Aircraft Wake Vortices

coherent structures in incoherent environments

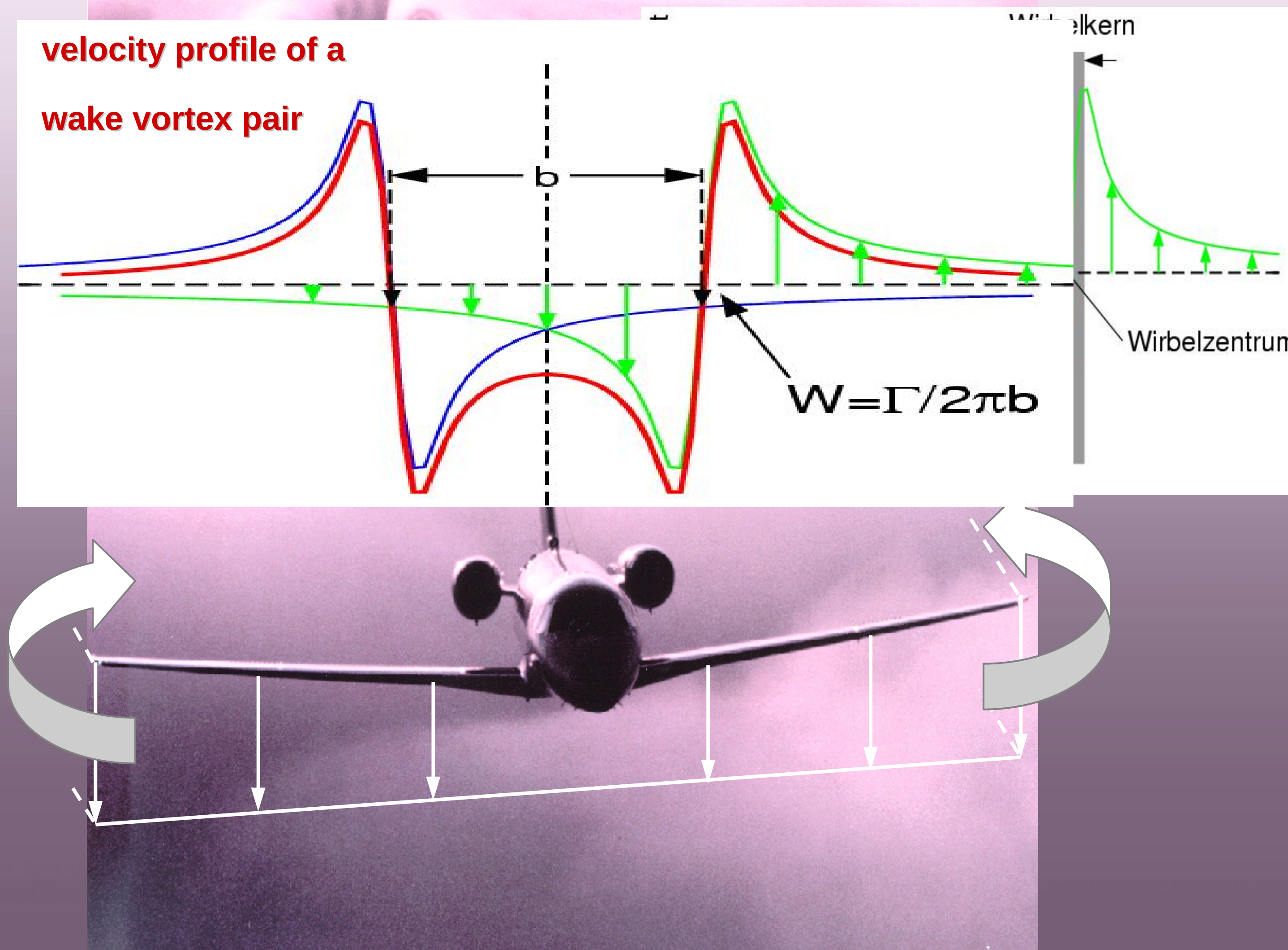
- physics
- motion and decay

- advisory systems for airports

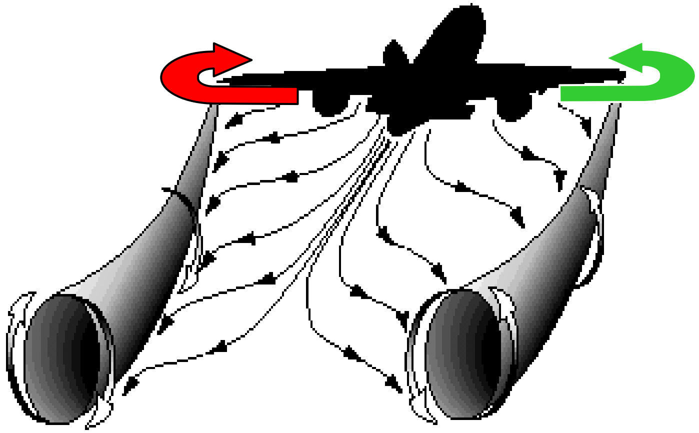
- questions, issues, and priorities

The physics of aircraft wake vortices

circulation: $$\Gamma = \frac{M g}{\rho (\pi / 4) B V}$$



Some characteristic numbers and features

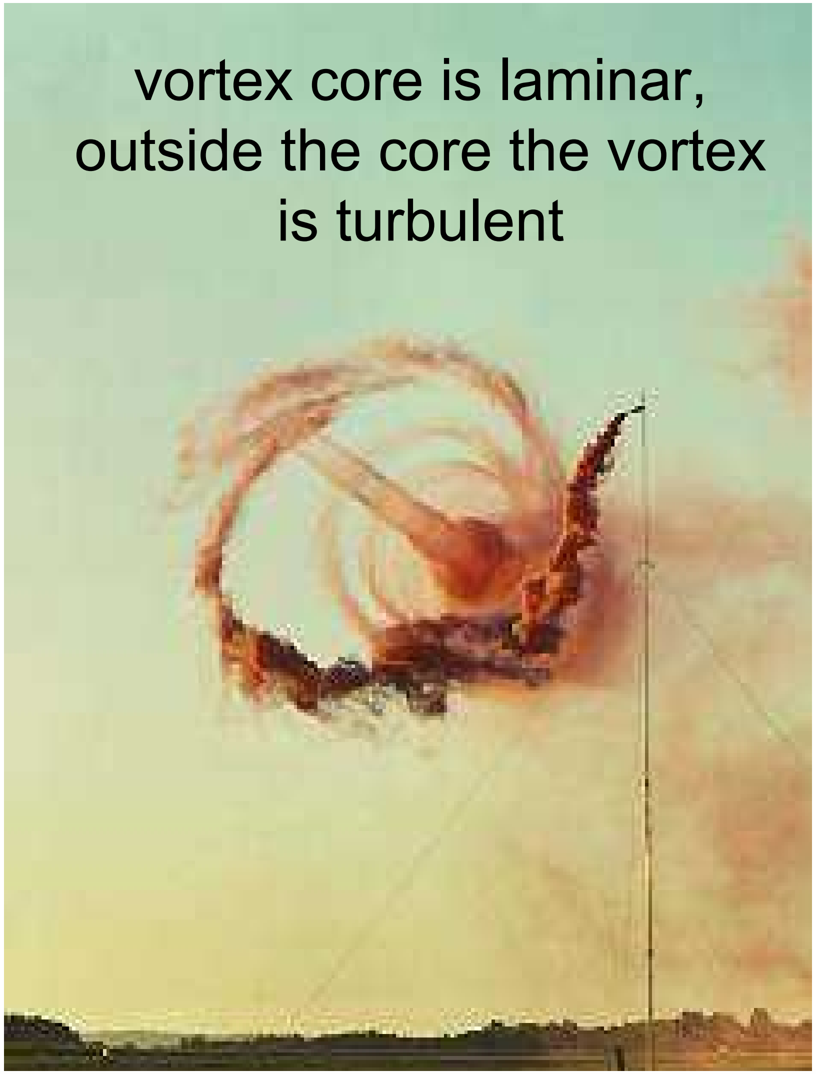


balance of forces at the flying aircraft

$$M\,g \;=\; \rho\, s\, B\, V\, \Gamma_0$$

e.g. Airbus A380:

weight	$M\,g$	=	4	MN
a/c speed (landing)	V	=	70	m/s
wing span	B	=	80	m
separation of 2 vort.	b_0	≈	63	m
circulation	Γ_0	=	730	m^2/s
core diameter	d_c	≈	4-8	m
max. tang. velocity	v_θ	≈	15-40	m/s
v. pair trailing speed	w_0	≤	2	m/s



Impact of the atmosphere on a/c wake vortices

Trajectories and decay of aircraft wake vortices in the atmosphere are determined by

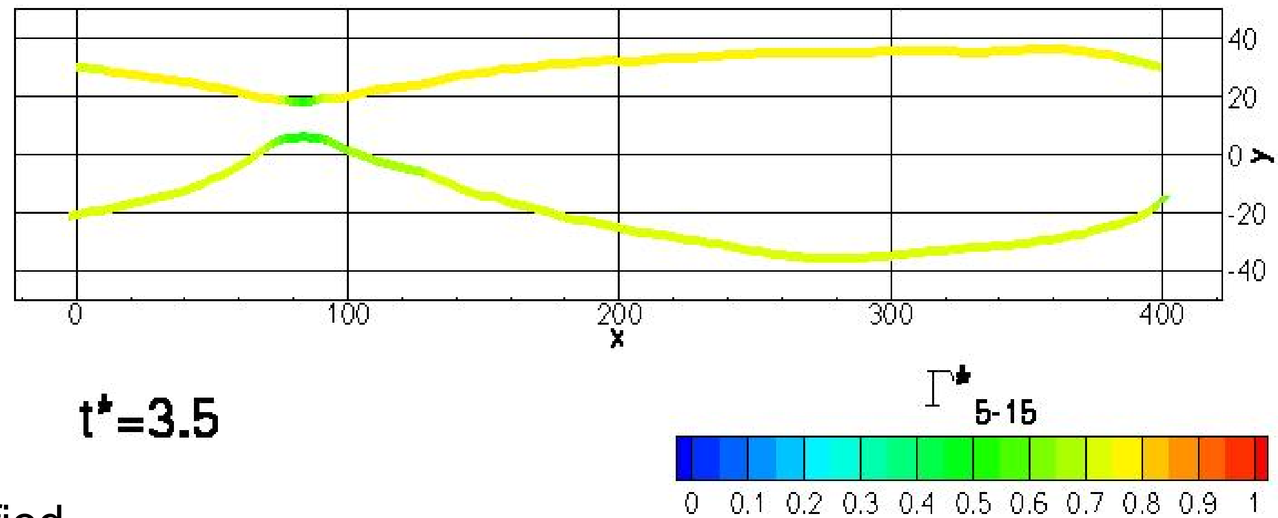
- **wind (head wind, tail wind, cross wind)**
- **turbulence**
- **shear of cross and axial wind components**
- **thermal stratification**
- **ground vicinity**

Normalisation

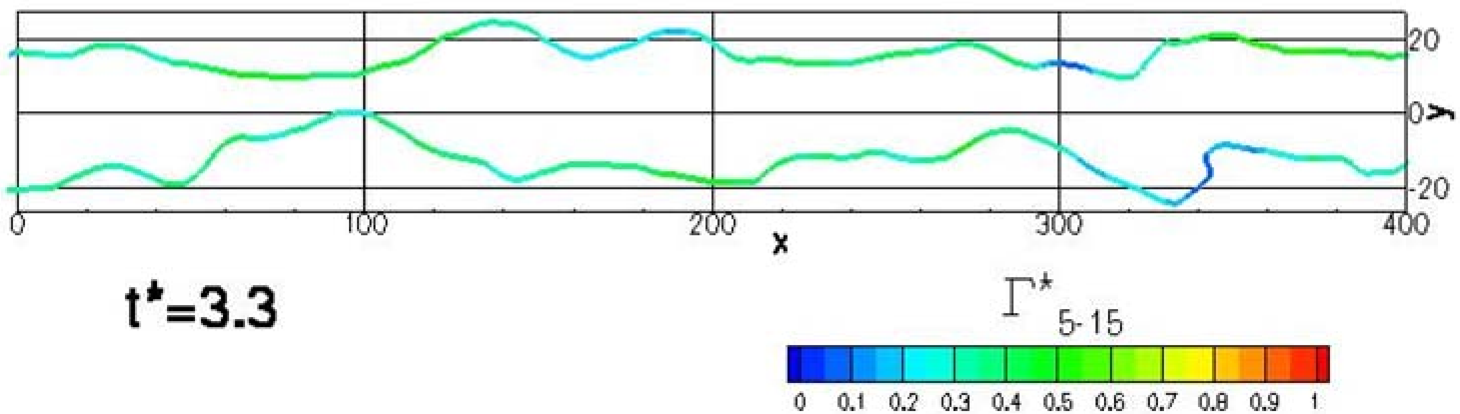
- **circulation by root circulation Γ_0 and averaged of radii 5-15 m**
- **length by vortex separation b_0**
- **time by the time t_0 in which a vortex pair trails 1 b_0 (≈ 30 s)**
- **normalised quantities are marked by ***

Turbulence and stratification

turbulent environment

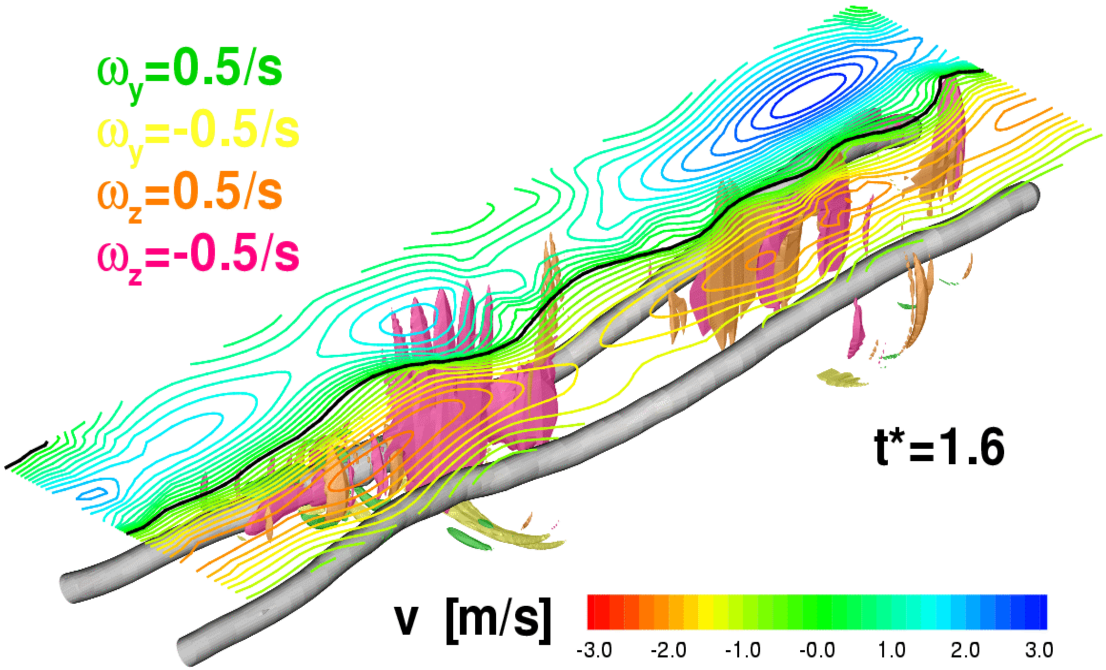


thermally stably stratified environment

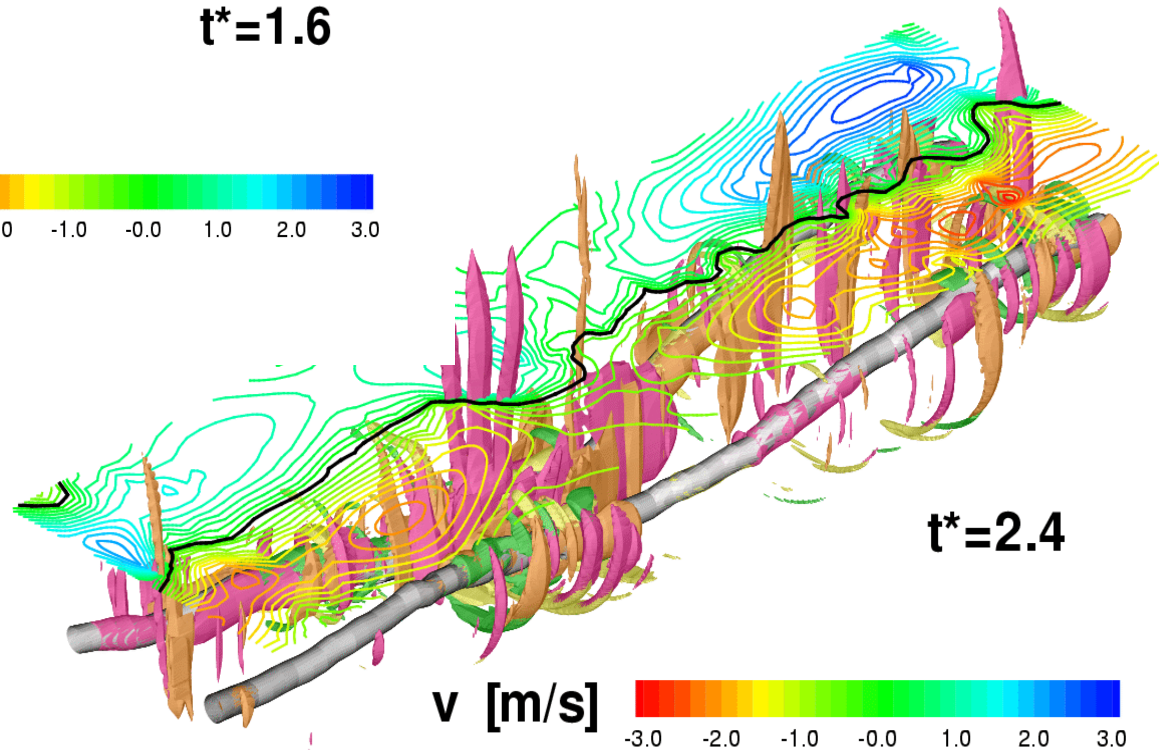


$$\frac{D\omega_{BV}}{Dt} = \frac{1}{\rho^2}\nabla\rho\times\nabla p$$

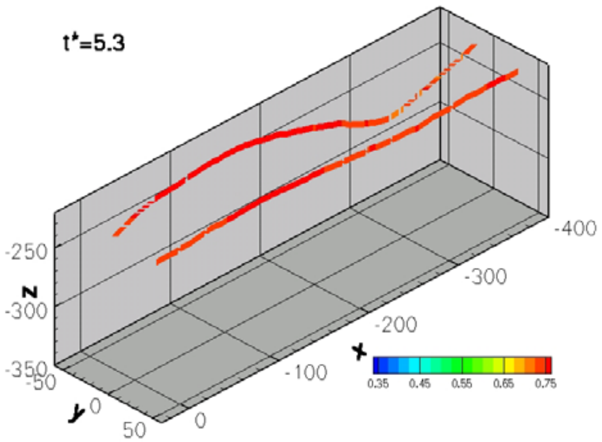
Decay mechanisms

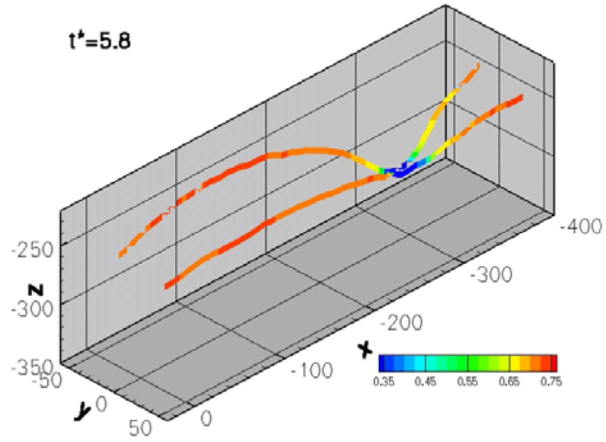


formation of secondary vorticity structures by stretching and tilting

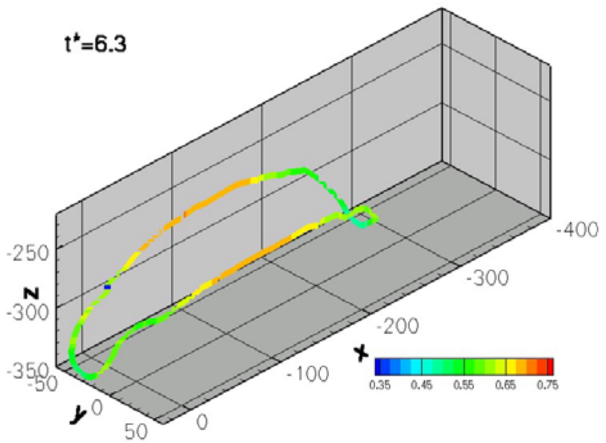


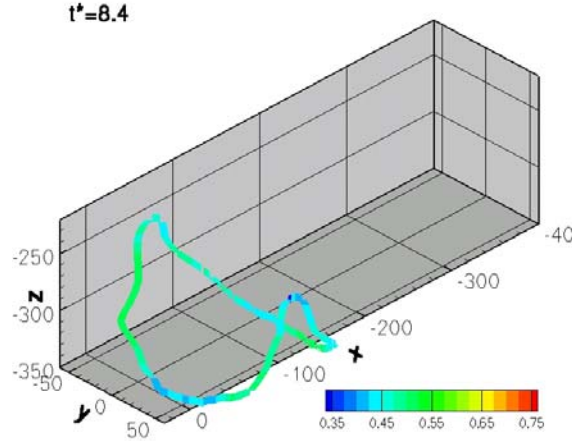
Decay mechanisms - vortex deformation and ring formation



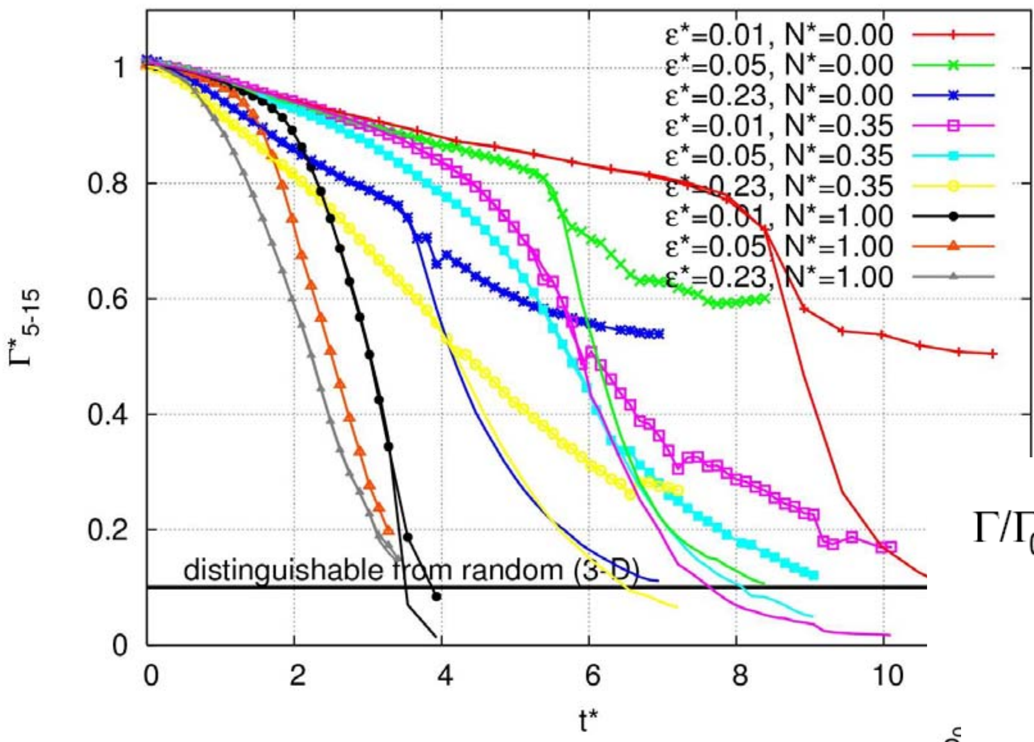


Crow instability, Γ^*_{5-15} colour coded

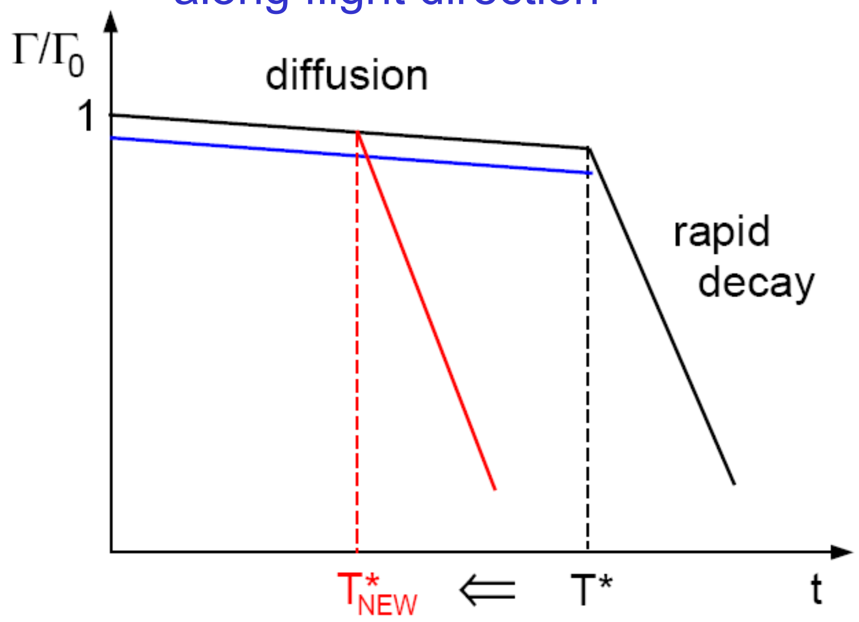




Decay mechanisms - circulation and descent

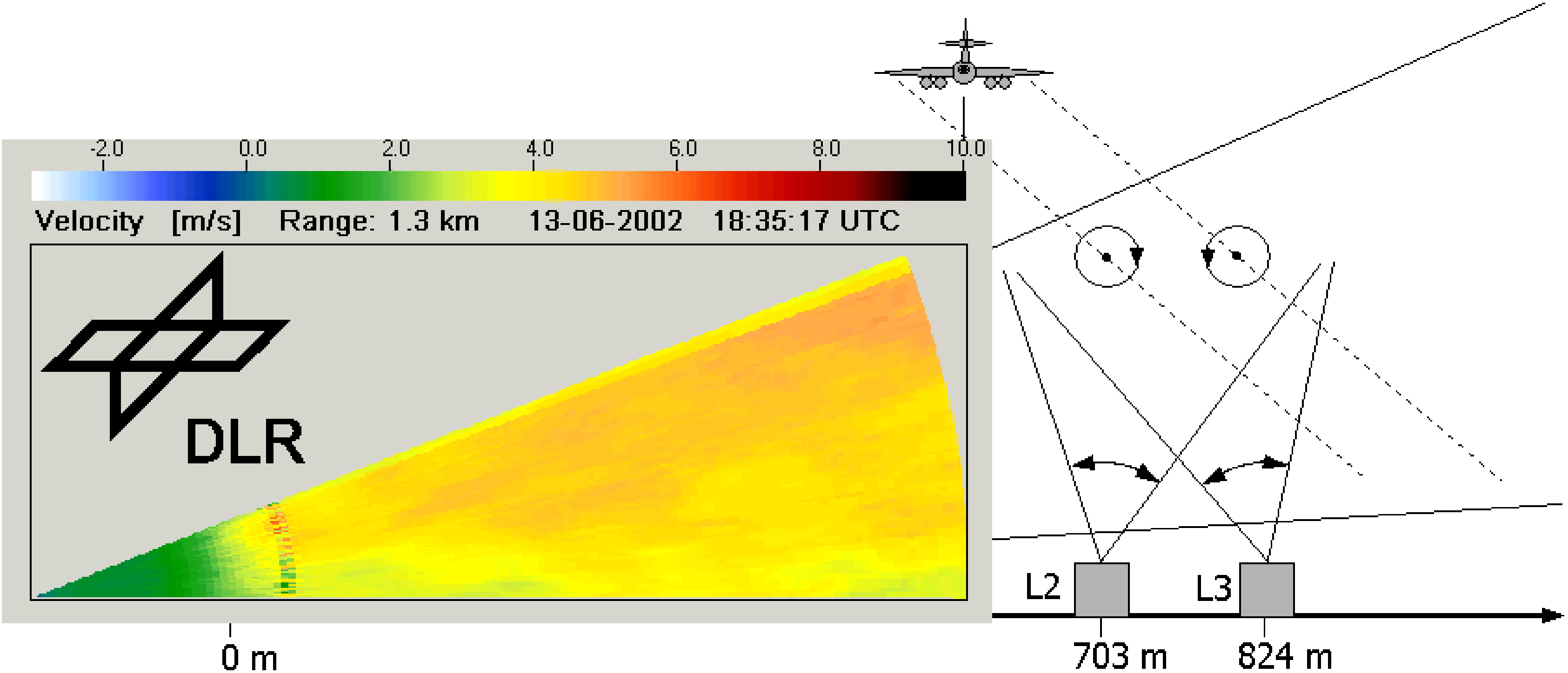


Concept of the 2-phase decay of vortex circulation along flight direction



Pulsed LIDAR as a vortex characterising field instrument

C-Wake and *AWIATOR* (F/T-1) campaigns in Tarbes 2002/2003

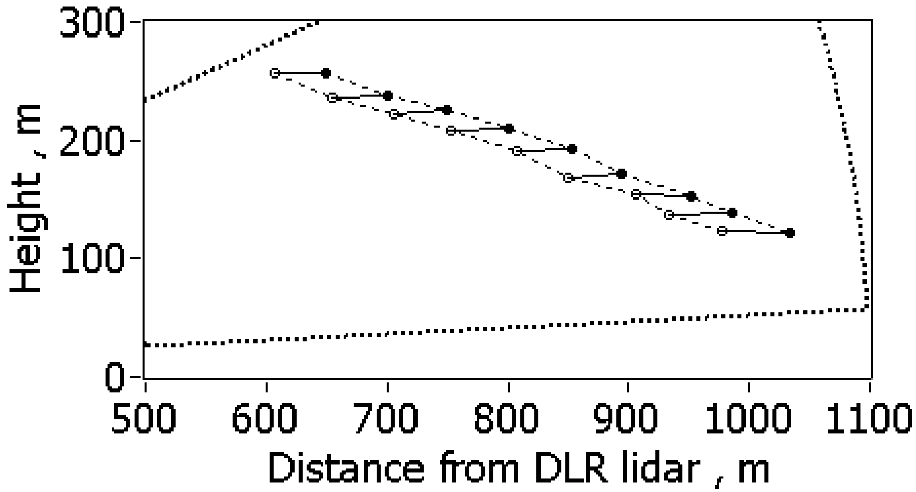


2 µm pulsed Lidar (DLR)

10 µm, cw Lidars (QinetiQ & ONERA)

Wake-vortex characterisation by 2 µm pulsed LIDAR

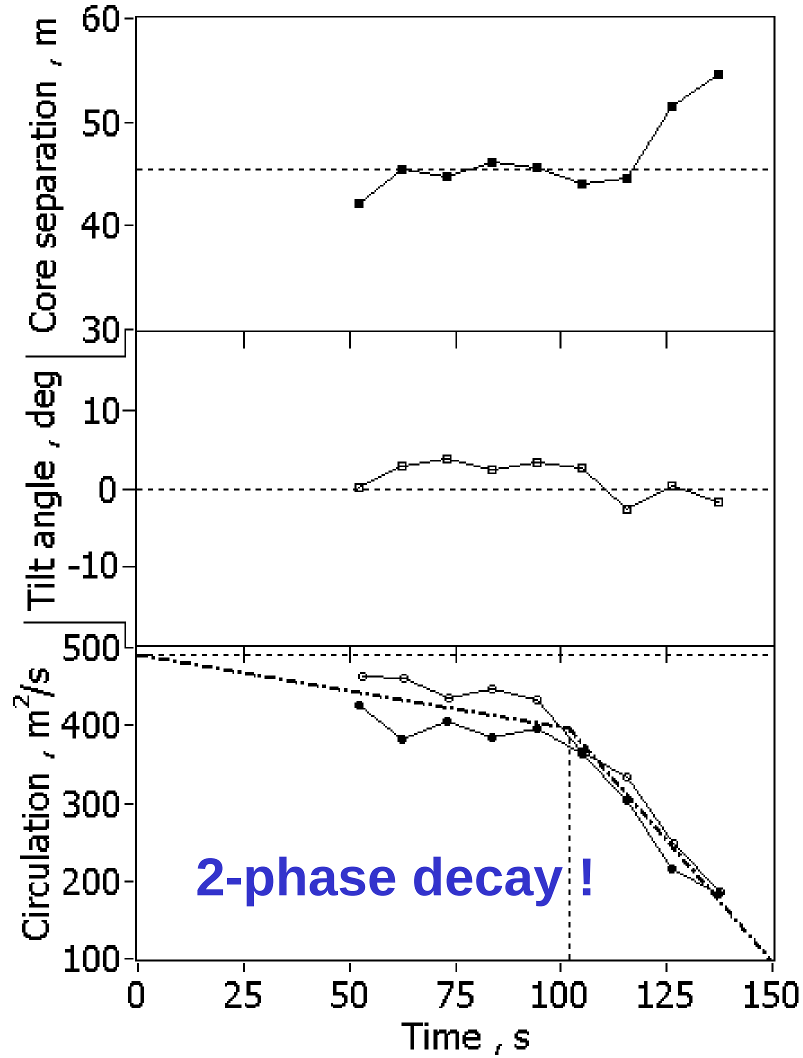
Over-flight 4-22



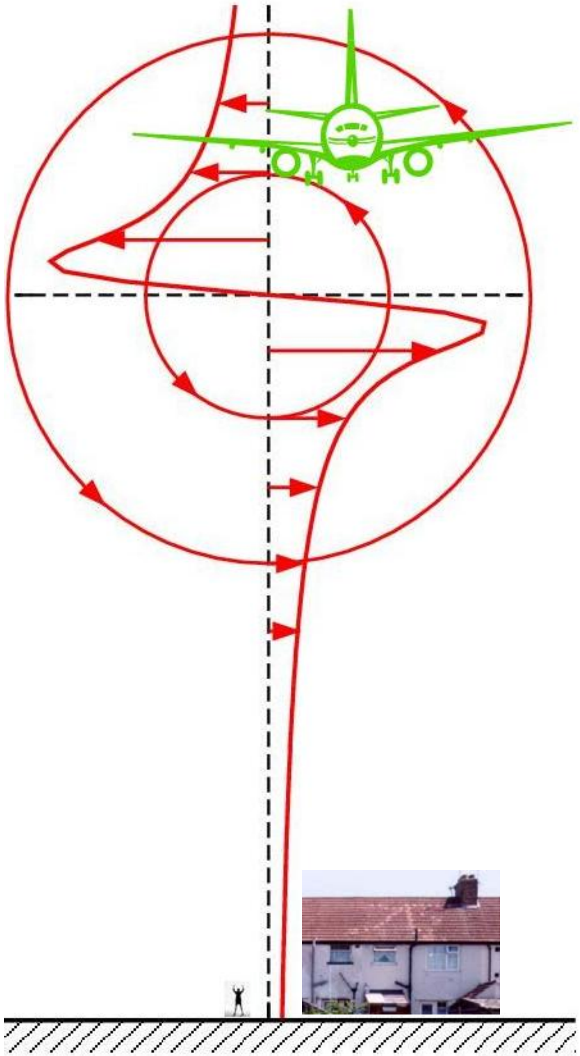
⇑ **Trajectories of the vortex pair**

Time series of vortex separation, tilt angle and circulation ⇒

open circles: port vortex,
full circles: starboard vortex

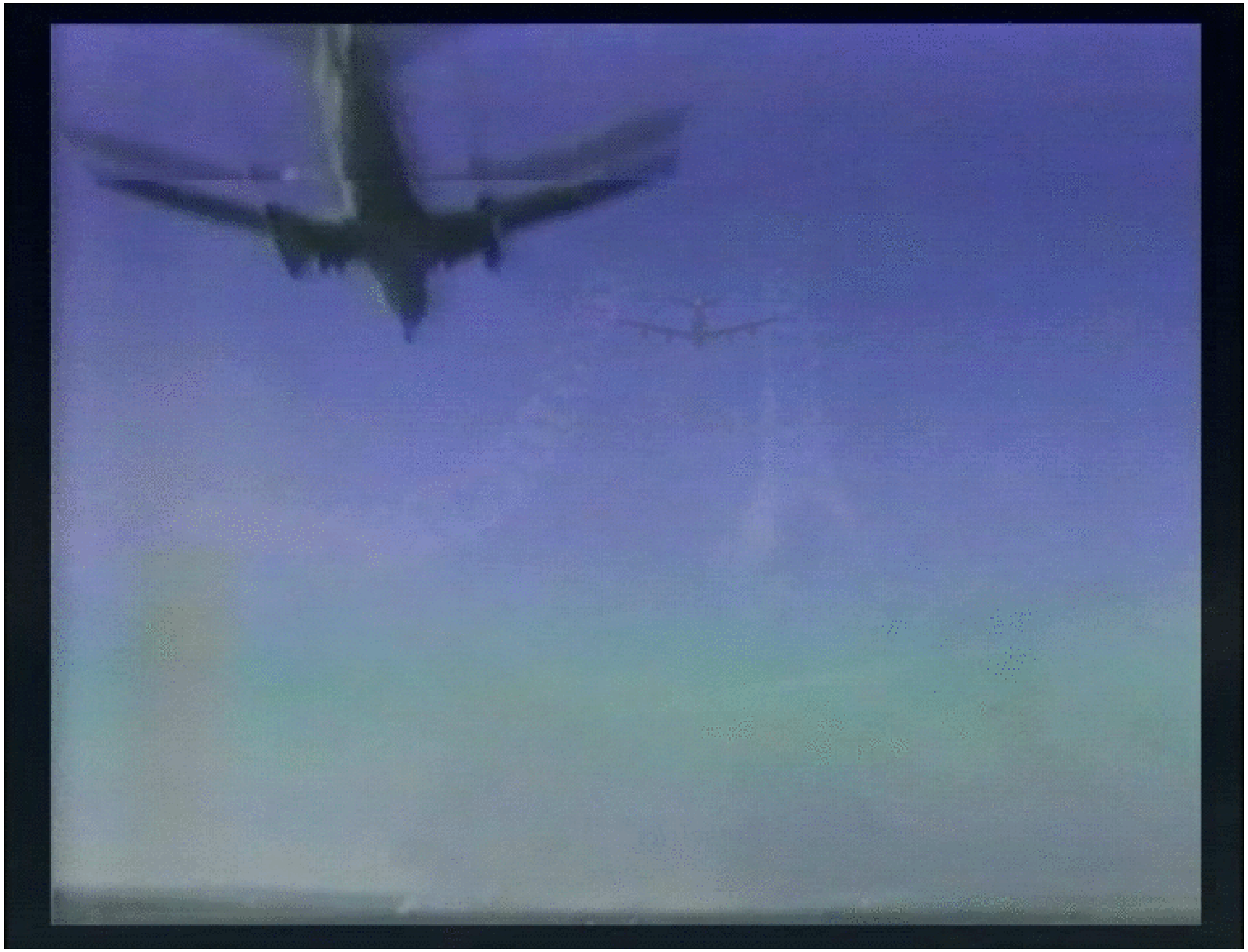


Very different impact of a vortex ...



... on house roofs or persons on ground

... on aircraft encountering a wake



B737 on final approach shortly after a B747 (NASA)

Challenge: Capacity - airports with CSPR, e.g. Frankfurt


Wirbelschleppe I + II
1999 - 2007
Aircraft, Airport, Cockpit, Air-Traffic Control
a DLR Project in the HGF Programme Theme “Verkehr und Umwelt”
a Collaborative Research Programme in the DLR-ONERA Partnership
in Transport Aircraft Research
in collaboration with many past, recent and future EU projects

A wake vortex advisory system - DLR's WSVBS

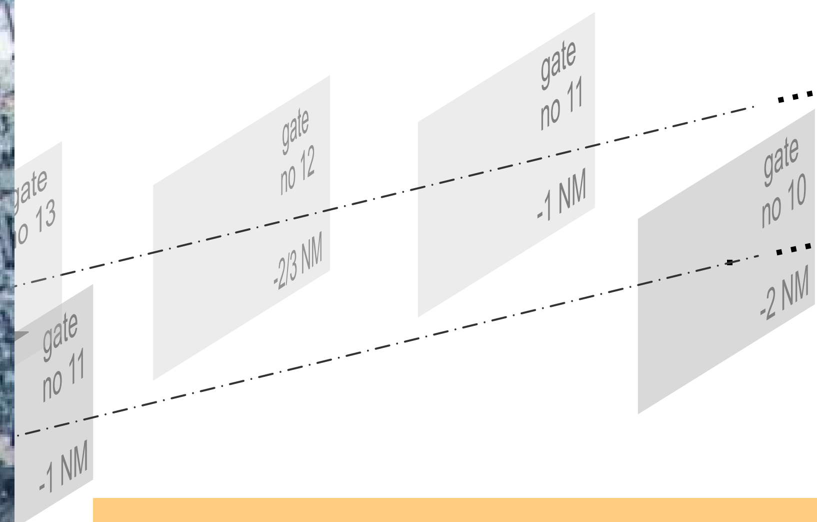
Wirbelschleppen-Vorhersage- & Beobachtungssystem

Frankfurt Airport

13 Gates

ng nominal ILS Flight Path

(Δx = 1/3 NM - 1 NM)

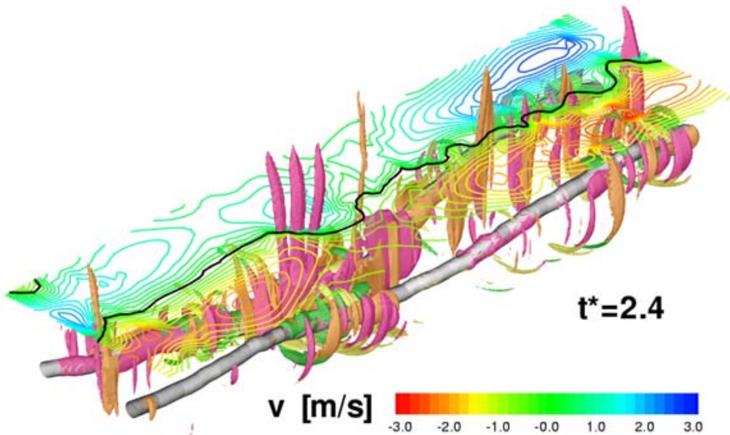


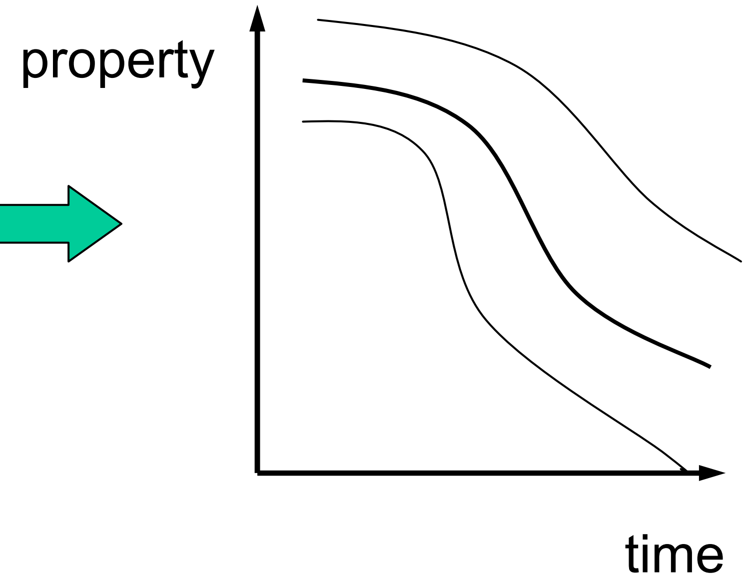
WV are monitored and predicted

➡ **temporal a/c separations**

➡ **procedures proposed for ATC**

wake-vortex real-time model – requirements





- **fast**
- **robust**
- **accurate**
- **reliable**
- **handle stochastic WV properties**
- **digest variable meteorology at scales between 100 m and 10.000 m**

Real-time wake predictor P2P -
Probabilistic wake transport and 2-phase decay model

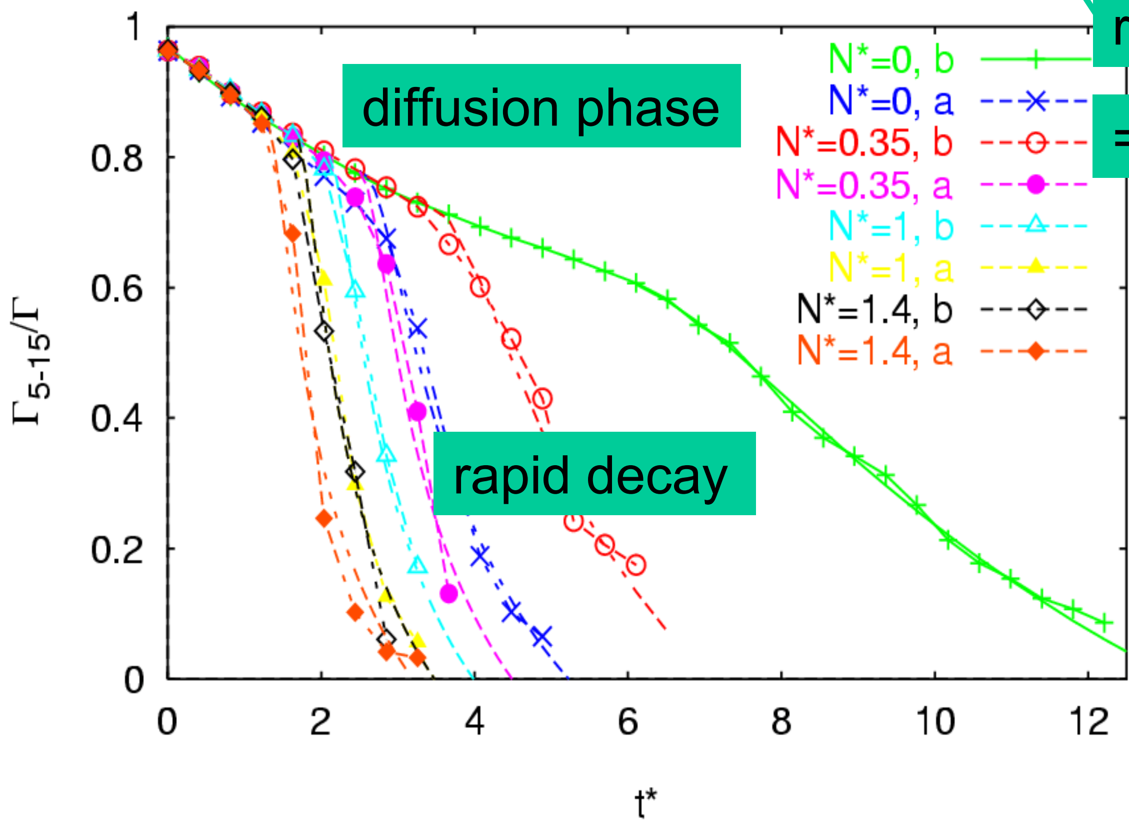
modelled decay:

$$\Gamma^*_{5-15}(t^*) = \underbrace{\underbrace{A - \exp\frac{-R^{*2}}{\nu_1^*(t^*-T_1^*)}}_{diffusion} - \exp\frac{-R^{*2}}{\nu_2^*(t^*-T_2^*)}}_{rapid\ decay}$$

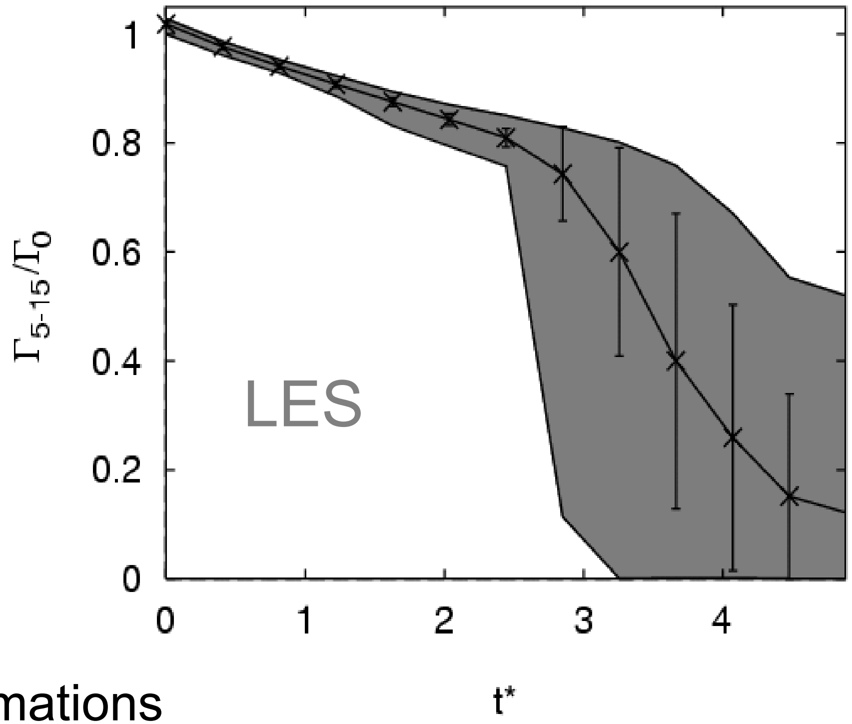
onset of rapid decay

respective decay rate

= f (ε*, N*)



probabilistic formulation



accounts for

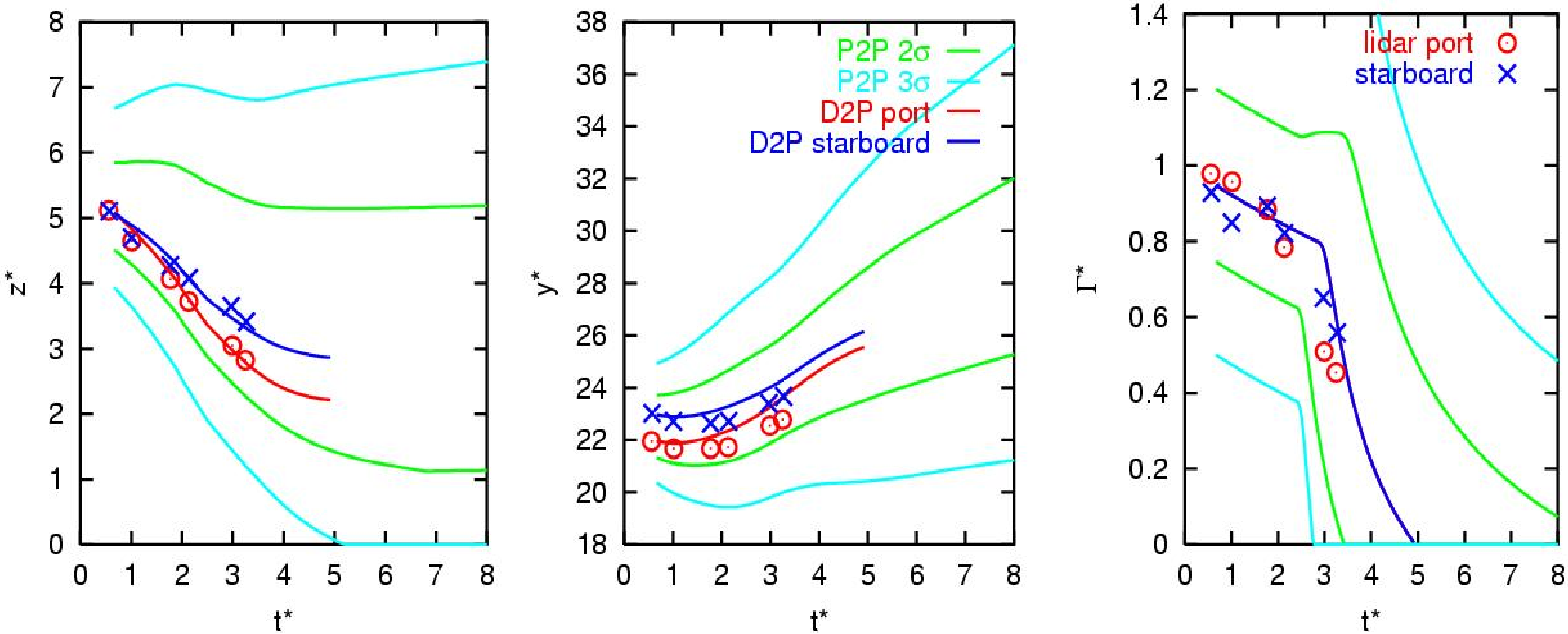
- uncertainty of flight path and a/c data
- uncertainty, variability, and limited predictability of environmental param.
- stochastic nature of turbulence
- complex vortex instabilities and deformations

by

- variation of decay parameters $(\upsilon^*_{2,u}, 0.8T^*_2); (\upsilon^*_{2,l}, 1.2T^*_2)$
- uncertainty allowances $\pm 0.2\Gamma_0$

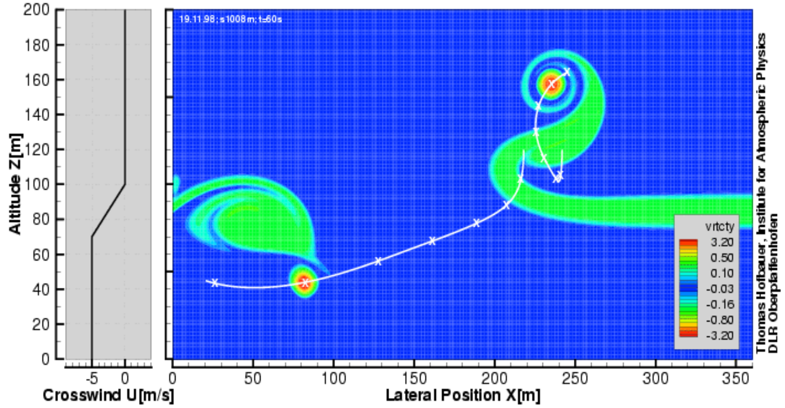
$$y^*_{u(l)}, z^*_{u(l)} = y^*, z^* + (-)\int \sqrt{(C_q q^*)^2 + (C_{sh} v^*_{sh})^2}\, dt^*$$

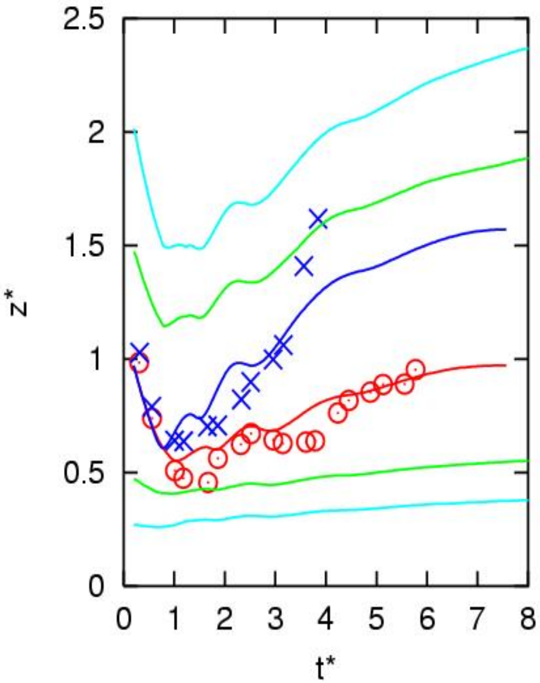
example - transport and decay with crosswind shear

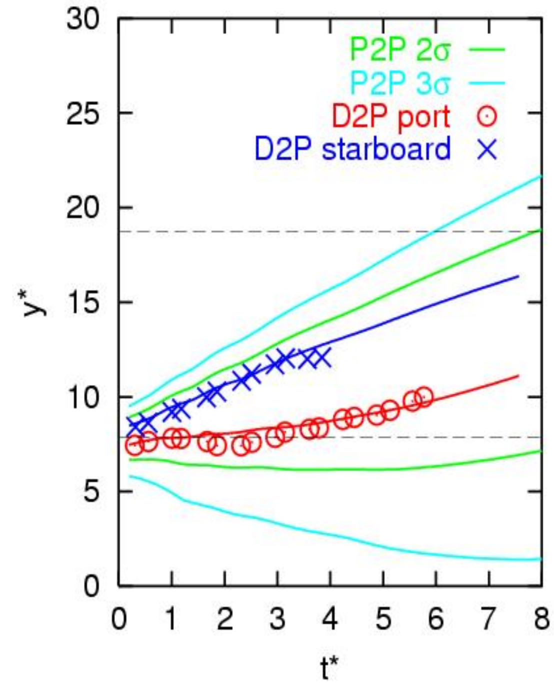


rebound for:

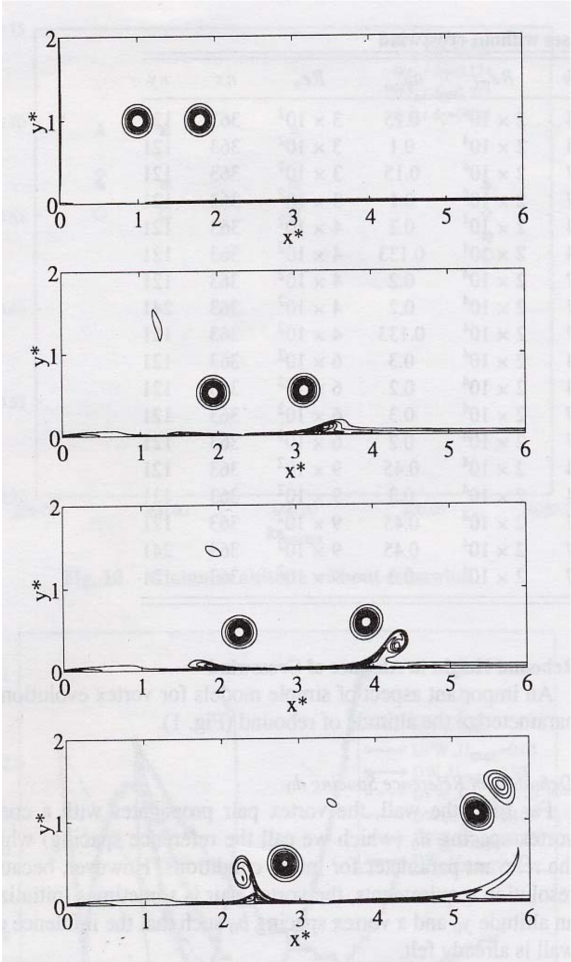
- wind shear
- convection
- stable stratification
- ground proximity

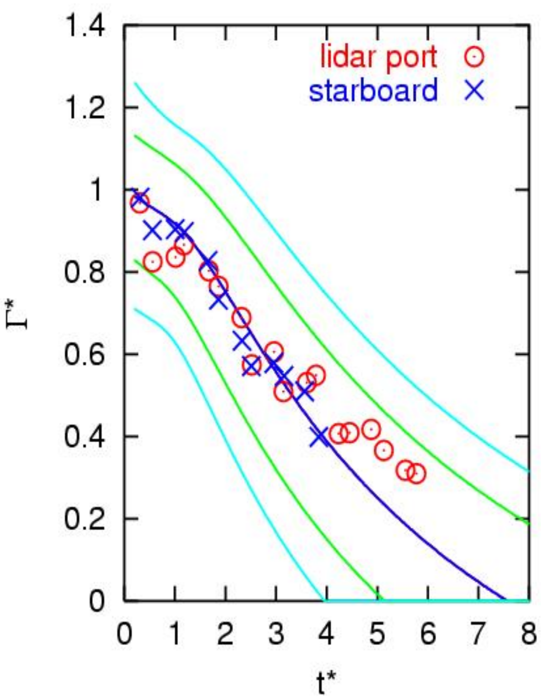


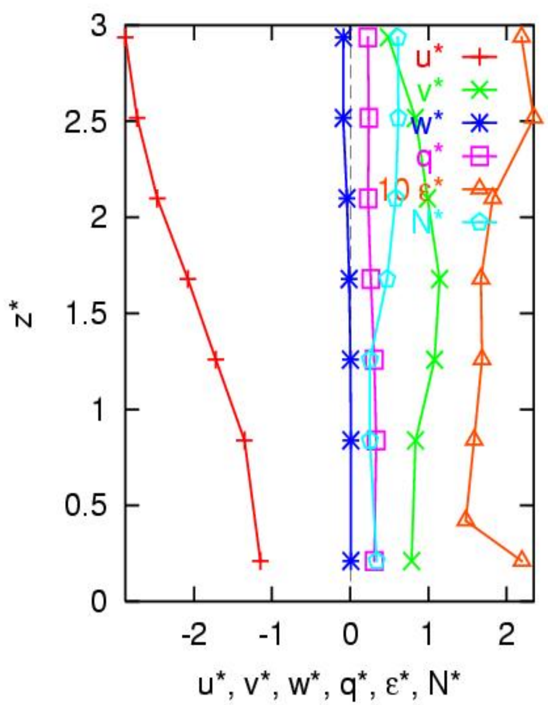




asymmetric rebound in ground proximity







Cerfacs

parameters

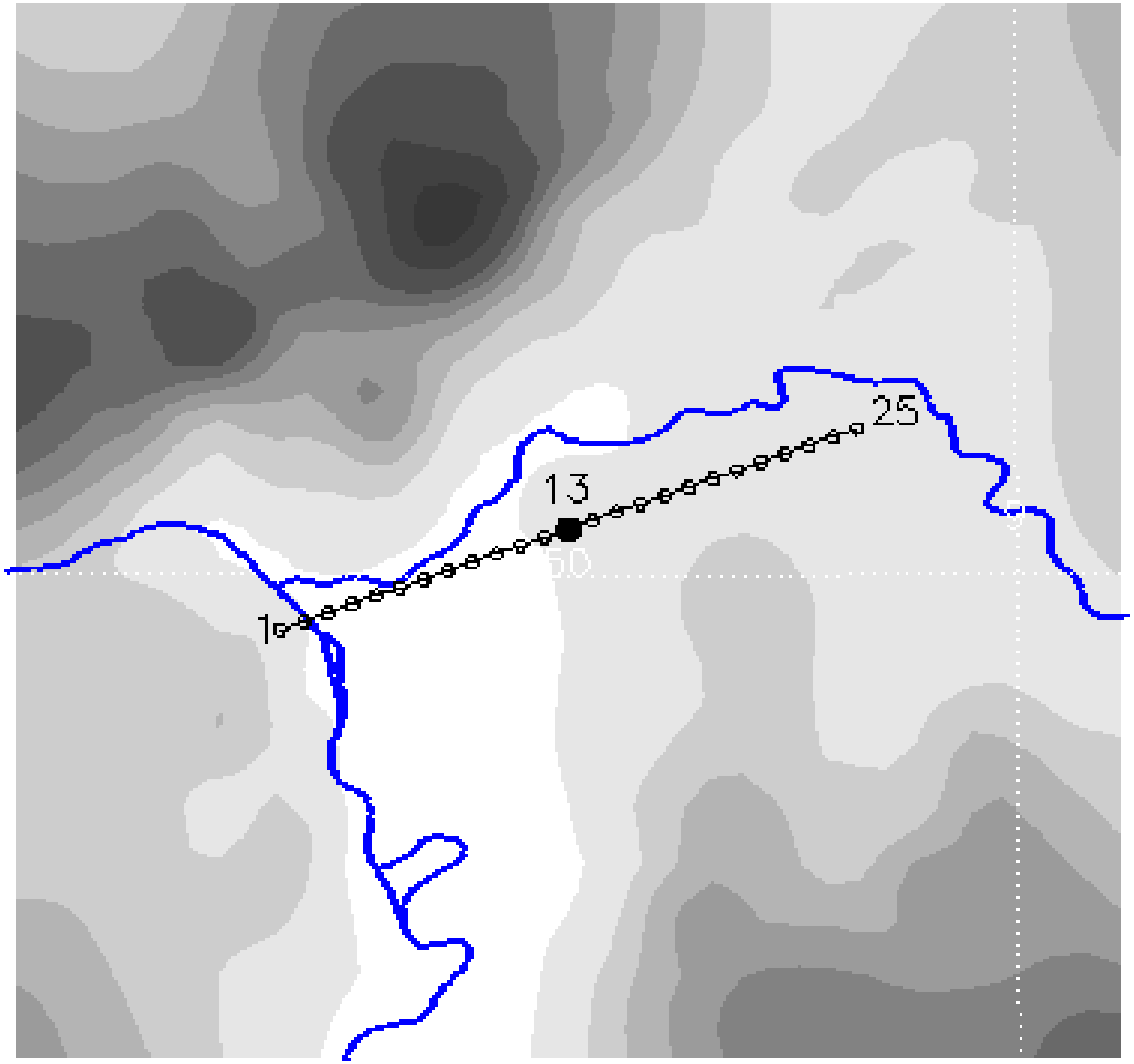
P2P accounts for effects of 3 components of wind, axial- and crosswind shear, turbulence, stable thermal stratification, and ground proximity

input data:

- a/c: $x_0, y_0, z_0, t_0, \gamma, V, m, b$
- meteo: $u(z), v(z), w(z), \rho(z), q(z), \varepsilon(z), \theta(z)$

MET data for wake prediction

- measured by profilers (WTR, AMDAR)
- forecast by local area NWP (COSMOairport)



Questions, issues, priorities

- prediction of aircraft wake vortices requires a probabilistic treatment
- aircraft parameters (trajectory, actual weight, speed, load factor) may be satisfactorily guessed
- highest impact from varying meteorological field data (wind, turbulence, stratification)
  - e.g., homogeneity of wind at the airport scale ?
- MET field data required at scales
  - horizontally 10 km, resolution 100 m
  - vertically 0 - 2 km, resolution 10 m
- local area NWP ensembles: enough spread ?

- Discuss and conclude:
  - Is NWP the right approach ?
  - Is nowcasting / persistency forecast better suited ?

Questions, issues, priorities

- …