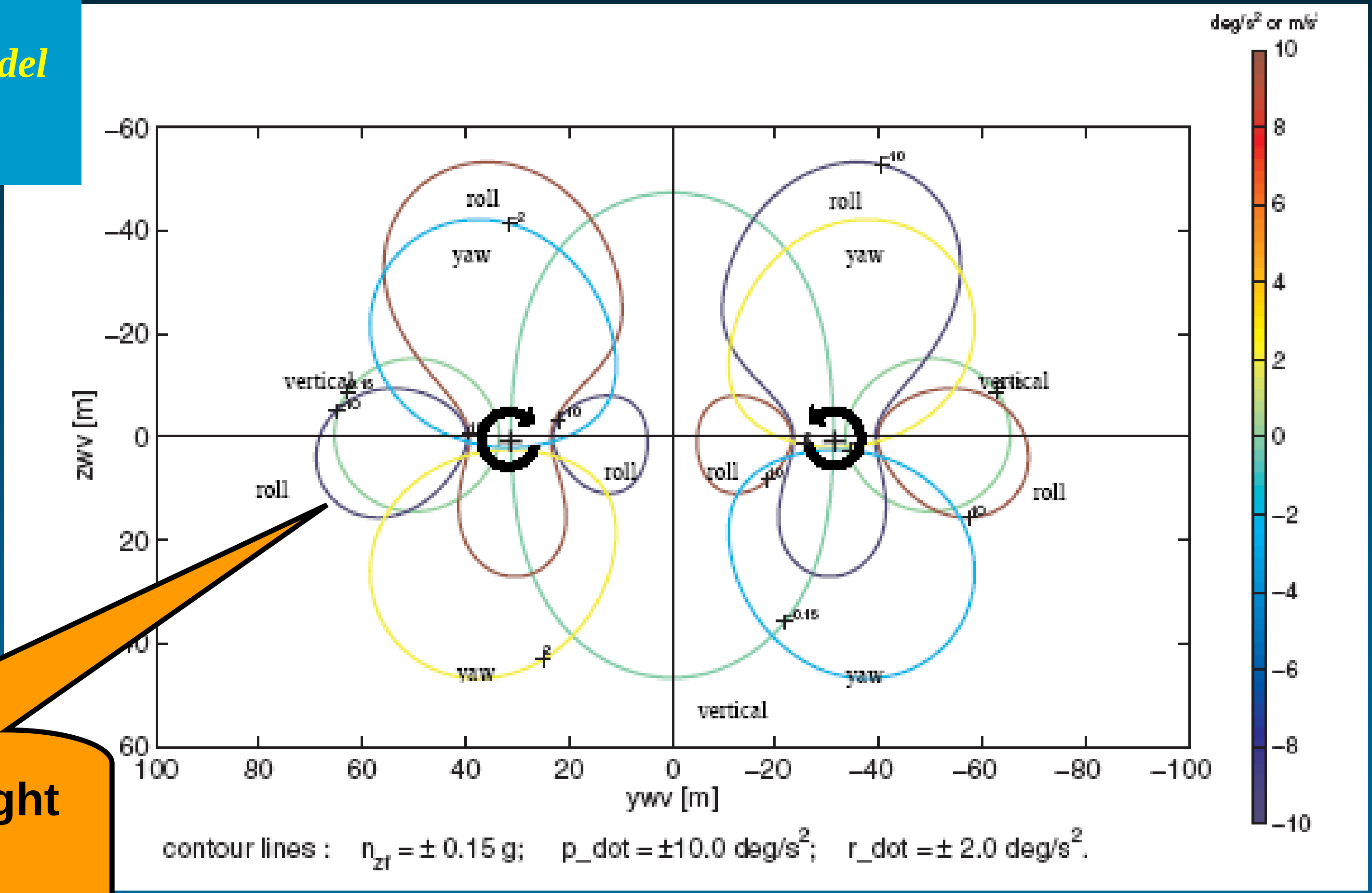
- Measurement of wind (from 100m to 1500m altitude) with a precision of 0.5 m/s
- and temperature (from 100m to 1000m altitude) with a precision of 0.5°C /100m

Areas with dominating roll, yaw, and vertical accelerations (VFW614 behind VLTA) S-Wake Study by Luckner (Airbus)

separation 5 Nm

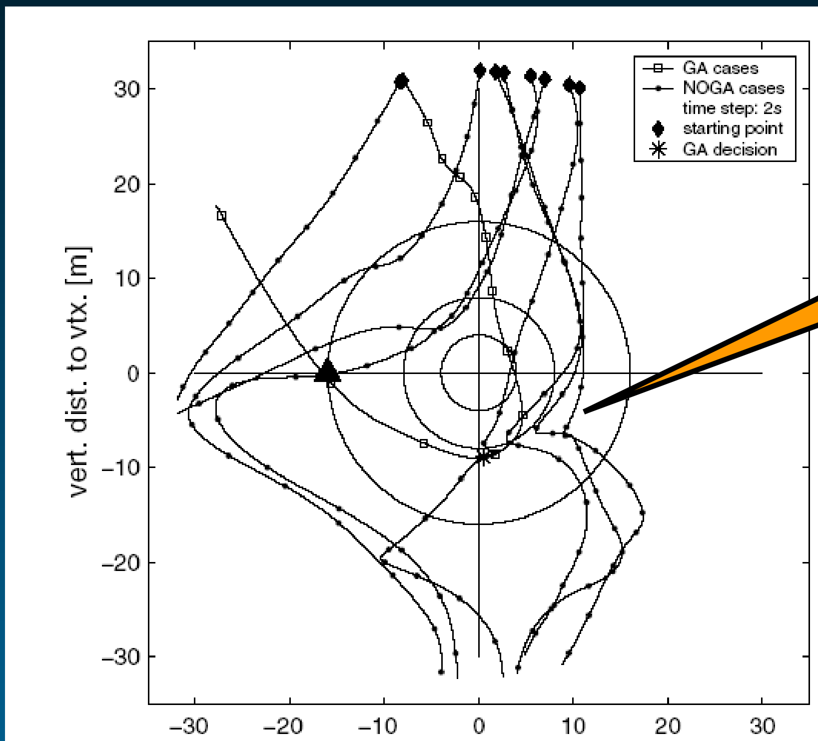
Winckelmans / Sarpkaya model

app. 80 % decay

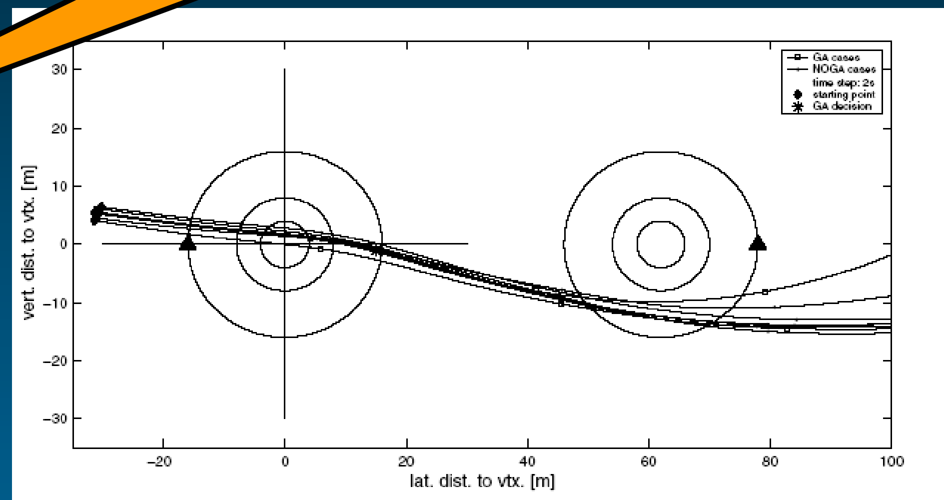


Vortex core detail might matter here !

Aircraft motion in wake encounter from flight simulation studies (S-Wake results, AIRBUS)



. . . and here

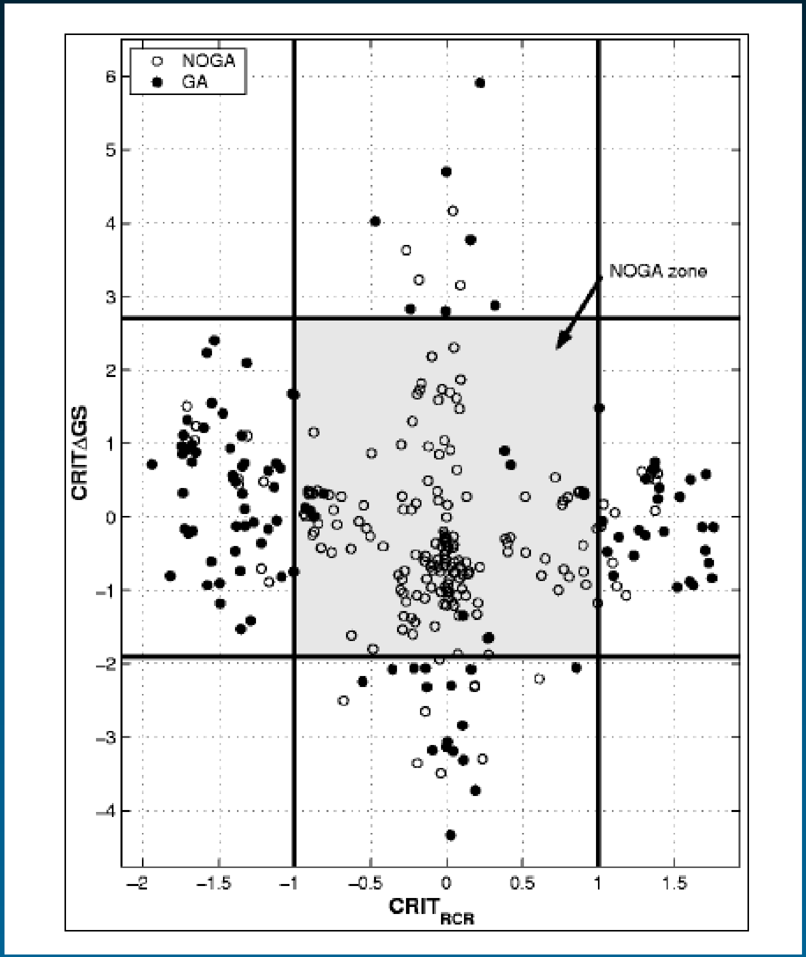


slow intercept from above

(vertical intercept is 2 deg.)

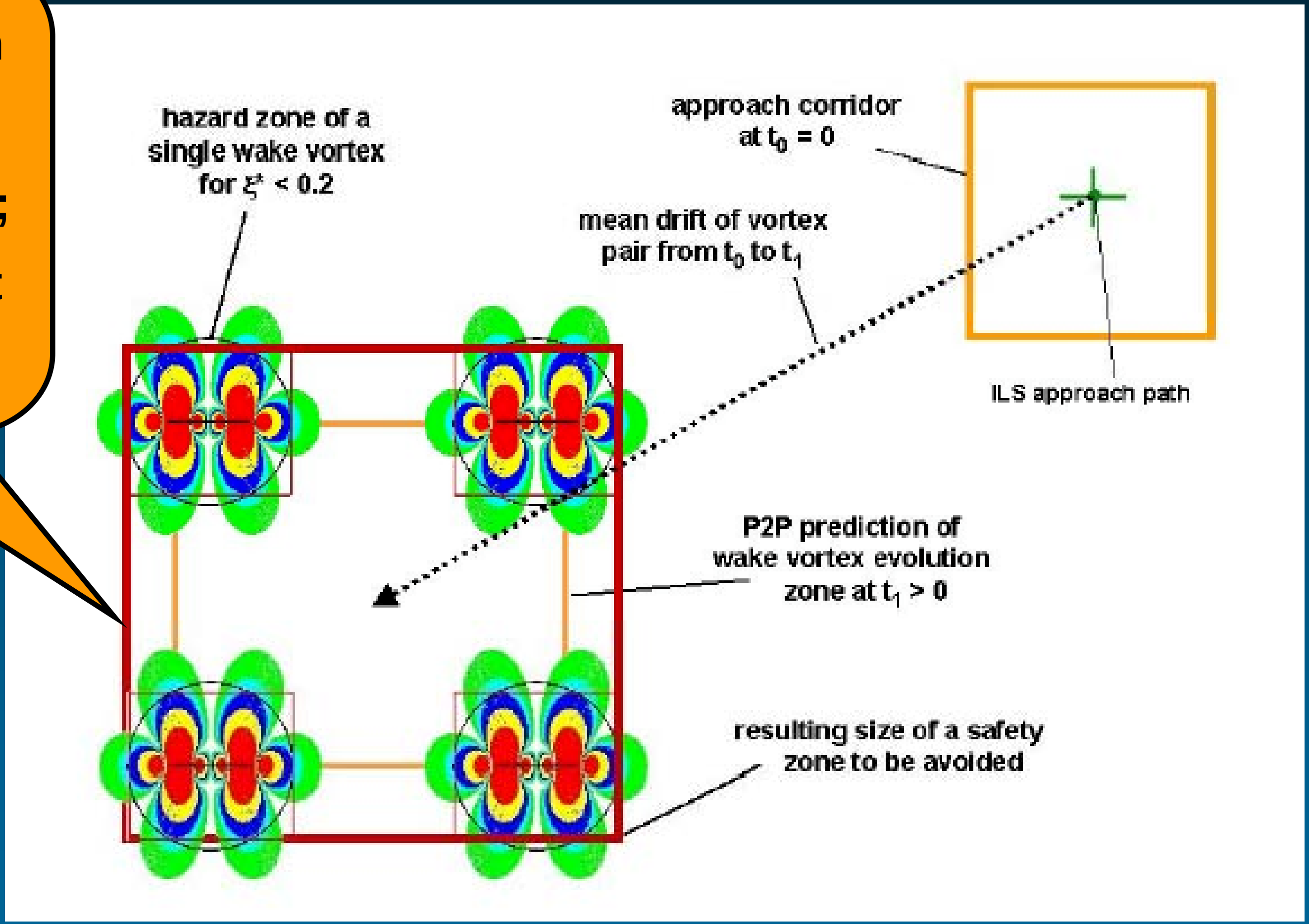
quick intercept from aside (horizontal intercept angle is 20 deg.)

“Combined Roll-Control Ratio and Vertical Acceleration” criterion for Go-Around decision (S-Wake flight simulator results, AIRBUS)

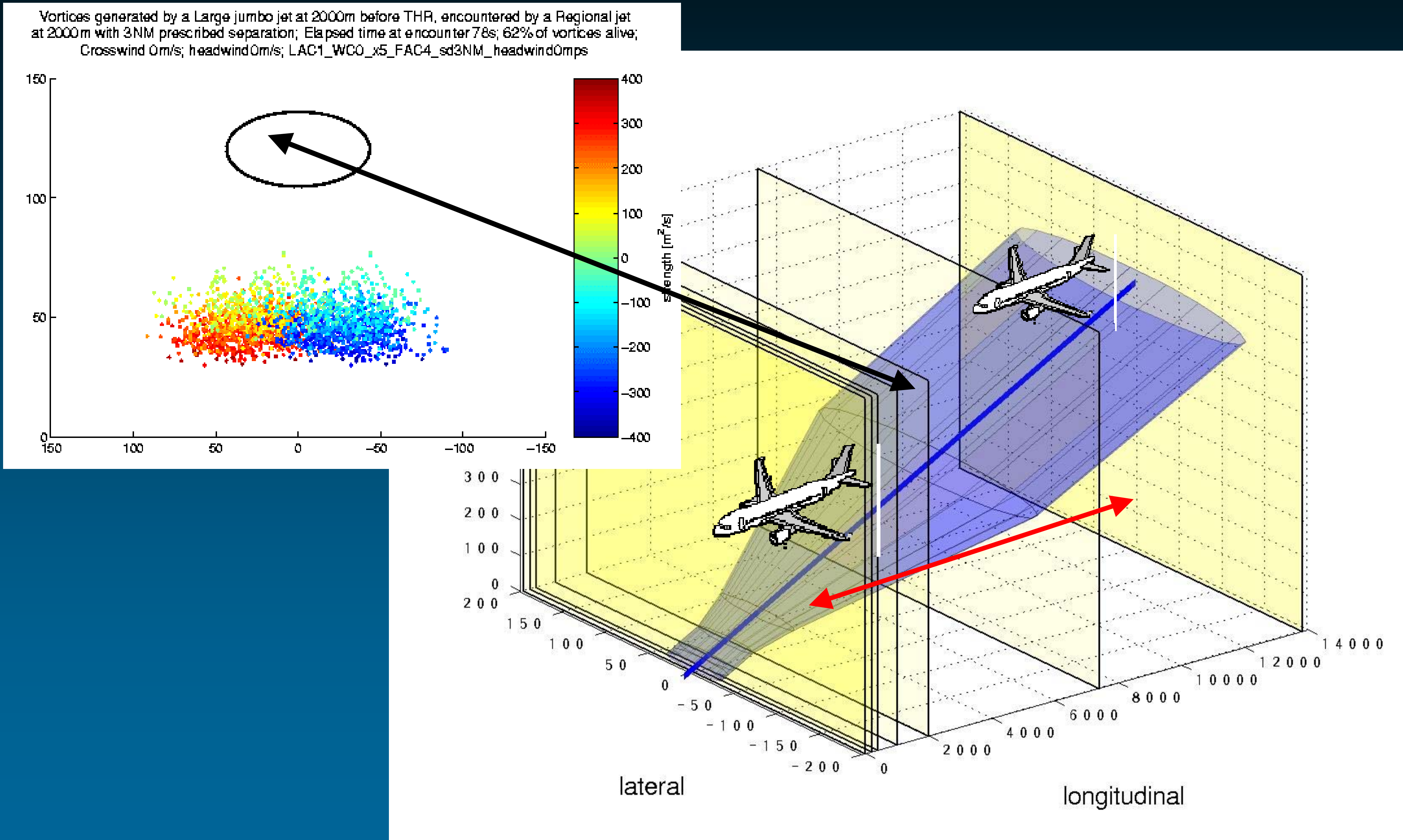


Determination of hazardous zone for wake vortex encounters (DLR, Hahn)

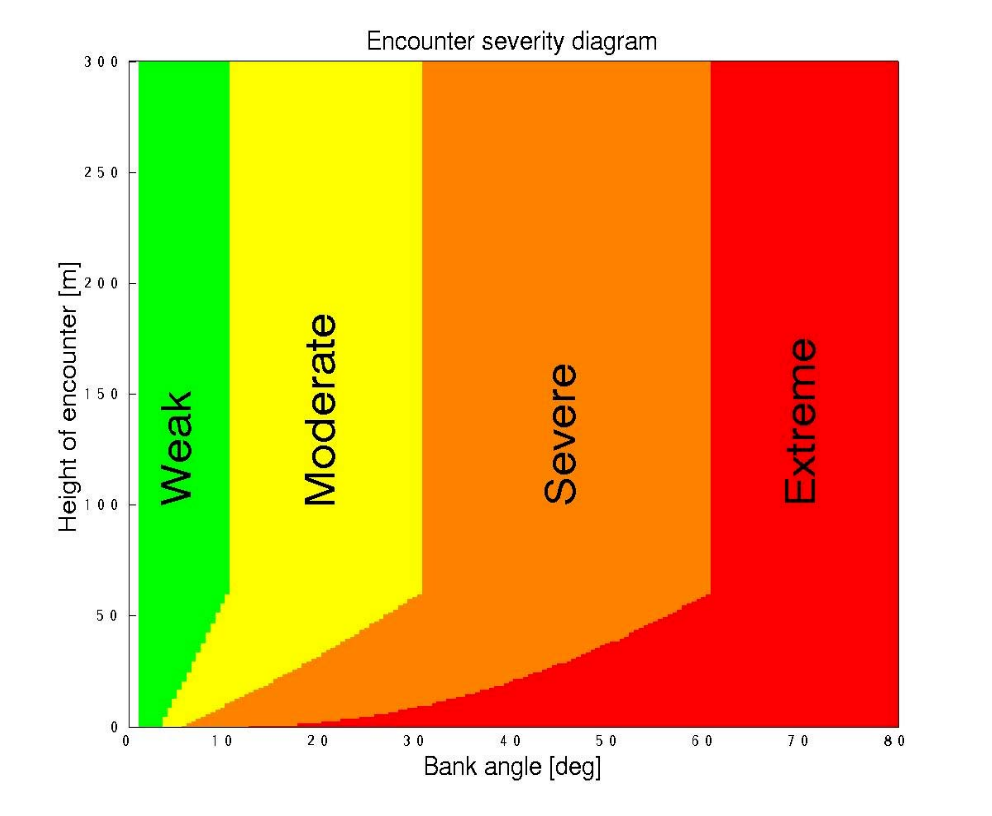
. . . . pragmatic, can be made to cover a 'class of followers' ; possibly somewhat conservative

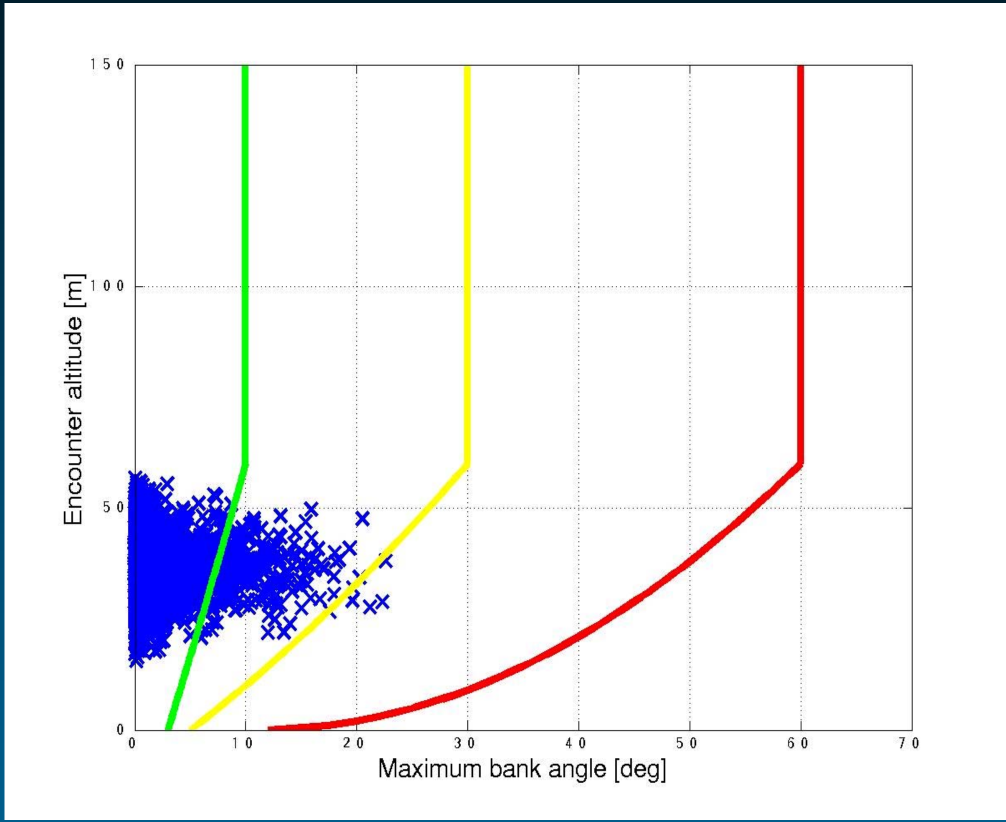


Probabilistic Wake Vortex Evolution Modelling (S-Wake, WAVIR, NLR)



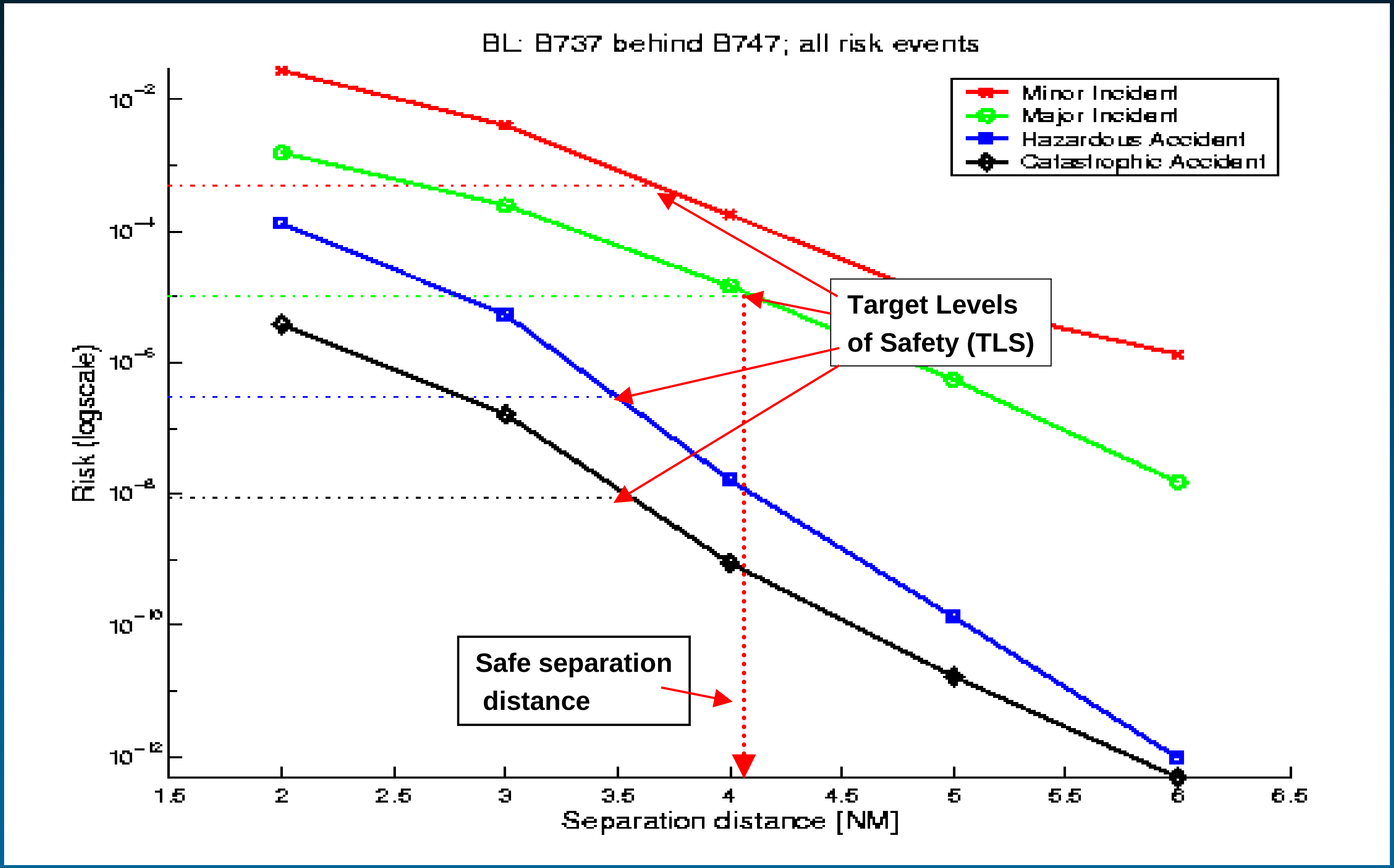
Encounter severity classification
Results from WAVIR Monte Carlo type simulations
(S-Wake, NLR)



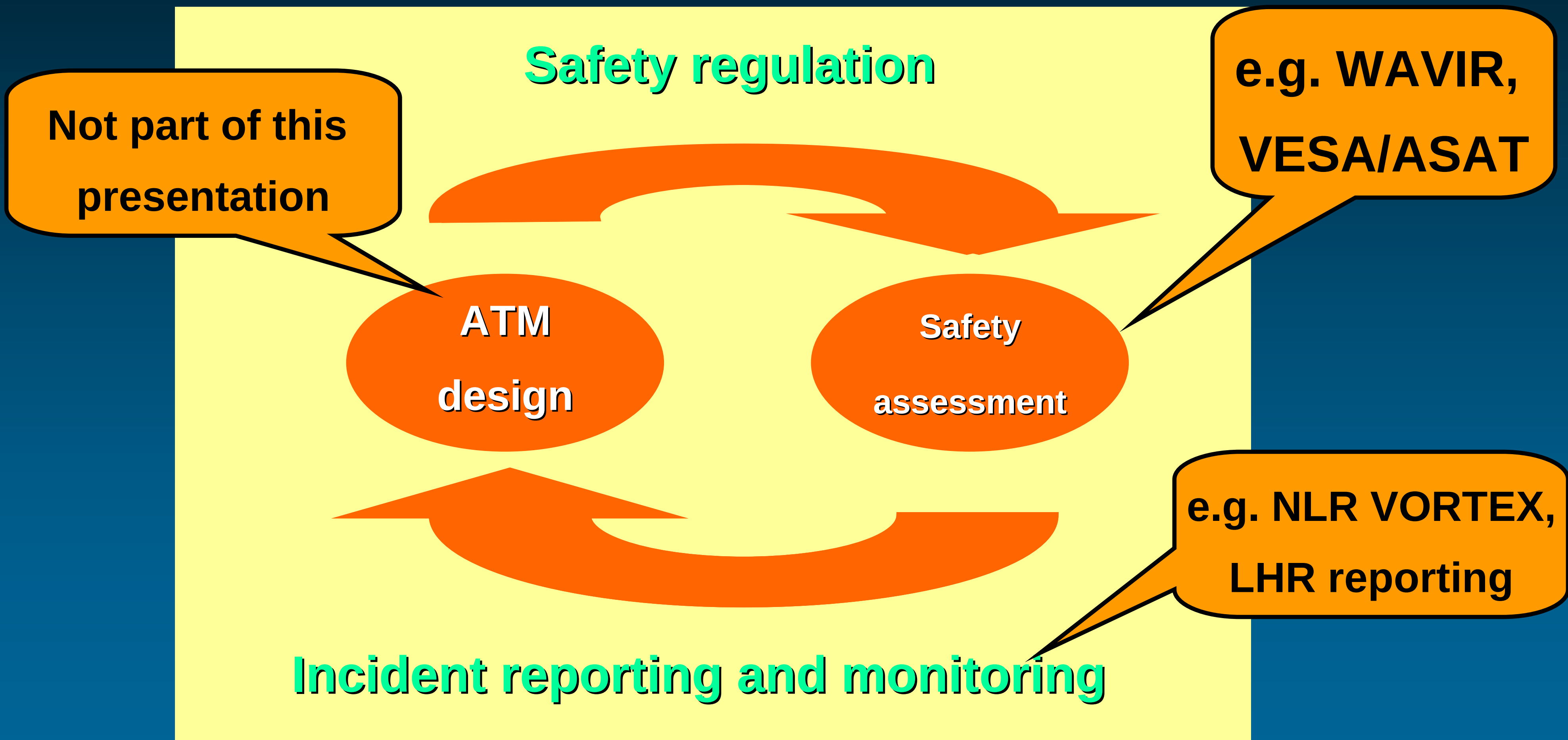


Bank angle versus loss of height / encounter altitude is used as *wake encounter* severity metric

Example of risk assessment for a B737 behind a B747 in 'average' weather conditions (S-wake, WAVIR, NLR)

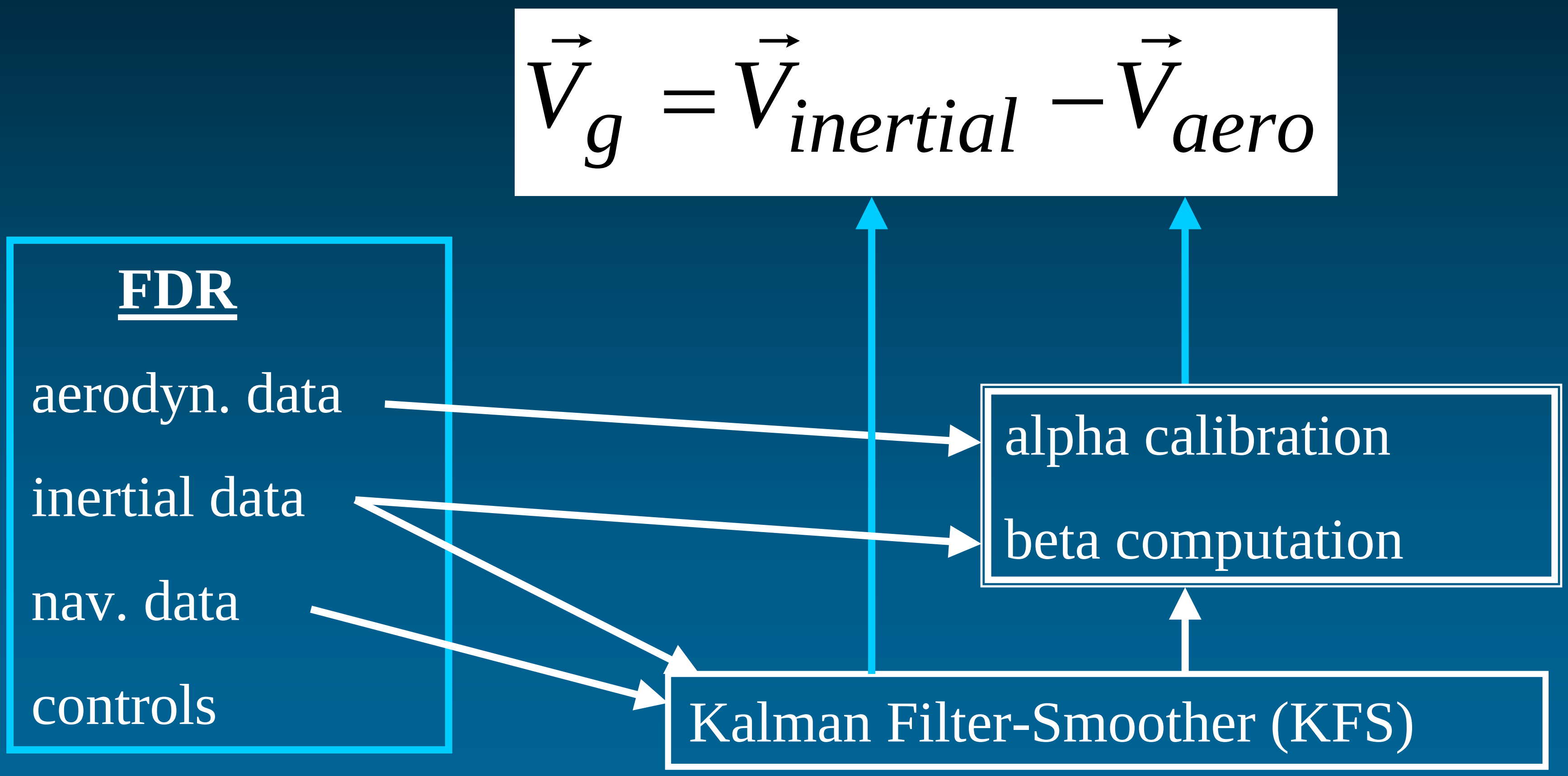


Introduction of new system and/or operational concept requires safety management approach



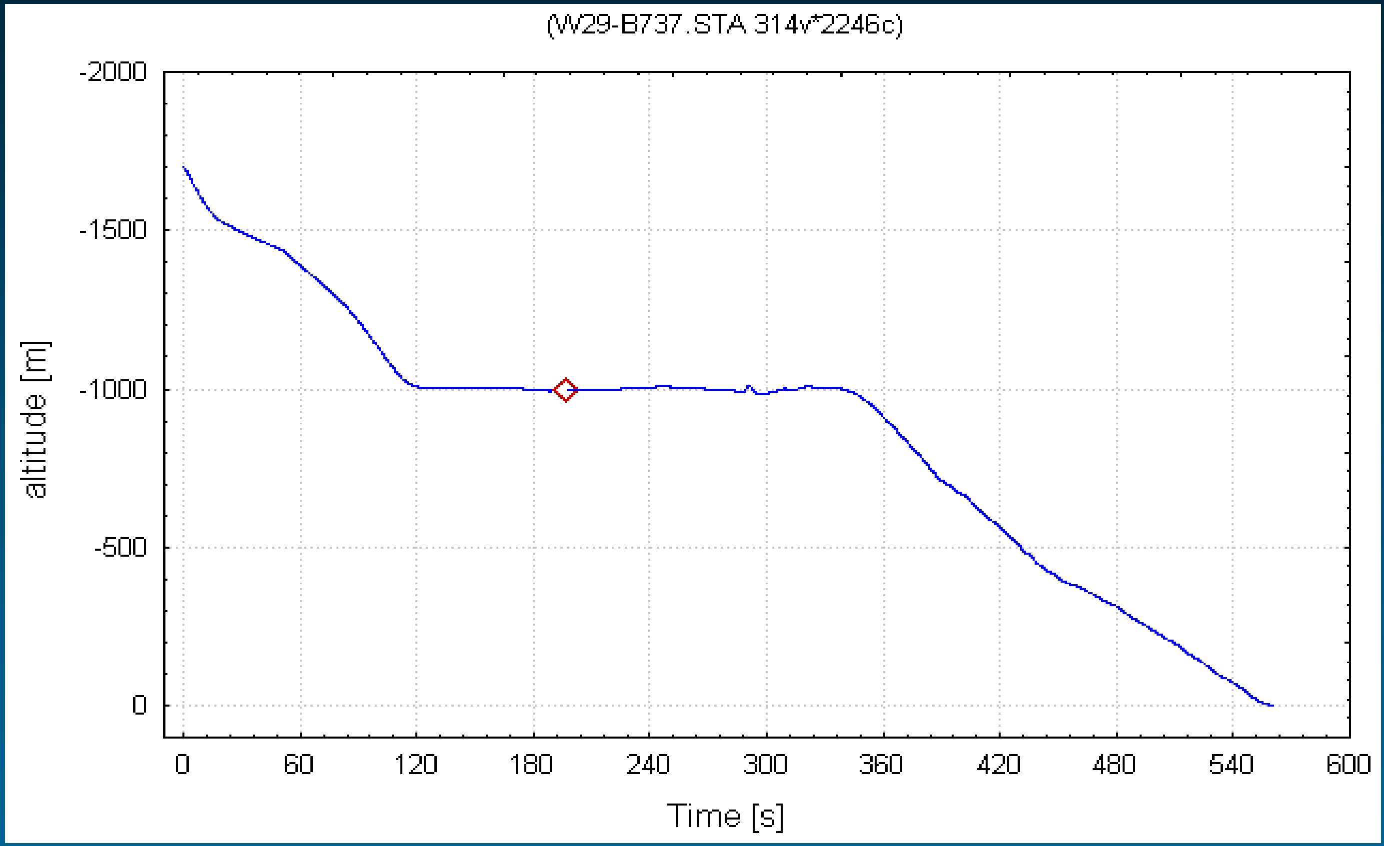
NLR – VORTEX: automated encounter detection from Flight Data Recordings

processes involved in determining the wind vector $\vec{V}_g$



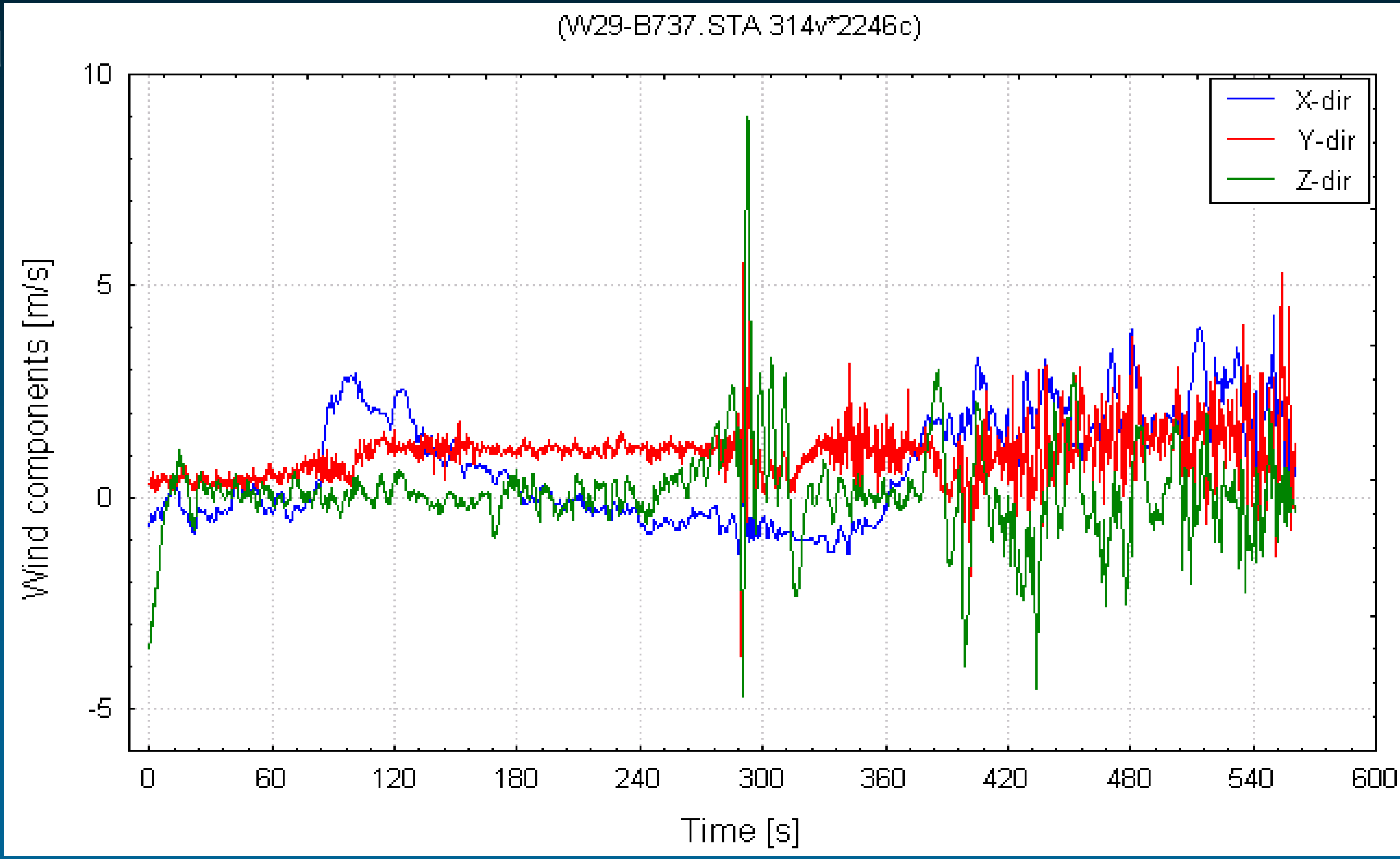
Example
B737 landing approach altitude

- **Possible WVE occurred midway at 3000 ft**



Example
wind components

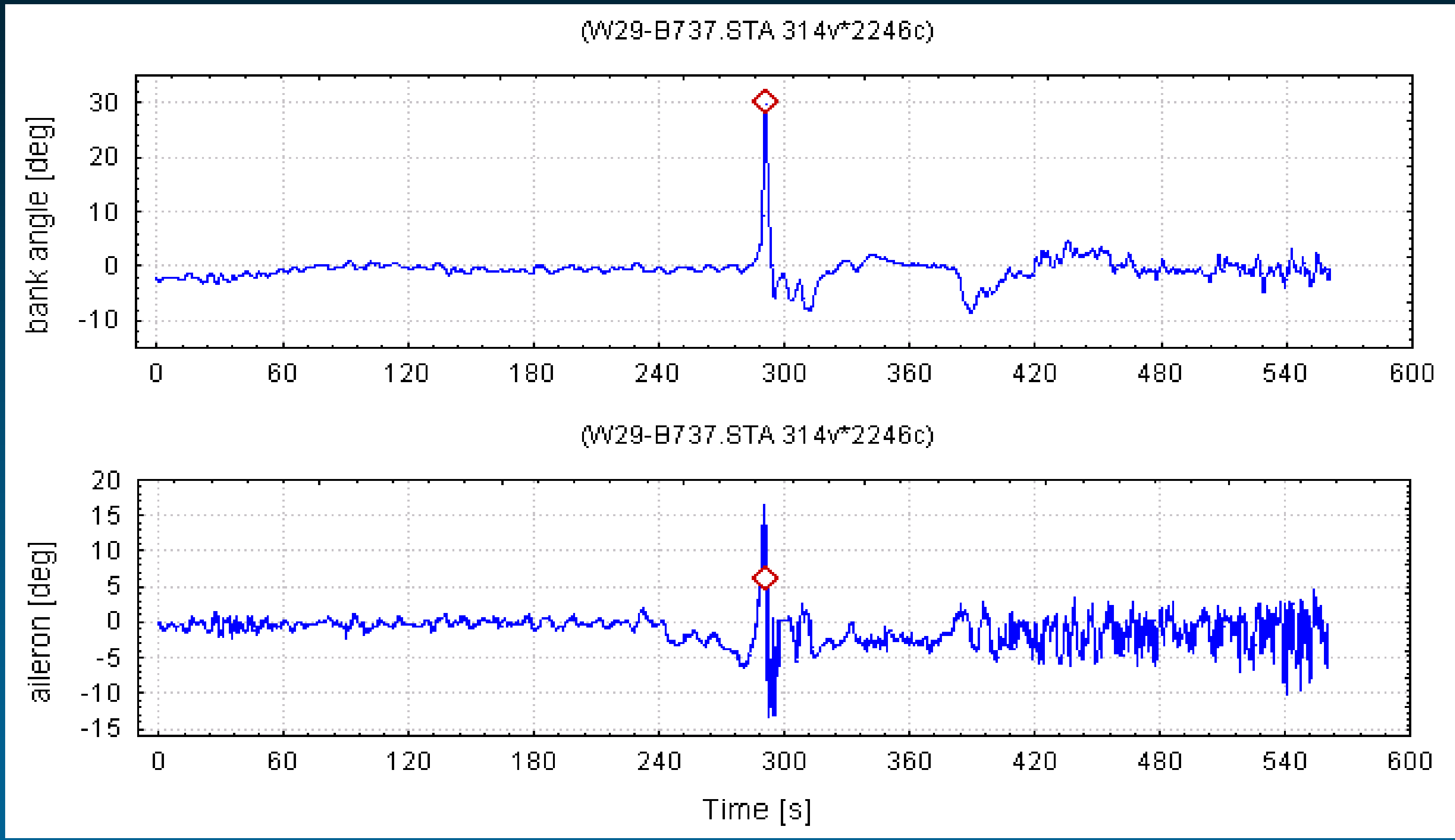
- **Peak in crosswind component**
- **Peak in vertical wind component**



Example

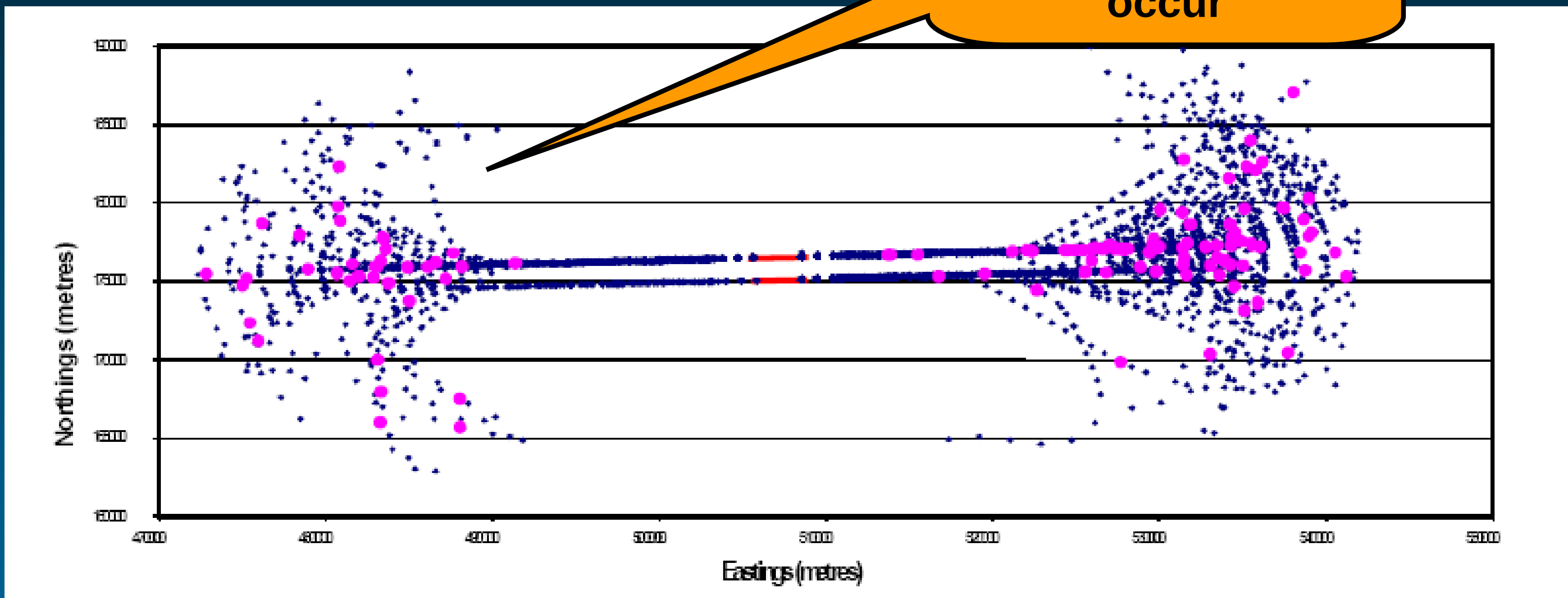
roll motion: bank and aileron

- **One single peak both in roll and aileron**
- **Bank angle disturbance about +30 deg!**



London Heathrow: detected wake vortex encounters from NLR VORTEX FDR analysis (from S-Wake Study NATS / NLR)

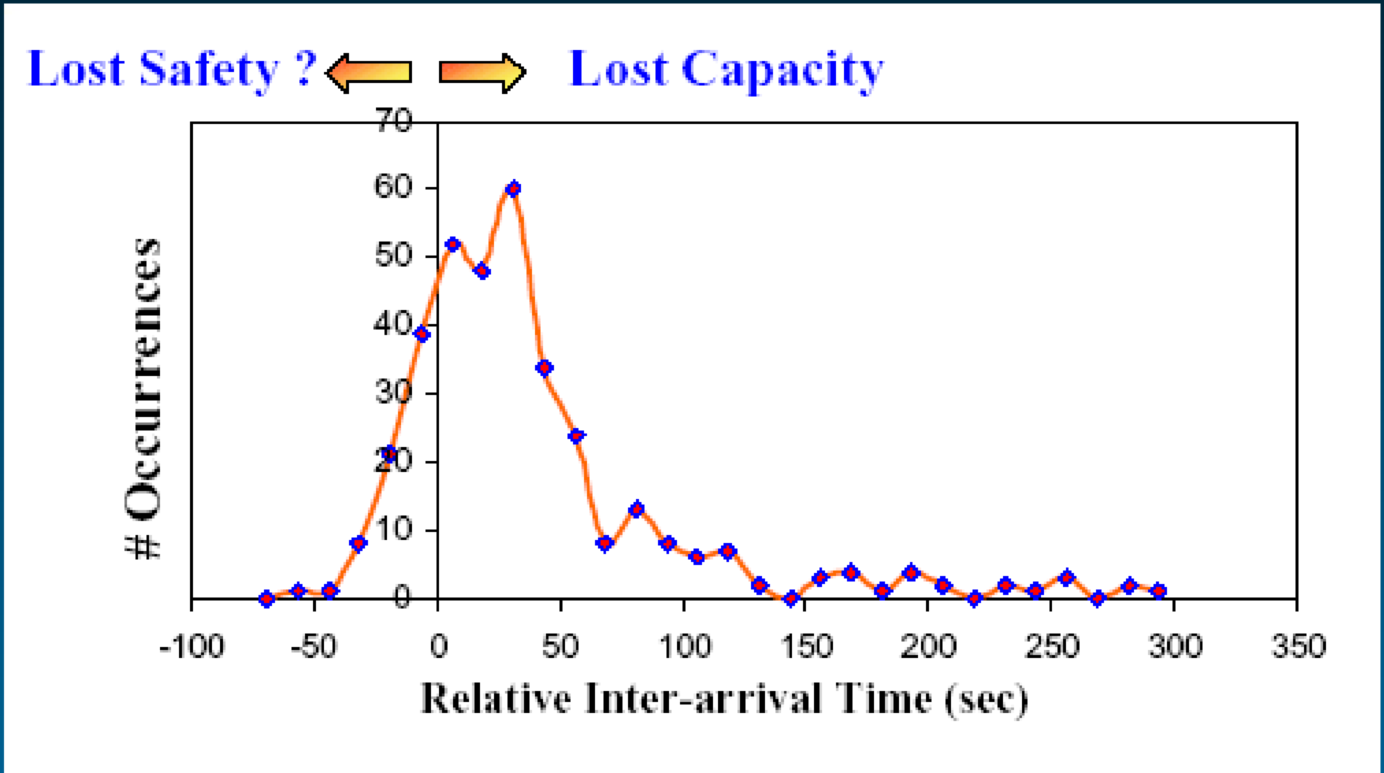
. . . encounters do occur



Violet dots are detected (likely) encounters; Blue dots are radar trackings from the flight path’s of detected encounters

Observed (relative) Inter-Arrival Times

Haynie, George Mason University.



Atlanta Runway 27 357 observations, VMC

Conclusions (1)

- **Establish sensitivities of encounter modelling for details of the wake vortex and refine wake characterisation if required (e.g. decay)**
- **Improve modelling for wakes in ground effect and its validation**
- **Push weather prediction to its limits, using the most up-to-date measuring techniques and numerical weather forecast**
- **Investigate (follower A/C class dependent !) hazard definition**

Conclusions (2)

- Improve and validate automated encounter reporting from FDR analysis
- Establish ‘current practice’ as (Airport dependent?) ‘base line’
- Agree on a safety assessment methodology (who ?)
- Organise ‘peer reviews’ to establish shortfalls in wake vortex safety assessment

To think about:

It is likely easier to construct a safe system than to rigorously prove that the system is safe.

Jens Konopka, DFS, Langen 2004

If ‘uncertainty is piled upon uncertainty’, the outcome will be worse than today; probabilistic modelling, respecting all details and including proper validation, is the only promising answer.

Bram Elsenaar, to be discussed

Thanks to all WakeNet2-Europe partners

- NLR (co-ordinator)
- IFALPA (Vereinigung Cockpit)
- DLR
- THALES-AVIONICS
- DFS
- UCL
- NATS En-Route Ltd (NERL)
- EUROCONTROL
- AIRBUS (dep co-ordinator)
- UK MetOffice
- QinetiQ
- ONERA

.....and to WakeNet-USA (FAA / NASA) !

WakeNet2-Europe is sponsored by the European Commision

. . . and

THANK YOU

for more information see the WebSite

http://wwwe.onecert.fr/projets/WakeNet2-Europe