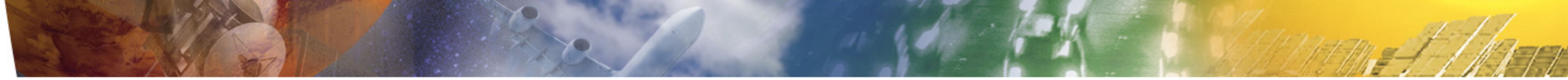
DLR's Models and Systems for RE-CATEGORIZATION

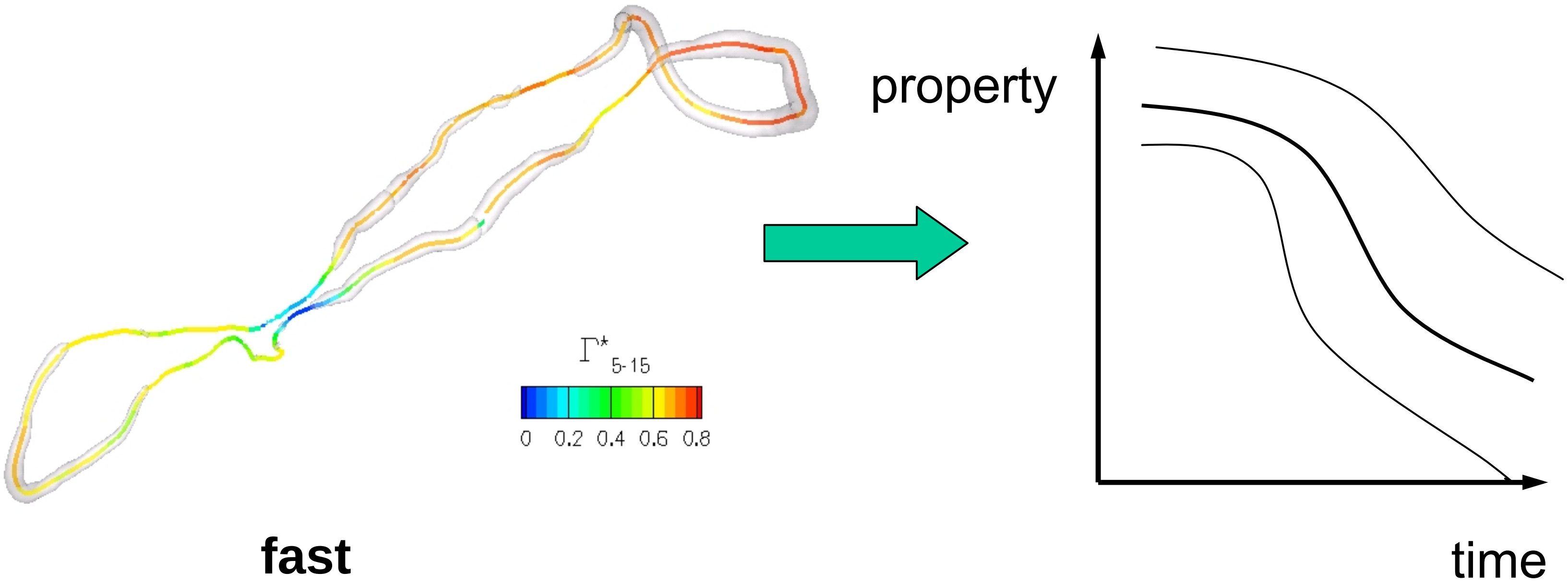
T. Gerz[1], F. Holzäpfel[1], J. Kladetzke[2], C. Schwarz[3]

[1]Institut für Physik der Atmosphäre, Oberpfaffenhofen
[2]Institut für Robotik und Mechatronik, Oberpfaffenhofen
[3]Institut für Flugsystemtechnik, Braunschweig
Deutsches Zentrum für Luft- und Raumfahrt

- P2P – Probabilistic Two-Phase WV transport & decay model
- WakeScene – WV scenarios simulation package — for RECAT II
- WSVBS – an advisory system to deliver separations — for RECAT III



wake-vortex real-time model – requirements



fast

robust

accurate

reliable

consider stochastic WV properties

Hennemann &. Holzäpfel, 5th Int. Symp. on Turbulence & Shear Flow Phenomena, TU Munich 2007

Concept of P2P –
Probabilistic 2-Phase WV transport & decay model

- transfer of LES skill to parametric model
  (adaptation to and calibration with LES data)
- hydrodynamic basis: $$\frac{\Gamma(r,t)}{\Gamma_0} = 1 - \exp\frac{-r^2}{4\upsilon t}$$
- well defined circulation: Γ_{5-15}
- probabilistic formulation $\Rightarrow$ envelopes enclosing e.g. 2σ-behavior
- training of model with measurement data

parameters

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

input data: • a/c: $x_0, y_0, z_0, \text{heading}\ , t_0, \gamma, \Phi, V, m, b$

• meteo: $u(z), v(z), w(z), \rho(z), q(z), \varepsilon(z), \theta(z)$

output data: Γ±δΓ(t) , y±δy(t), z±δz(t)
at certain flight path positions (gates)

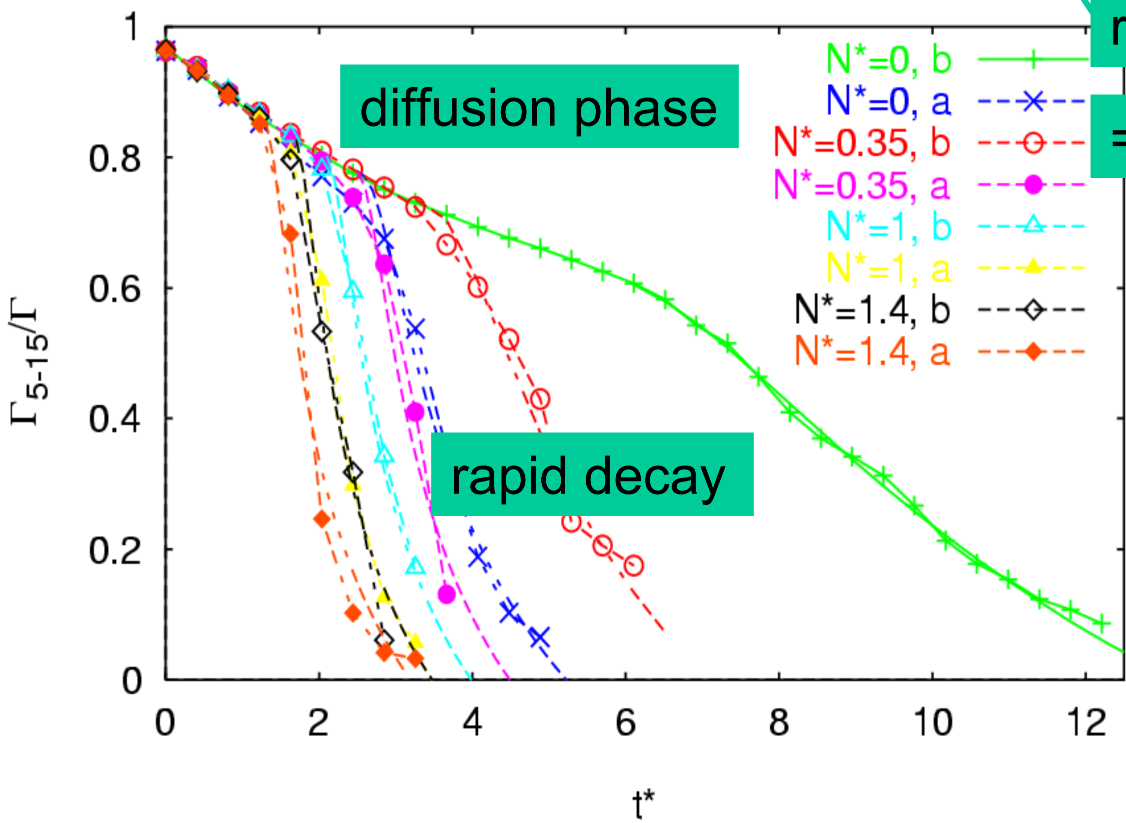
model equations — two-phase decay

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

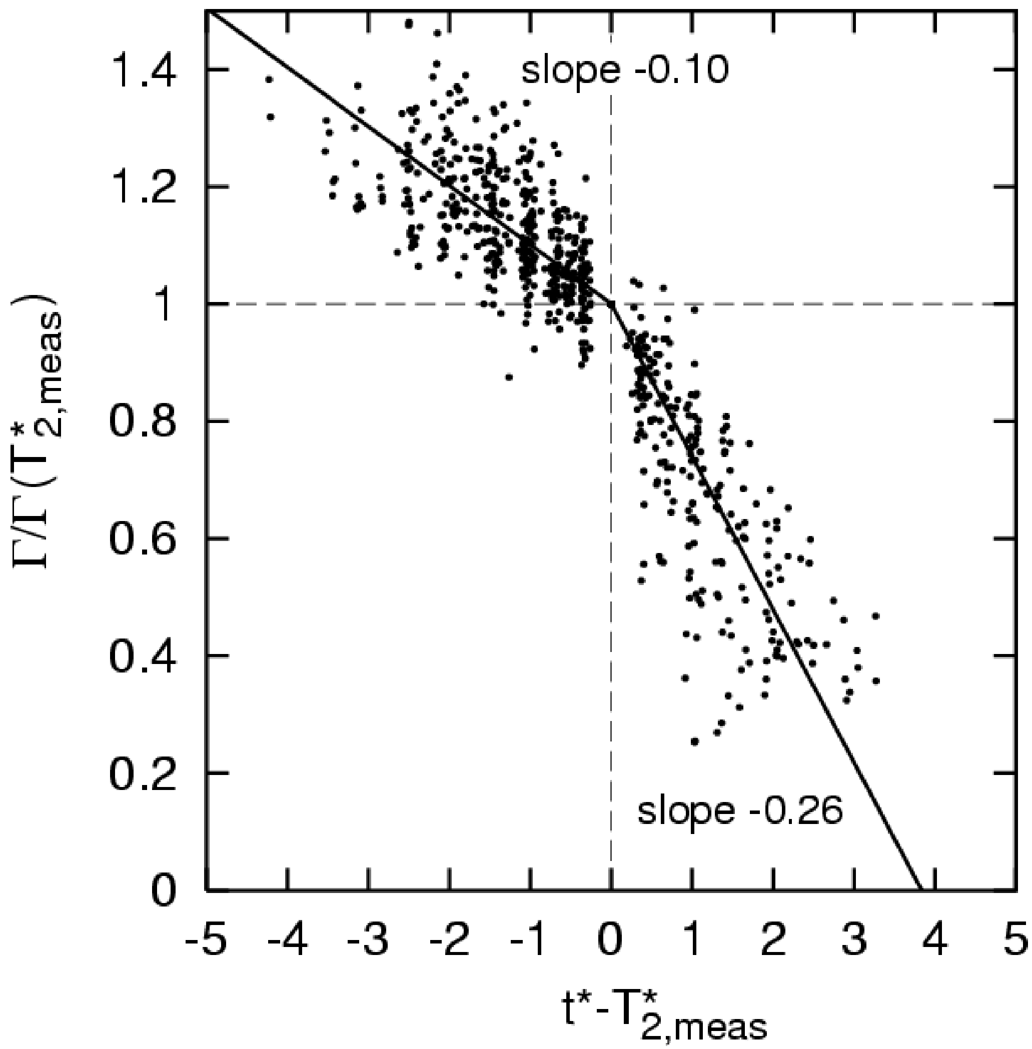
onset of rapid decay

respective decay rate

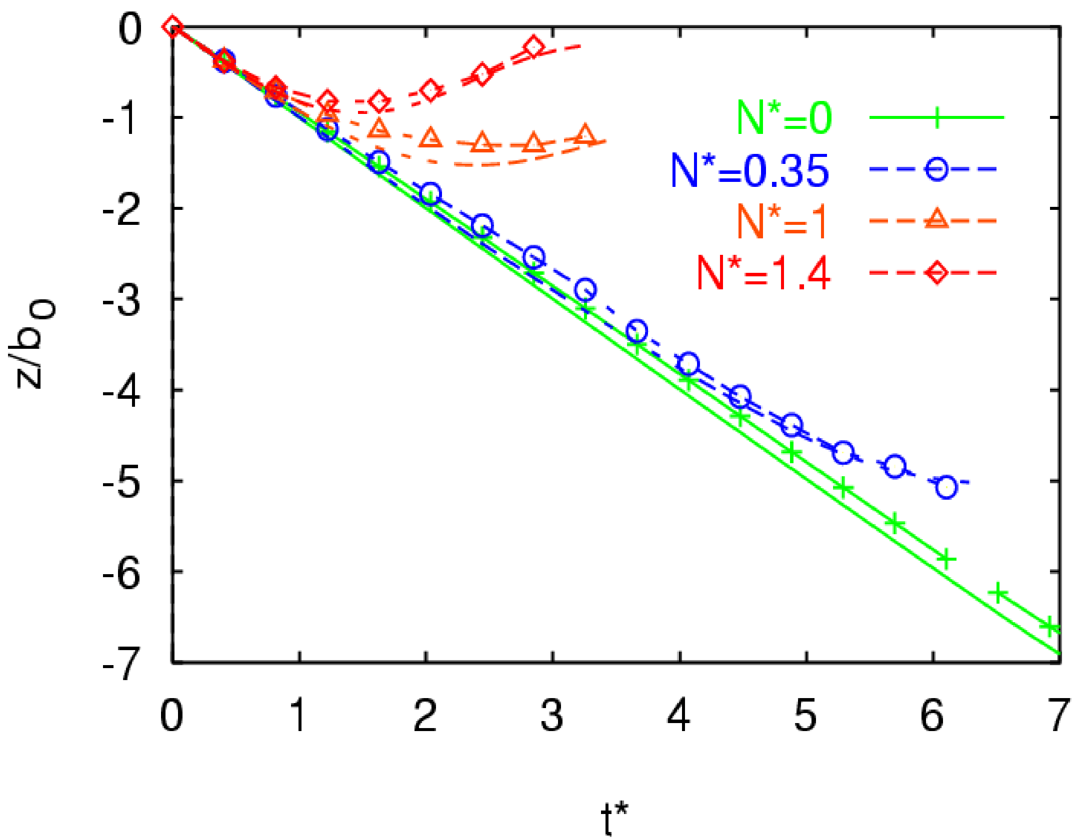
= f (ε*, N*)



lidar — two-phase decay



descent speed



non-linear relation between circulation and descent speed

⇒ stagnating or even re-bounding vortices in strongly stably stratified environment

Probabilistic Concept

fixed uncertainties:

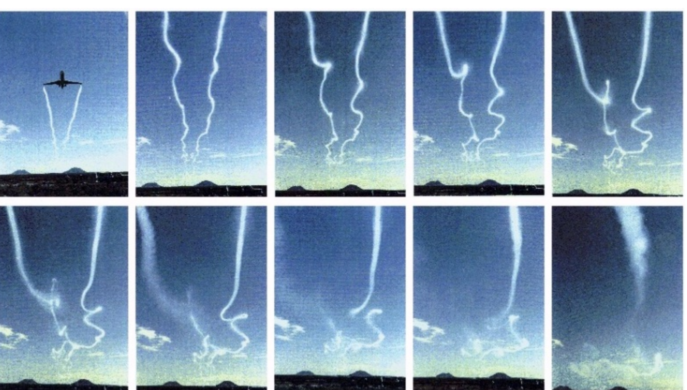
- variation of decay parameters $(\upsilon^*_{2,u}, 0.8T^*_2); (\upsilon^*_{2,l}, 1.2T^*_2)$
- uncertainty allowances $\pm b_0, \quad \pm 0.2\Gamma_0$

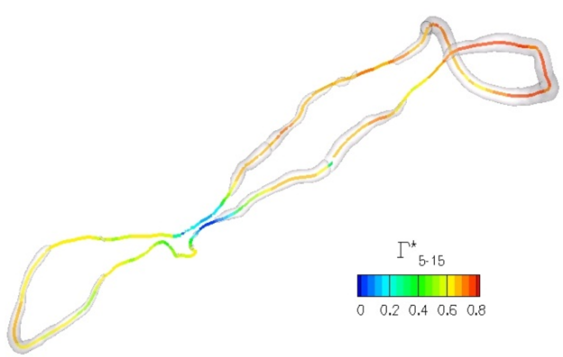
dynamic uncertainties:

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

model calibration with measurement data:

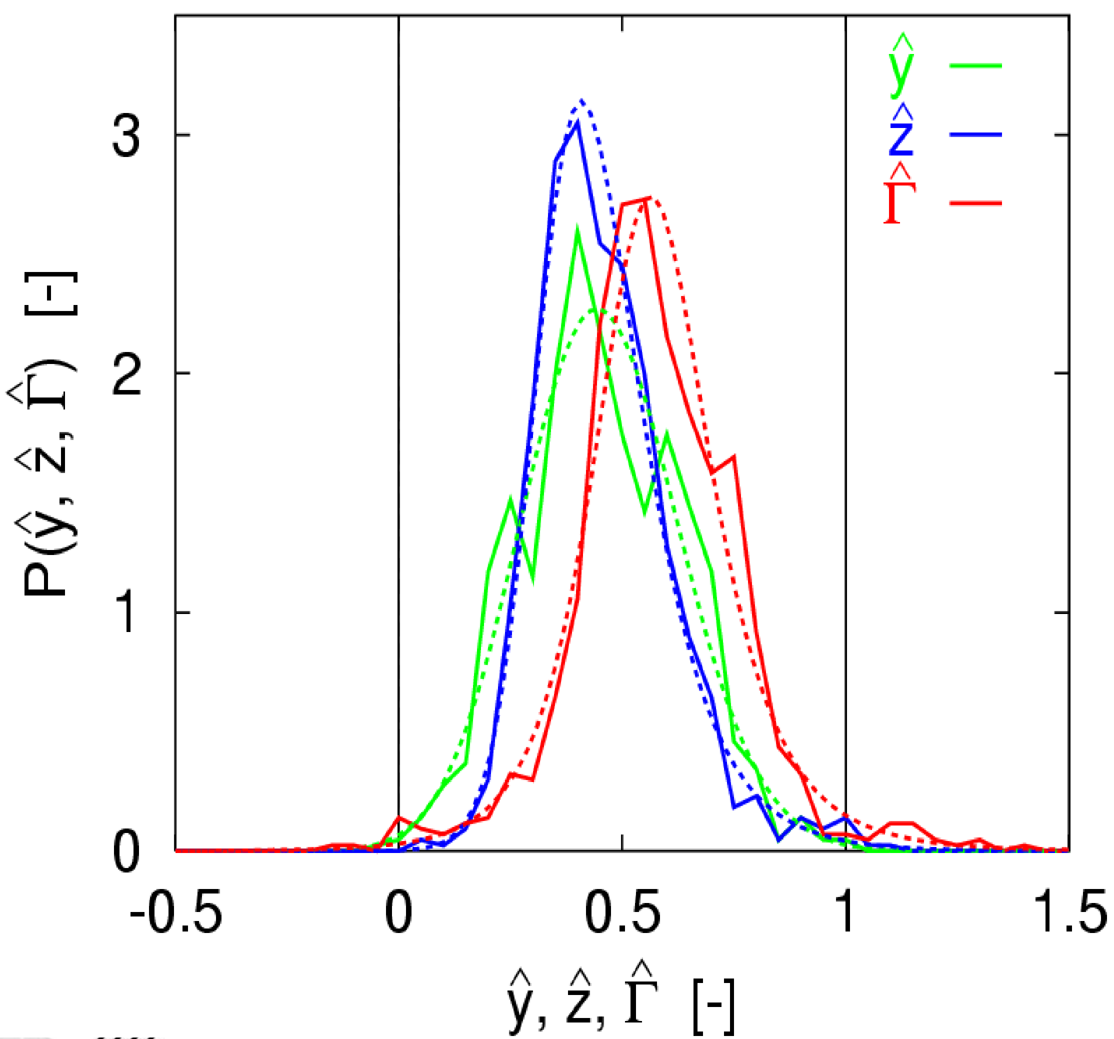
- uncertainty allowances (see next slide)

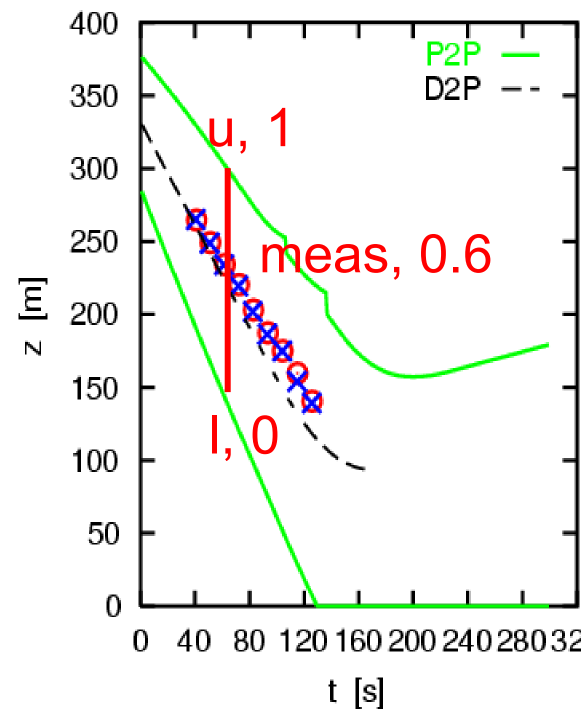




Model Calibration with Measurement Data

prediction of envelopes with defined probabilities



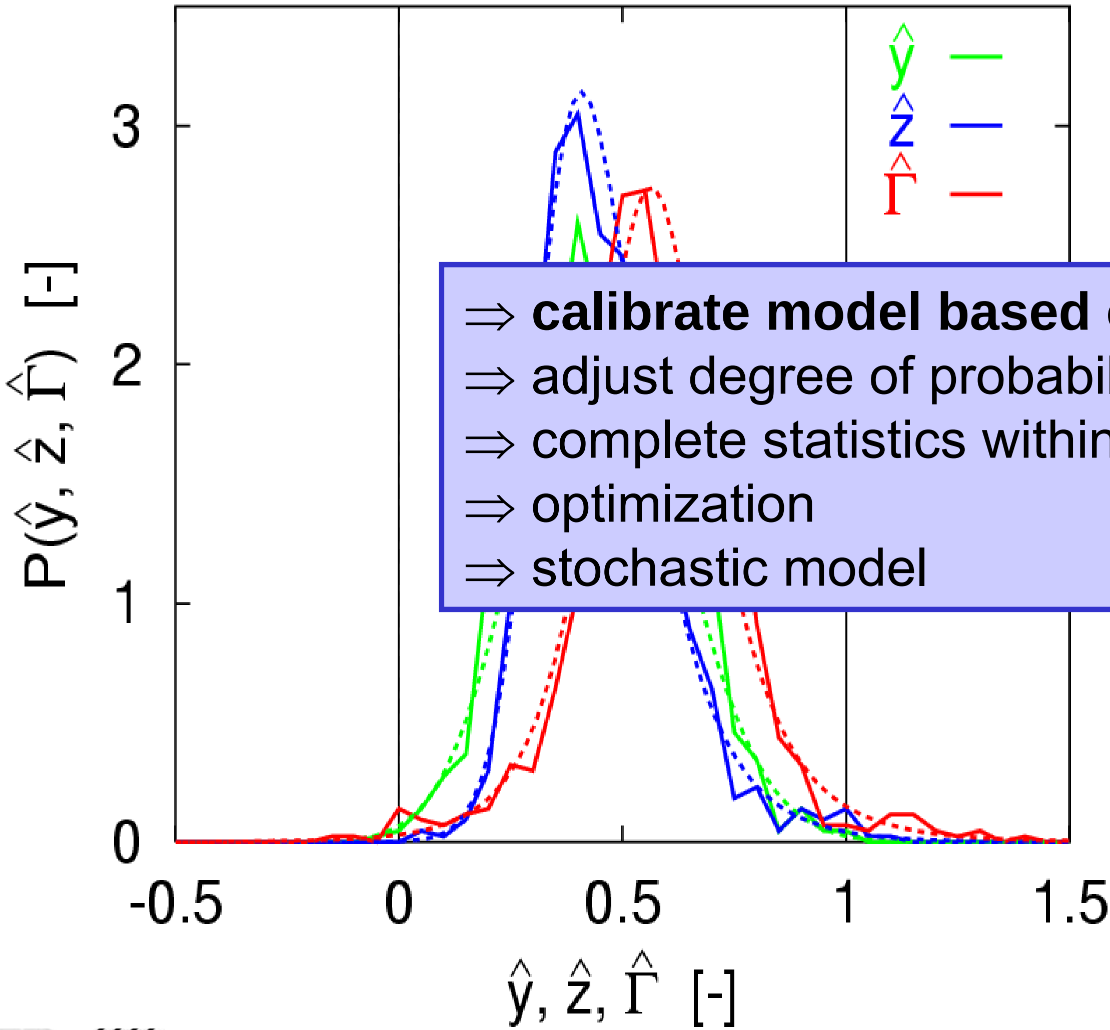


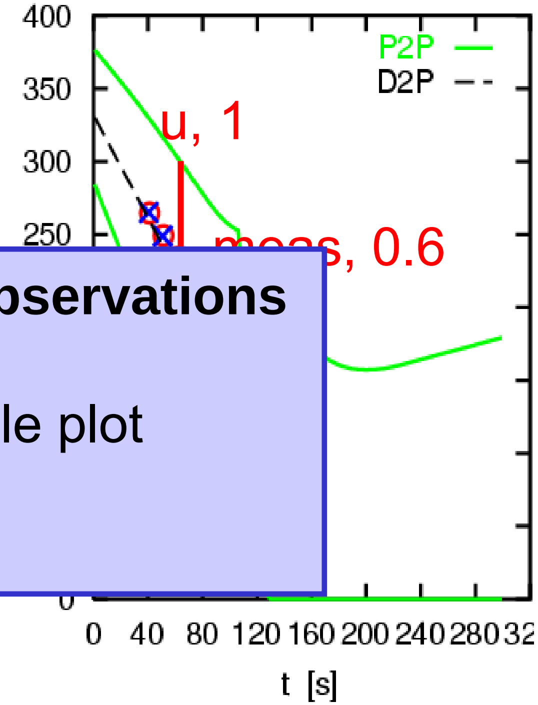
$$\hat{z} = \frac{z_{meas} - z_l}{z_u - z_l}$$

Holzäpfel, J. Aircraft **43** 2006

Model Calibration with Measurement Data

prediction of envelopes with defined probabilities



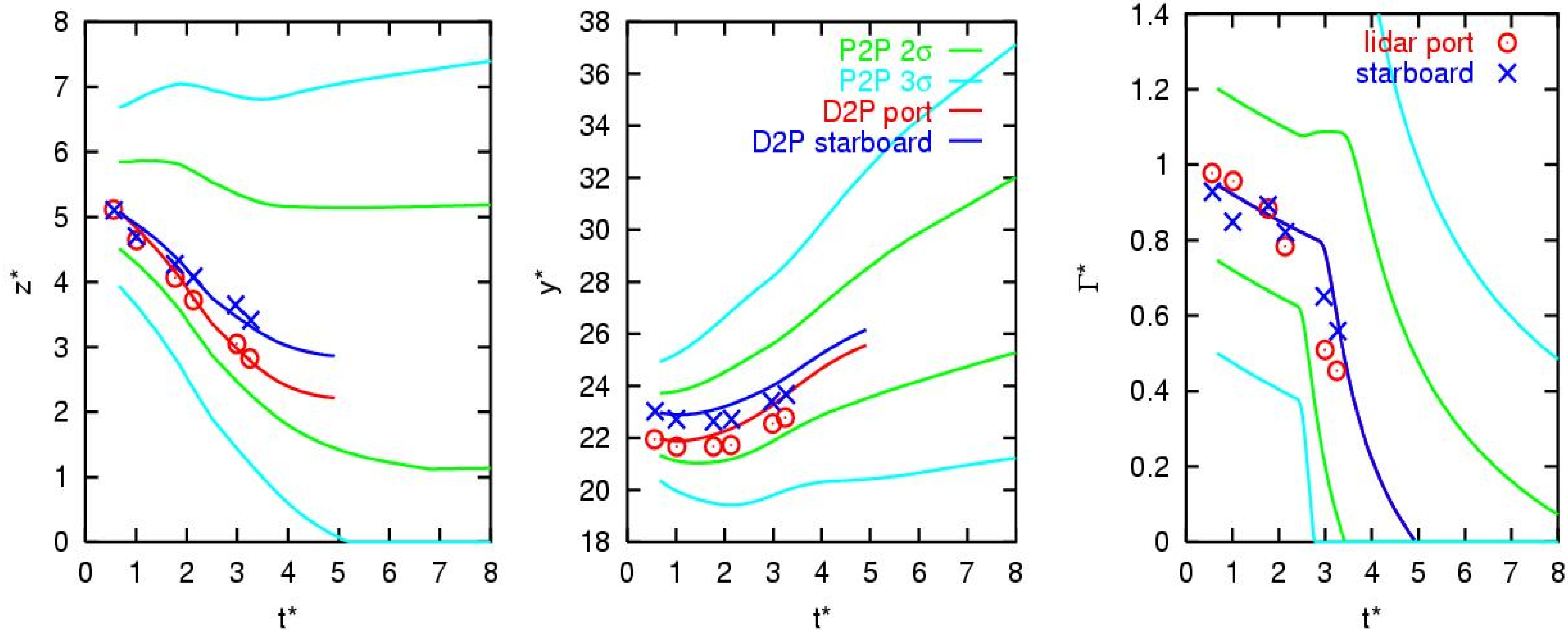


- ⇒ **calibrate model based on observations**
- ⇒ adjust degree of probability
- ⇒ complete statistics within single plot
- ⇒ optimization
- ⇒ stochastic model

$$\hat{z} = \frac{z_{meas} - z_l}{z_u - z_l}$$

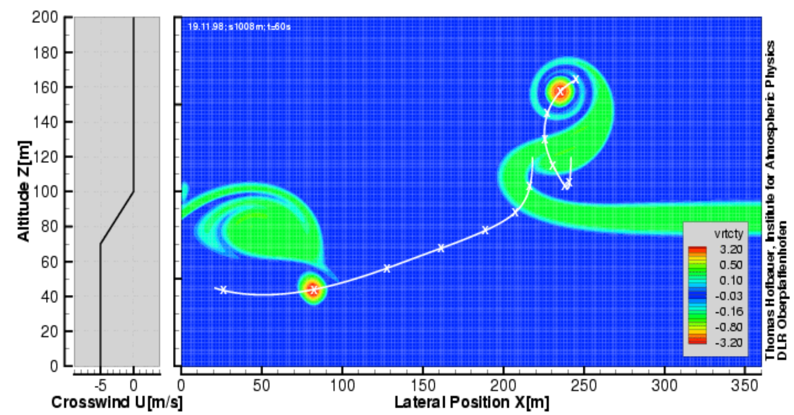
Holzäpfel, J. Aircraft **43** 2006

example 1 – wake-vortex evolution with crosswind shear

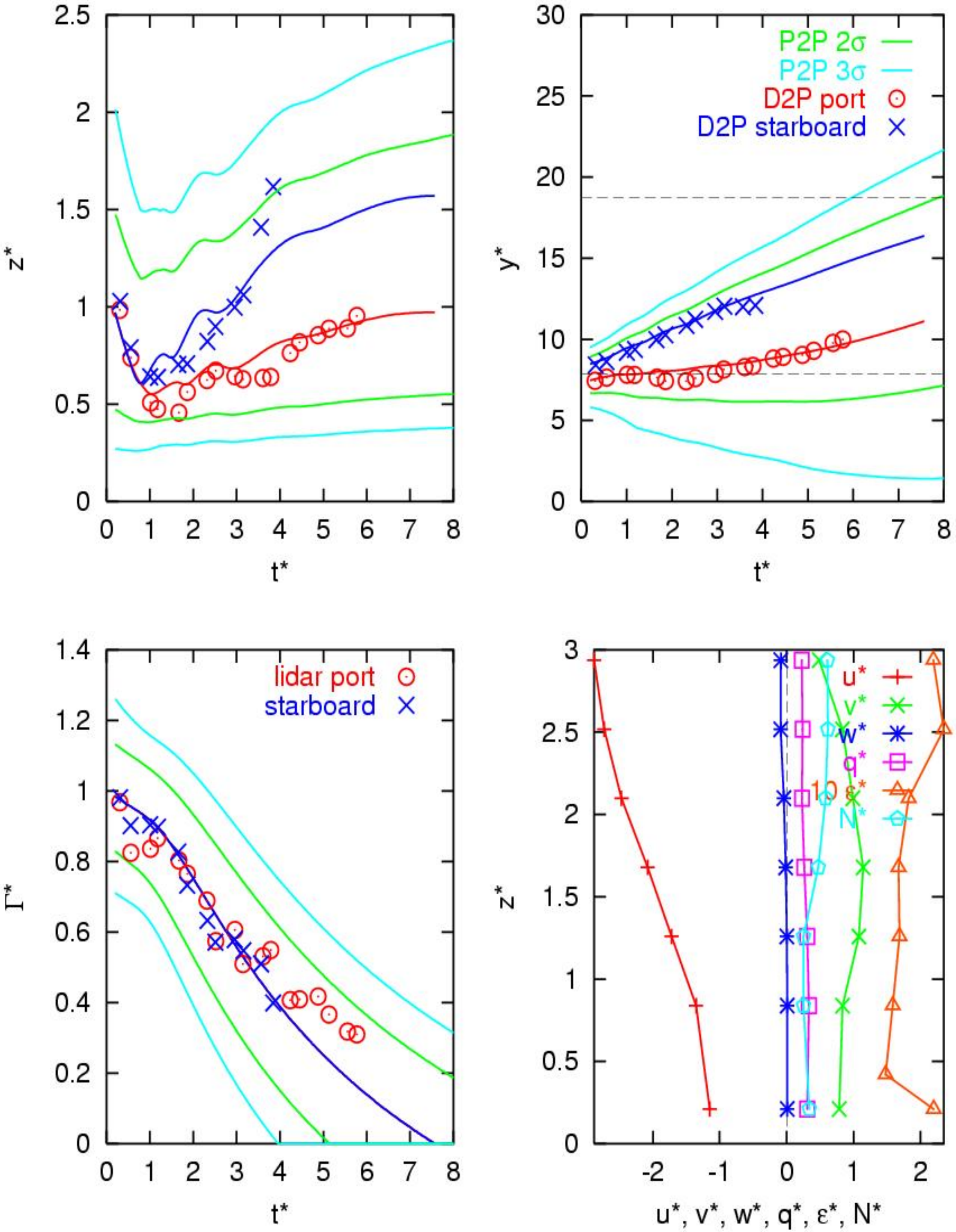


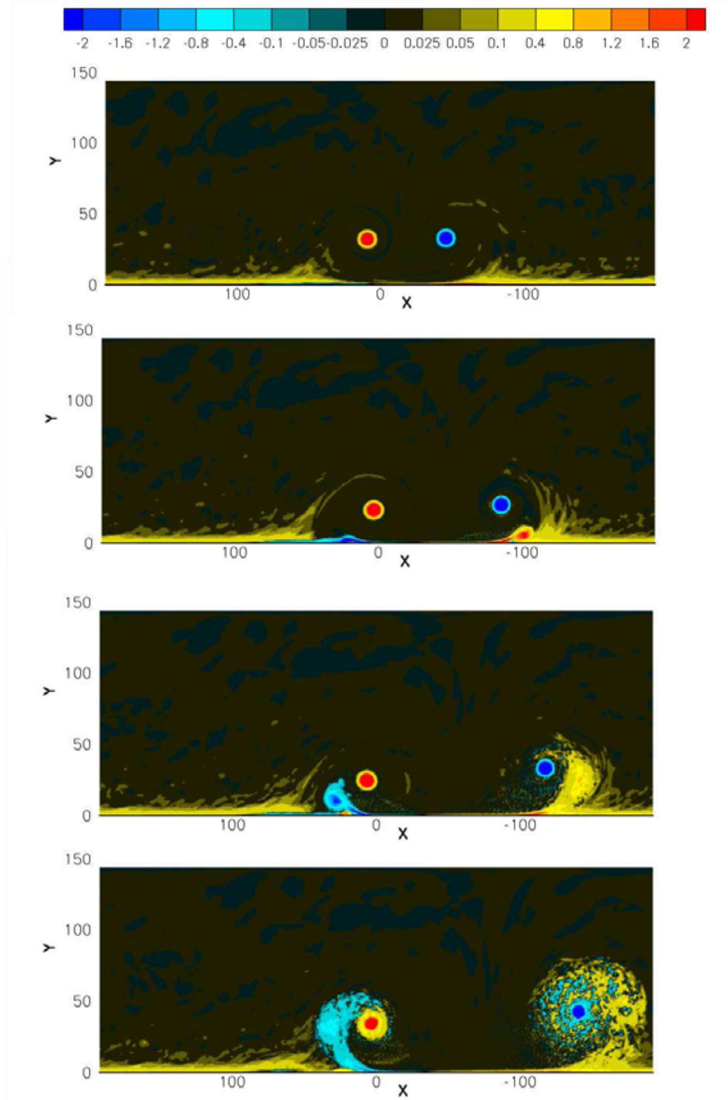
rebound for:

- wind shear
- convection
- stable stratification
- ground proximity



example 2: asymmetric rebound in ground proximity





Anton Stephan

P2P validation work - survey

campaign	No. cases	det./prob. scoring	compared to	a/c types	flight phases	documentation
Memphis, TN (1994, 1995)	282 211	X/-	APA	23 hvy/med/li	arrival OGE/IGE	J. Aircraft 2003/2004
Dallas Fort Worth, TX (1997)	191	X/-		16 hvy/med/li	arrival OGE/NGE	J. Aircraft 2004
WakeOP (2001)	41	X/-	APA	ATTAS	level/hi-lift OGE	J. Aircraft 2004
WakeTOUL Tarbes (2002)	32	X/X	APA	A340	lev/arr/cl/hi OGE	J. Aircraft 2006
AWIATOR FT1 Tarbes (2003)	32	X/X	APA	A340	level/take-off/OGE	J. Aircraft 2006
WakeFRA Frankfurt (2004)	282 + 233	X/X	APA / DVM	25 hvy/med	arrival IGE/OGE	AIAA J. 2007
CREDOS EDDF-1 (2007)	137	X/-	DVM	12 heavy	departure OGE	CREDOS D2-3, 2008
CREDOS EDDF-2 (2007)	~ 9,000	X/-	DVM	28 med/hvy	departure IGE/NGE	CREDOS D2-3, 2009
unpublished					cruise/arr. OGE/IGE	

Prediction Skill

deterministic scoring results

model with perfect (MET) data would be much better

	RMS $\Delta\Gamma_{5-15} / \Gamma_0$	RMS $\Delta z / b_0$	RMS $\Delta y / b_0$
best median	0.128	0.118	0.402
worst median	0.240	0.452	0.968

worst median	86 m²/s	17 m	34 m

P2P – References

- F. Holzäpfel, “Probabilistic Two-Phase Wake Vortex Decay and Transport Model”, J. Aircraft **40,** 323-331, 2003.
- F. Holzäpfel F., R.E. Robins, “Probabilistic Two-Phase Aircraft Wake-Vortex Model: Application and Assessment”, J. Aircraft **41**, 1117-1126, 2004.
- F. Holzäpfel, “Probabilistic Two-Phase Aircraft Wake-Vortex Model: Further Development and Assessment”, J. Aircraft **43**, 700-708, 2006.
- F. Holzäpfel, M. Steen, “Aircraft Wake-Vortex Evolution in Ground Proximity: Analysis and Parameterization”, AIAA J. **45**, 218-227, 2007.
- M. Frech, F. Holzäpfel, “Skill of an aircraft wake-vortex transport and decay model using short-term weather prediction and observation”, J. Aircraft **45**, 461-470, 2008.

WakeScene – Wake Vortex Scenarios Simulation Package (D - Departure / A - Arrival)

purpose: Monte Carlo simulation of departures and arrivals of aircraft pairings and estimation of frequency and severity of encounters

components: traffic mix
aircraft trajectories
meteorological conditions
WV transport and decay
encounter identification
statistical analysis

applications: VLTA, RECAT, WVAS,
sensitivity analysis, optimization, safety case

history

2003-04: concept for assessment of encounters behind B747 & A380 (PA, FL, FT, RM)

2004-05: WakeScene-A (PA, FL, FT, RM)
Aerosp. Sci. Techn. **13** 2009

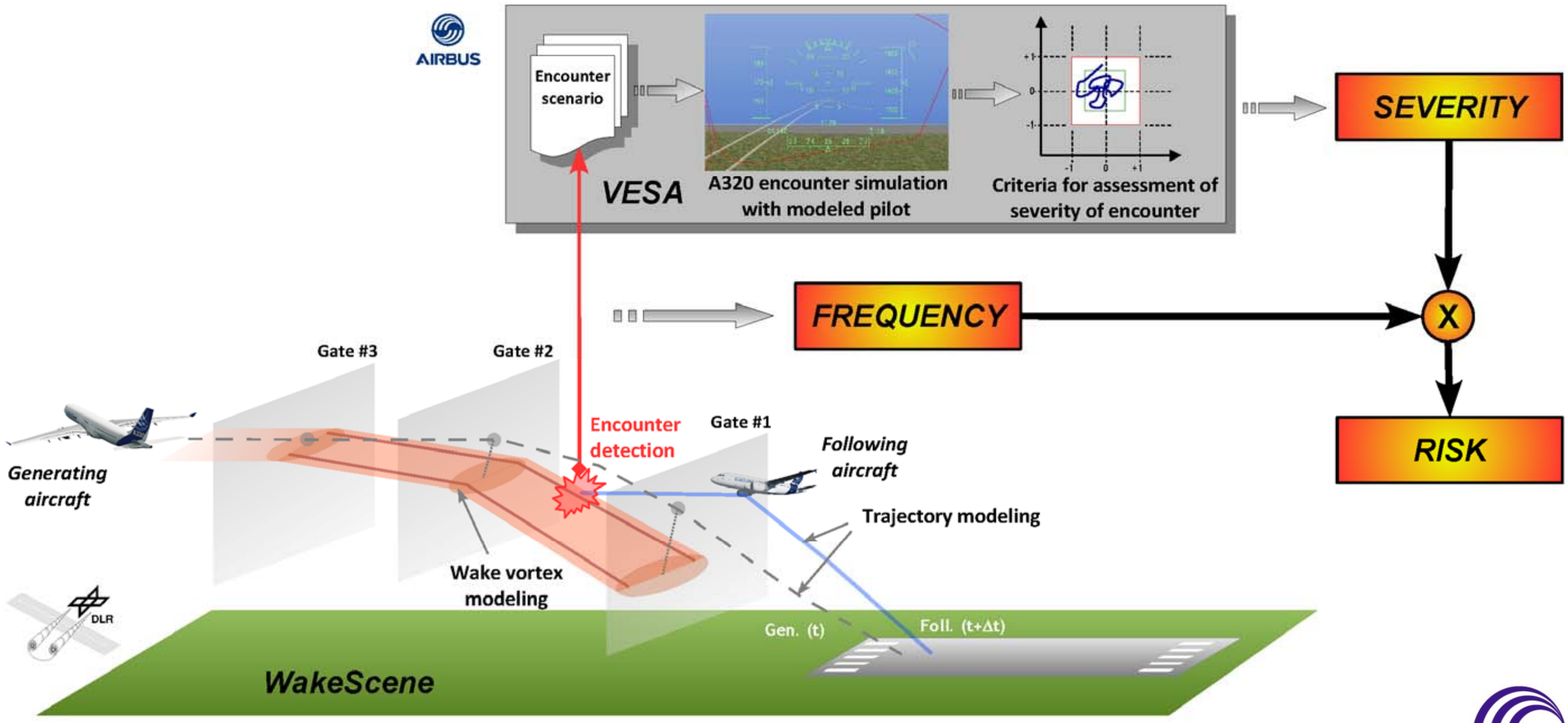
2006-09: WakeScene-D for CREDOS (PA, FL, FT, RM, AD, TUB, UCL)
J. Aircraft **46** 2009, J. Aircraft **48** 2011

2009-11: Wetter & Fliegen:
- Re-Categorization (PA, FL, FT, RM)
- risik analysis of WSVBS (PA, FL, FT, RM)

M. Frech, T. Gerz, A. Tafferner (PA), K.-U. Hahn, C. Schwarz (FT), H.-D. Joos, J. Kladetzke (RM), B. Korn, H. Lenz, G. Ringel (FL), S. Amelsberg, R. Luckner (TU Berlin), G. Höhne, S. Kauertz (Airbus), I. De Visscher, G. Winckelmans (UCL)

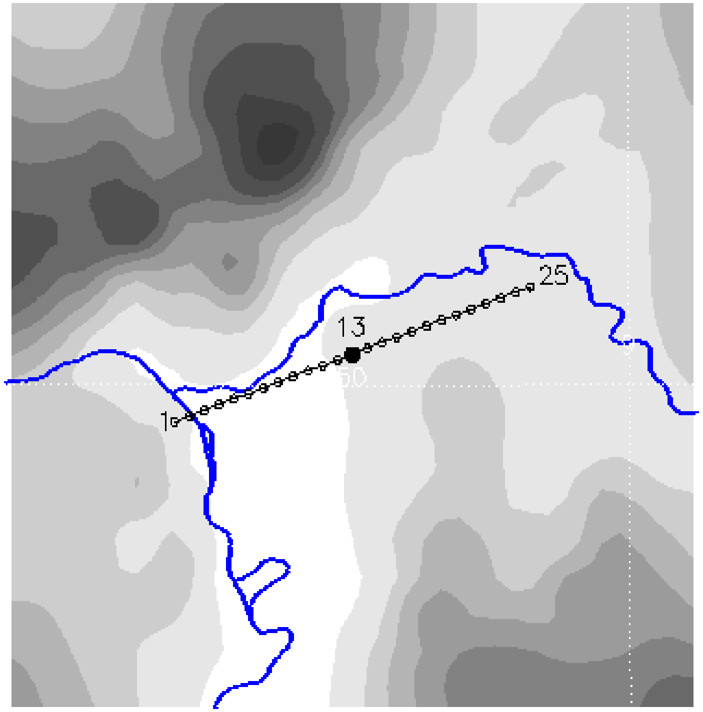
WakeScene-D – VESA-D

wake vortex scenarios simulation package – vortex encounter severity assessment



Meteorological Data Base - NOWVIV

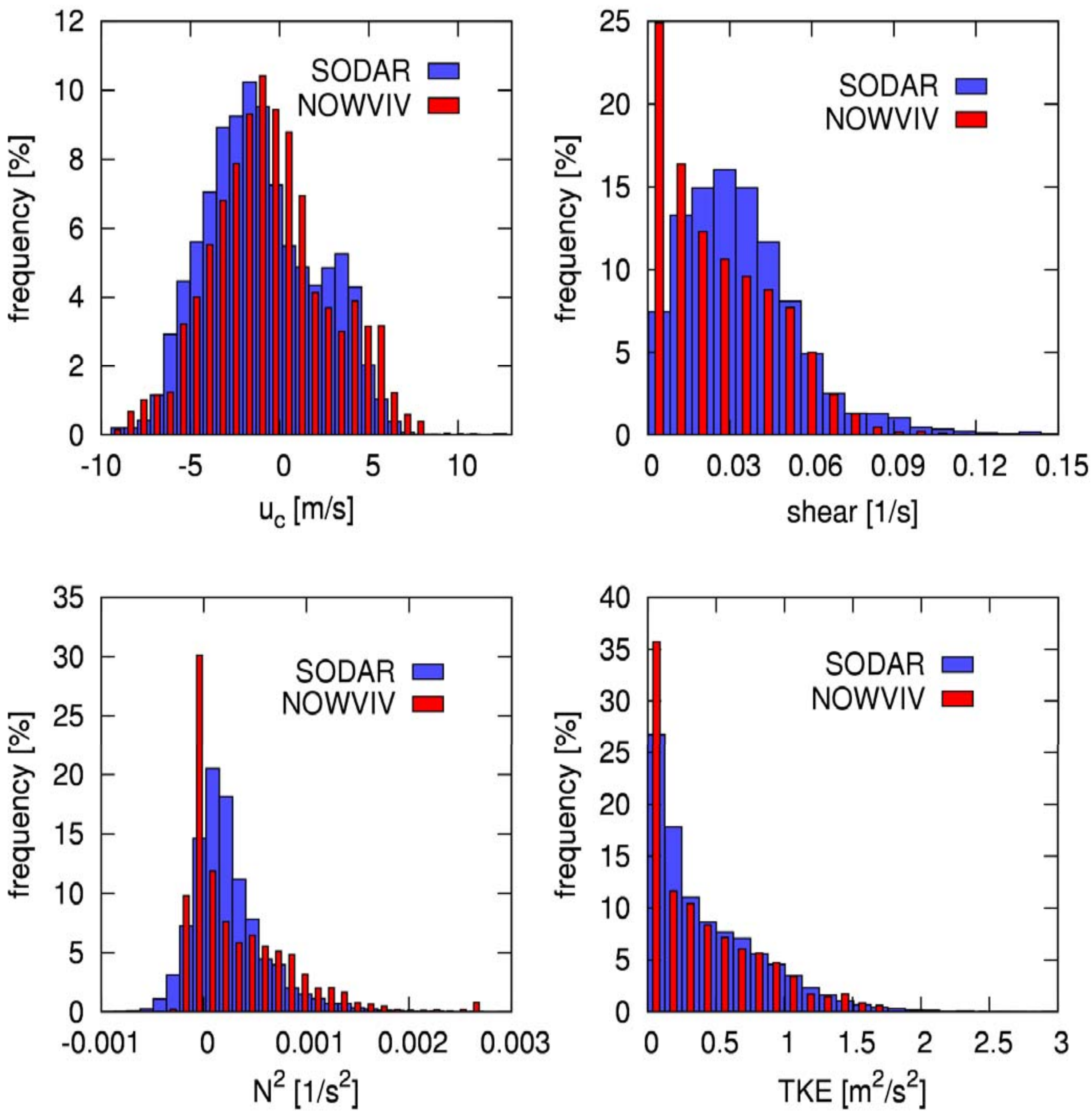
(NOWcasting wake-Vortex Impact Variables)



- 1.11.03 - 31.10.04
- initial and boundary data:
  data assimilation model LM
- 2 nests (250 x 250 km^2, Δ=6.3 km,
  90 x 90 km^2, Δ=2.1 km)
- 60 levels,
  $z < 1100$ m: $8 \text{ m} \leq \Delta z \leq 50$ m, 26 levels
- output frequency 10 min ($1.3 \cdot 10^6$ profiles)
- EDR direct model output or derived from TKE
- verified against:
  - climatological data
  - measurement data (26.8.04 - 5.10.04)
  - 2 case studies

Frech et al., J. Appl. Meteor. Climat. **46** 2007

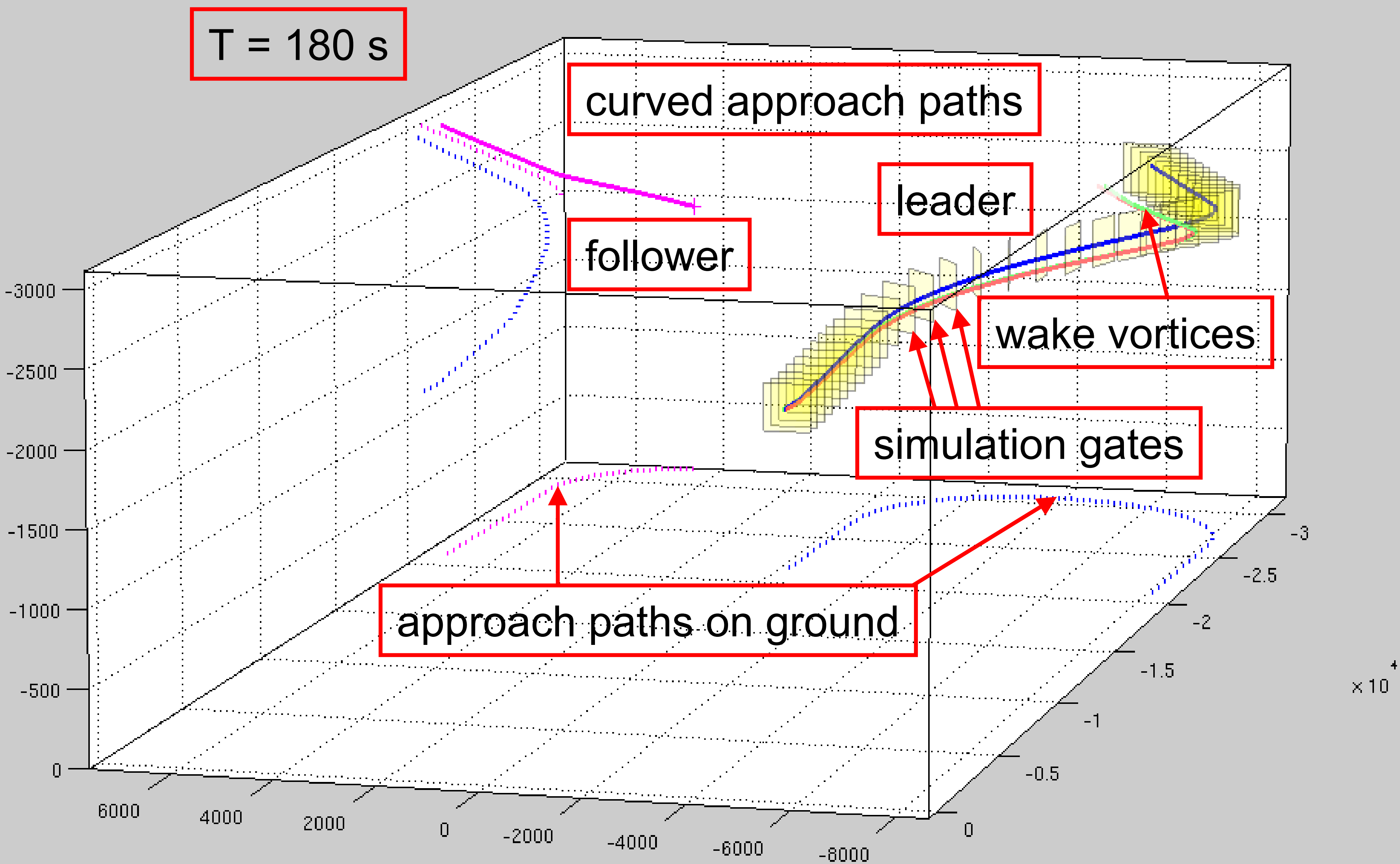
Meteorological Data Base – Validation



40 days
z = 100 m

WakeScene-D / 26-May-2011 / Nowviv-file: 200408060910, Generator: B744, Follower: B733, WV model: D2P

WakeScene-A

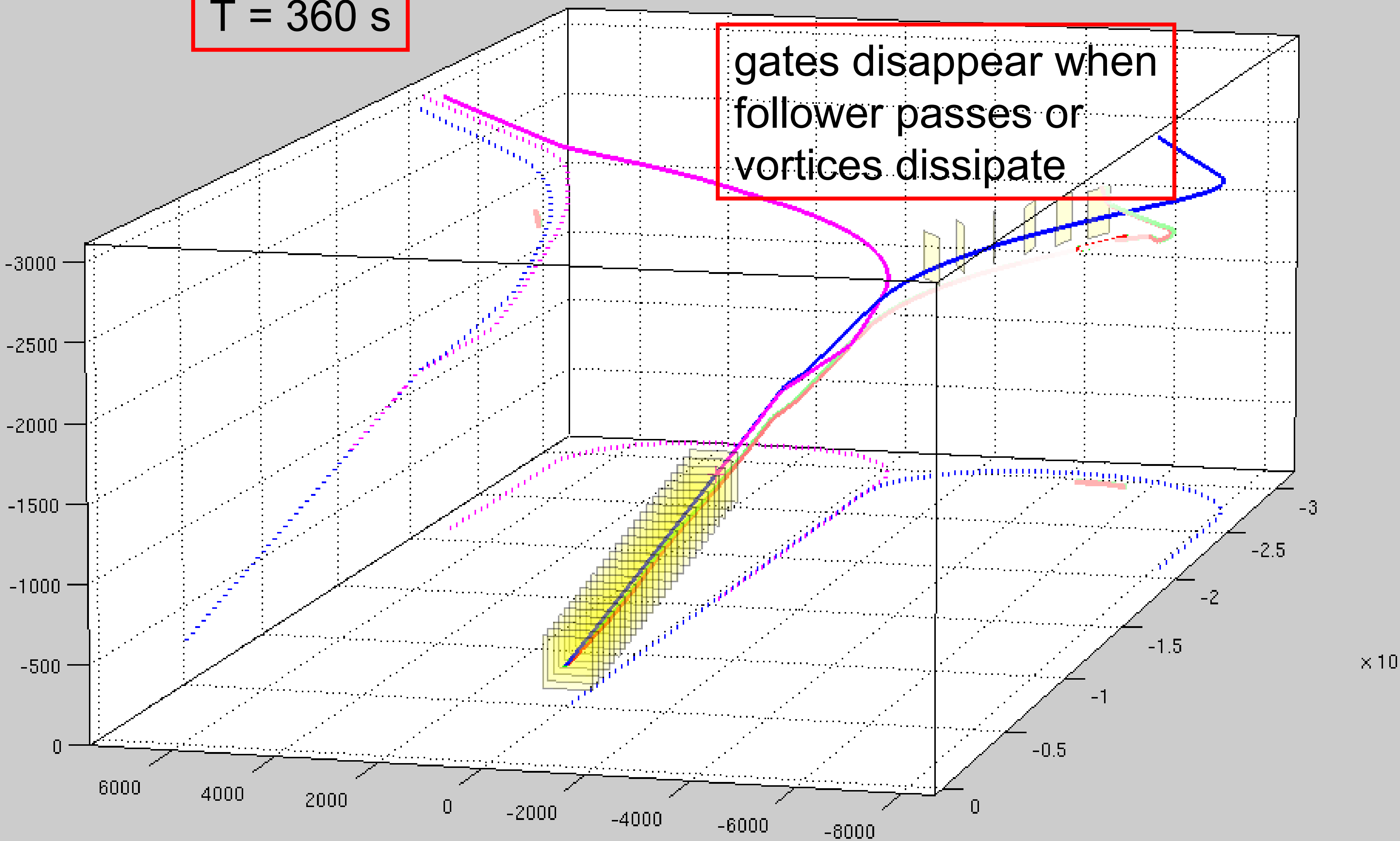


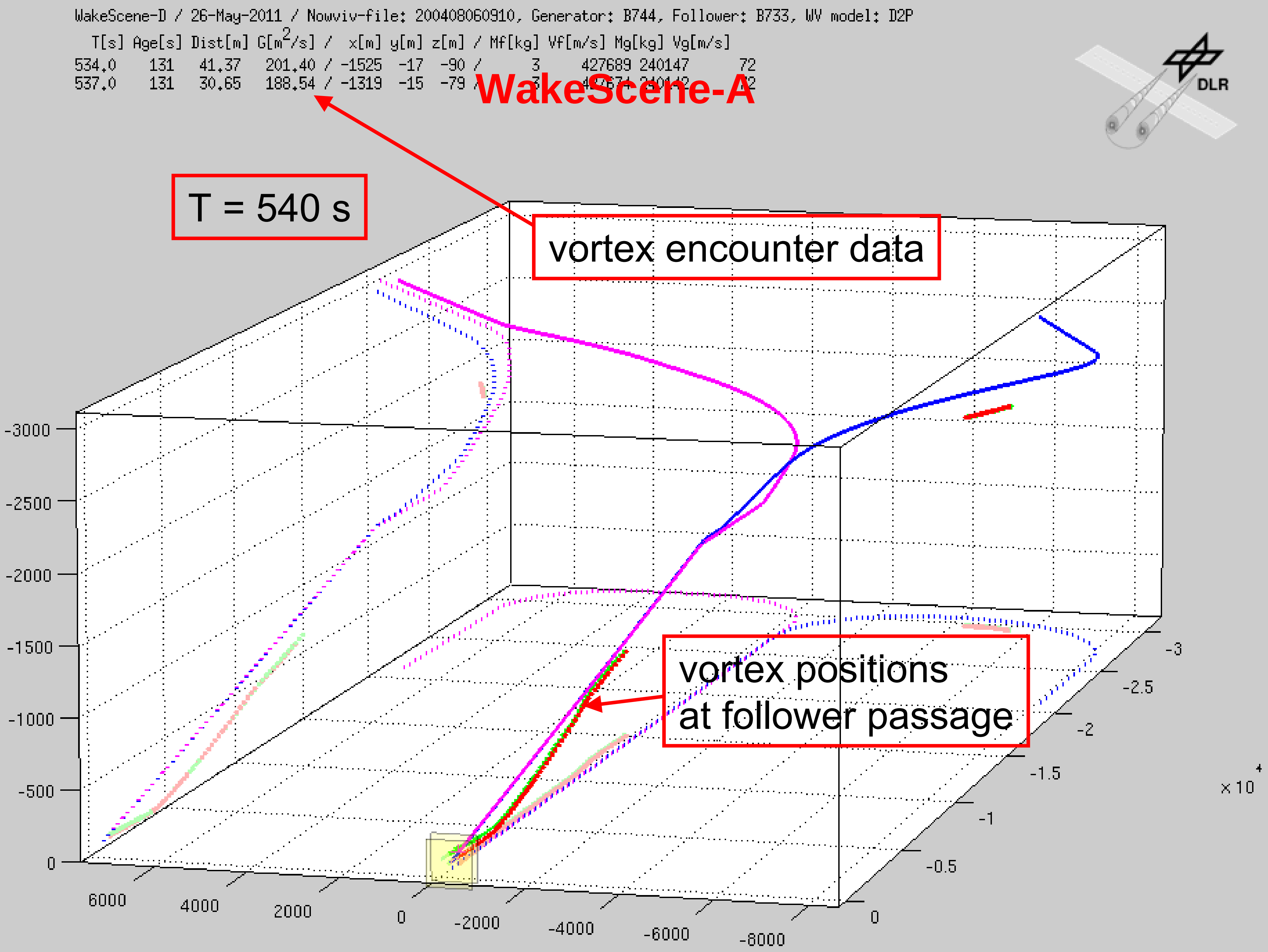
WakeScene-D / 26-May-2011 / Nowviv-file: 200408060910, Generator: B744, Follower: B733, WV model: D2P

WakeScene-A

T = 360 s

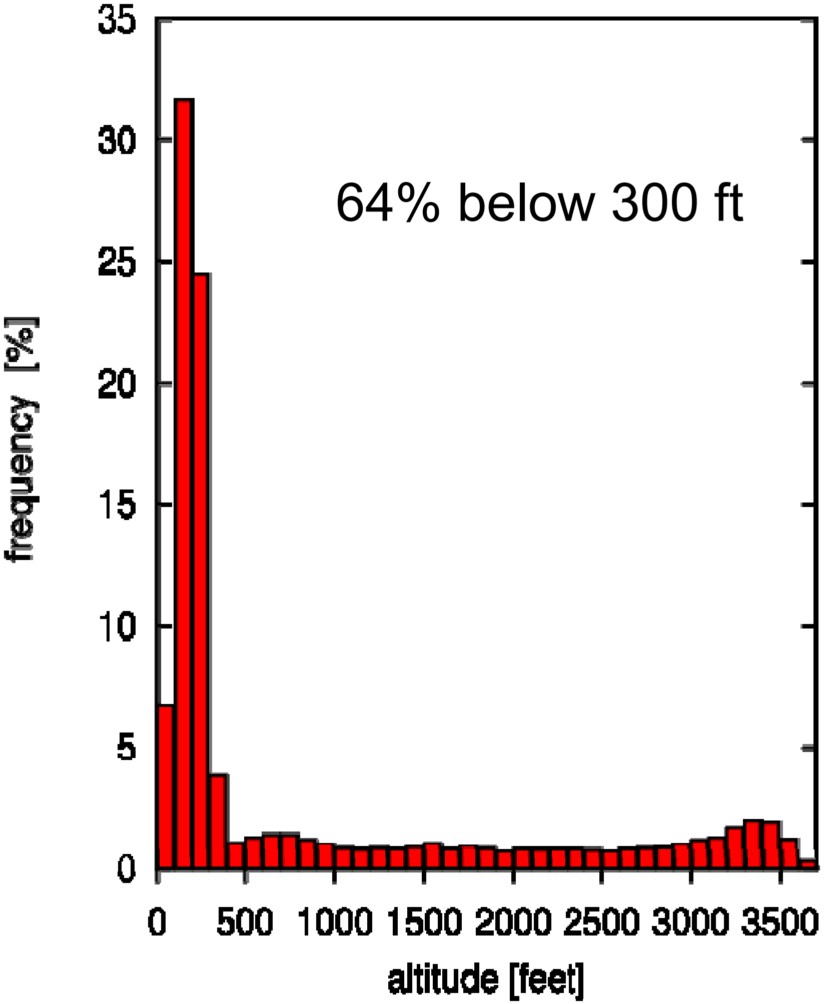
gates disappear when follower passes or vortices dissipate



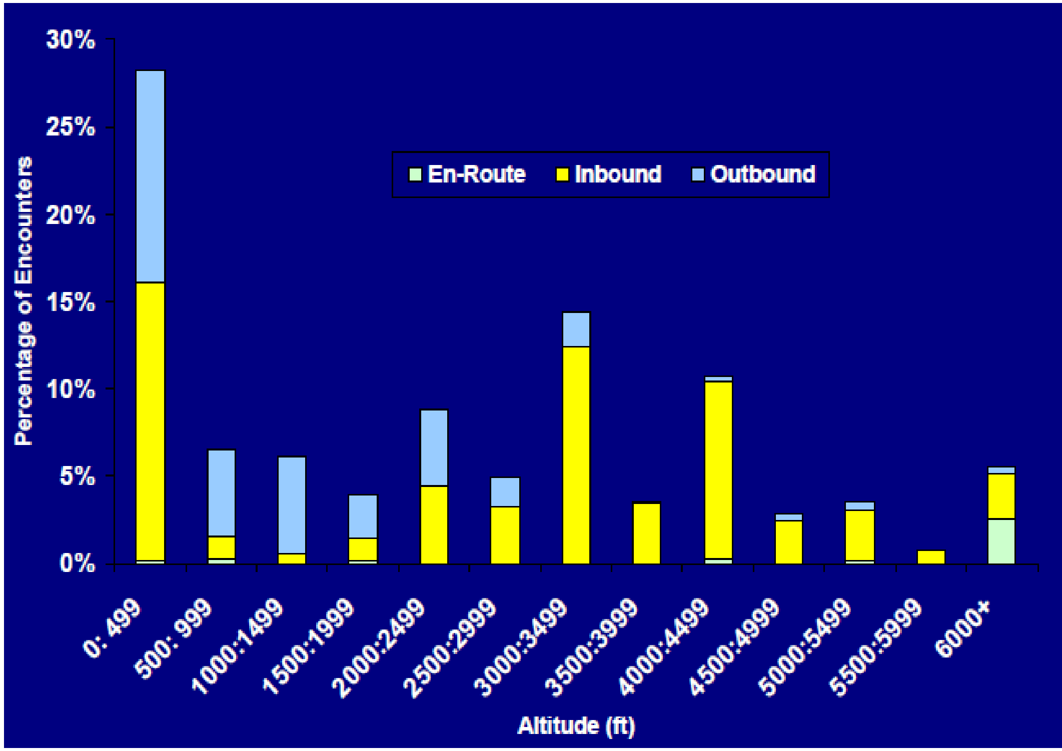


WakeScene-D / 26-May-2011 / Nowviv-file: 200408060910, Generator: B744, Follower: B733, WV model: D2P
T[s] Age[s] Dist[m] G[m2/s] / x[m] y[m] z[m] / Mf[kg] Vf[m/s] Mg[kg] Vg[m/s]
534.0 131 41.37 201.40 / -1525 -17 -90 / 3 427689 240147 72
537.0 131 30.65 188.54 / -1319 -15 -79 /
WakeScene-A
DLR
T = 540 s
vortex encounter data
vortex positions at follower passage
-3000
-2500
-2000
-1500
-1000
-500
0
6000
4000
2000
0
-2000
-4000
-6000
-8000
0
-0.5
-1
-1.5
-2
-2.5
-3
x 10
4

statistics – encounter height



100.000 approaches, leader B747,
follower A320, VFW614,
5 NM separation, full meteo, D2P



NATS: reported encounters 2000 to 2004

WakeScene-D
CREDOS setup

- from RWY along 5 standard departure routes up to 3000 ft
- generator a/c: A306, A310, A333, A343, B744, B772
- follower a/c: A320, AT45, B733, CRJ (FRA traffic mix)
- aircraft trajectory model (3 DoF, stochastic variation of 6 parameters)
- 1-year statistics of meteo conditions for Frankfurt airport (NOWVIV)
- 2 wake-vortex prediction models (D2P, DVM)
- identification of potential encounters
- convenient control, interpolation, statistical, and graphical evaluation capabilities of MCS (MOPS)
- interface to VESA

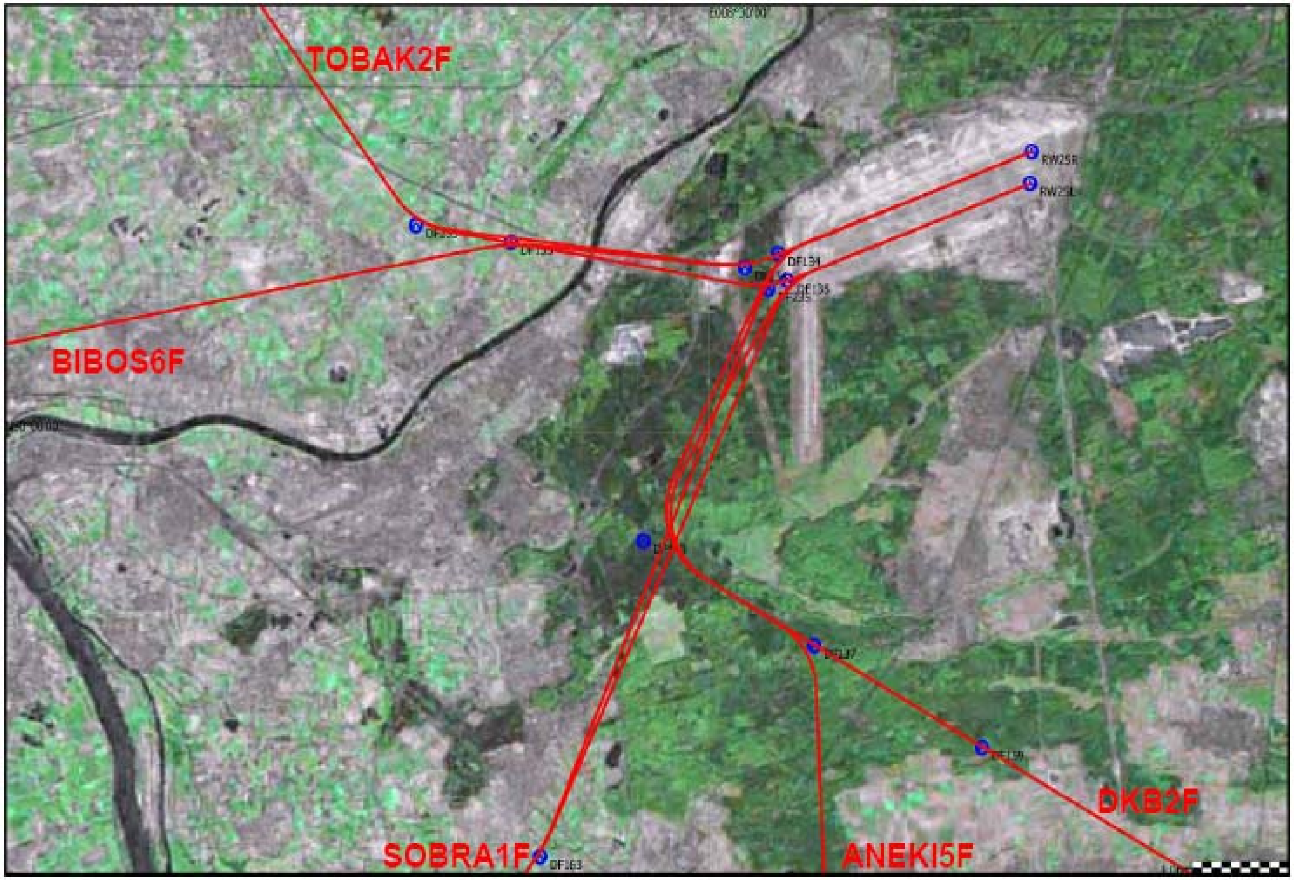
Technische Universität Berlin

UCL Université catholique de Louvain

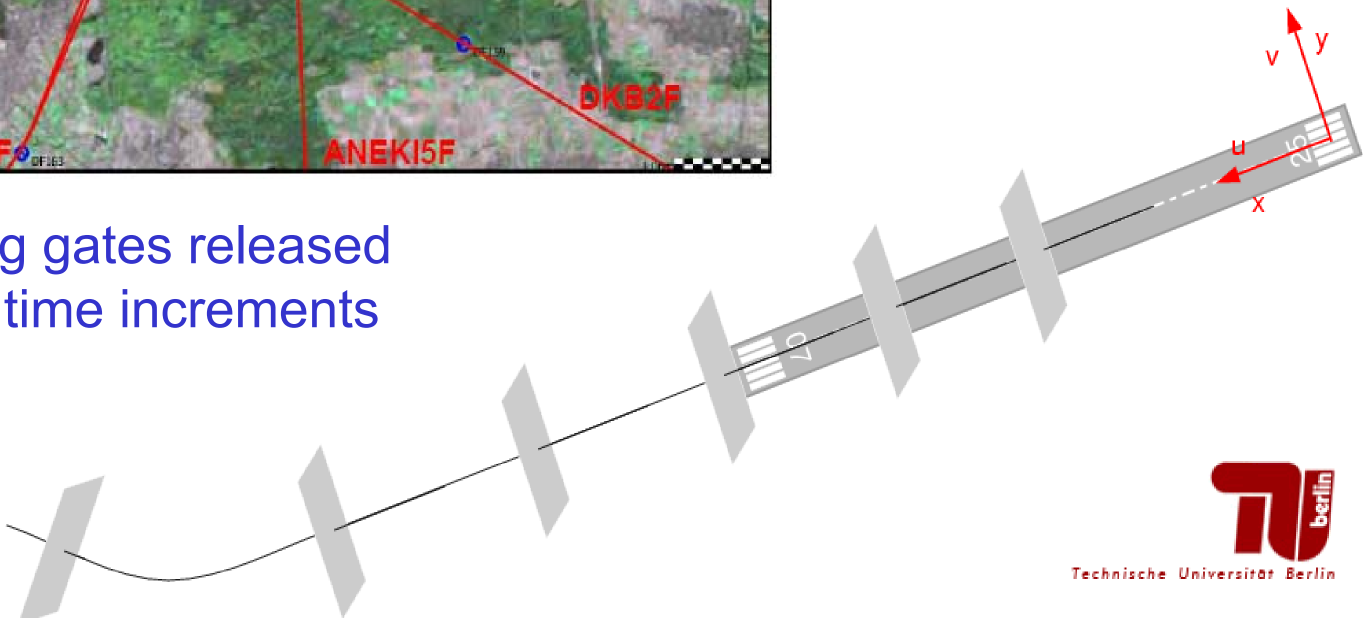
CREDOS

DLR

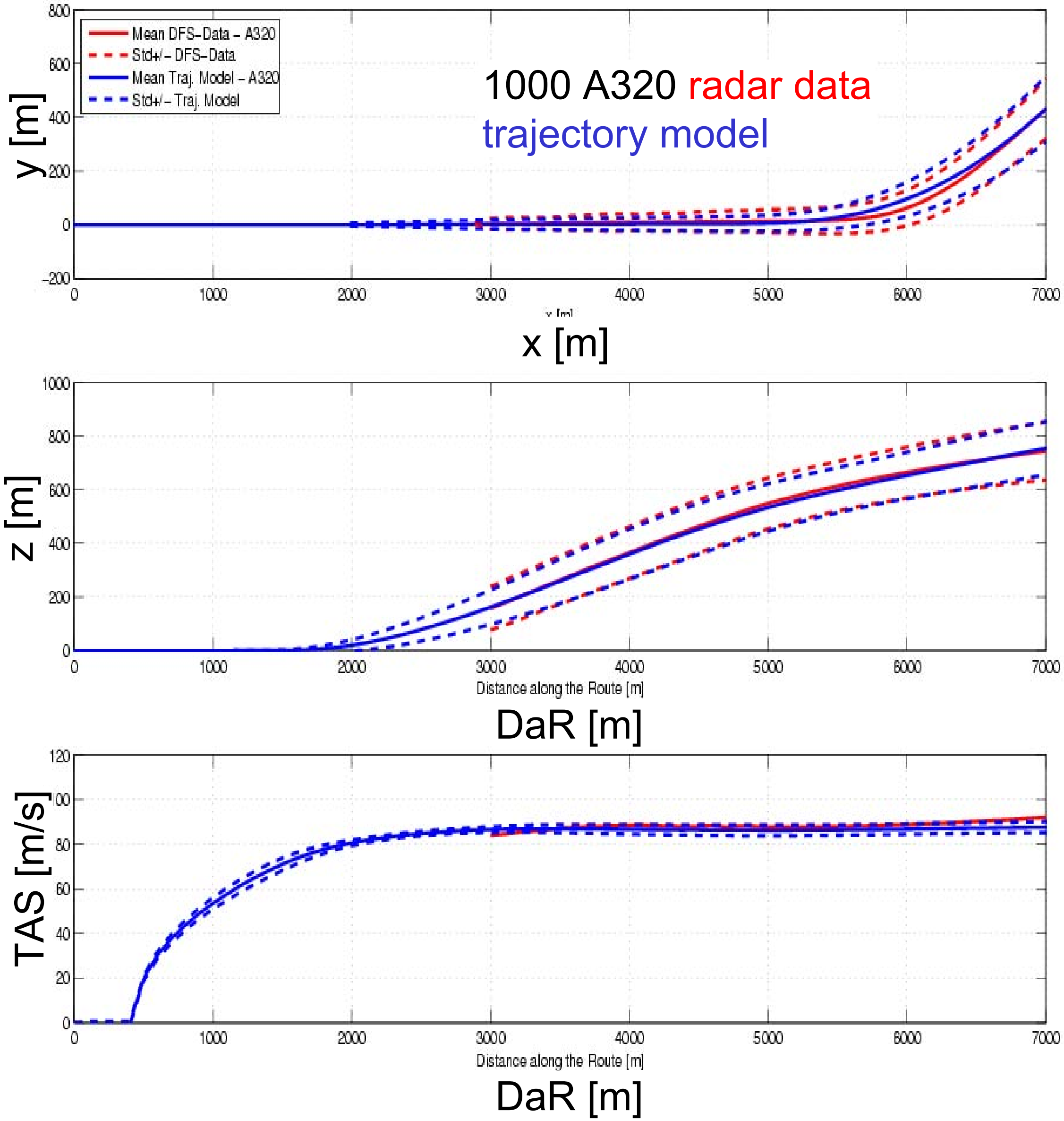
departure routes



control gates



inclined and moving gates released along flight path in time increments of e.g. 5 s

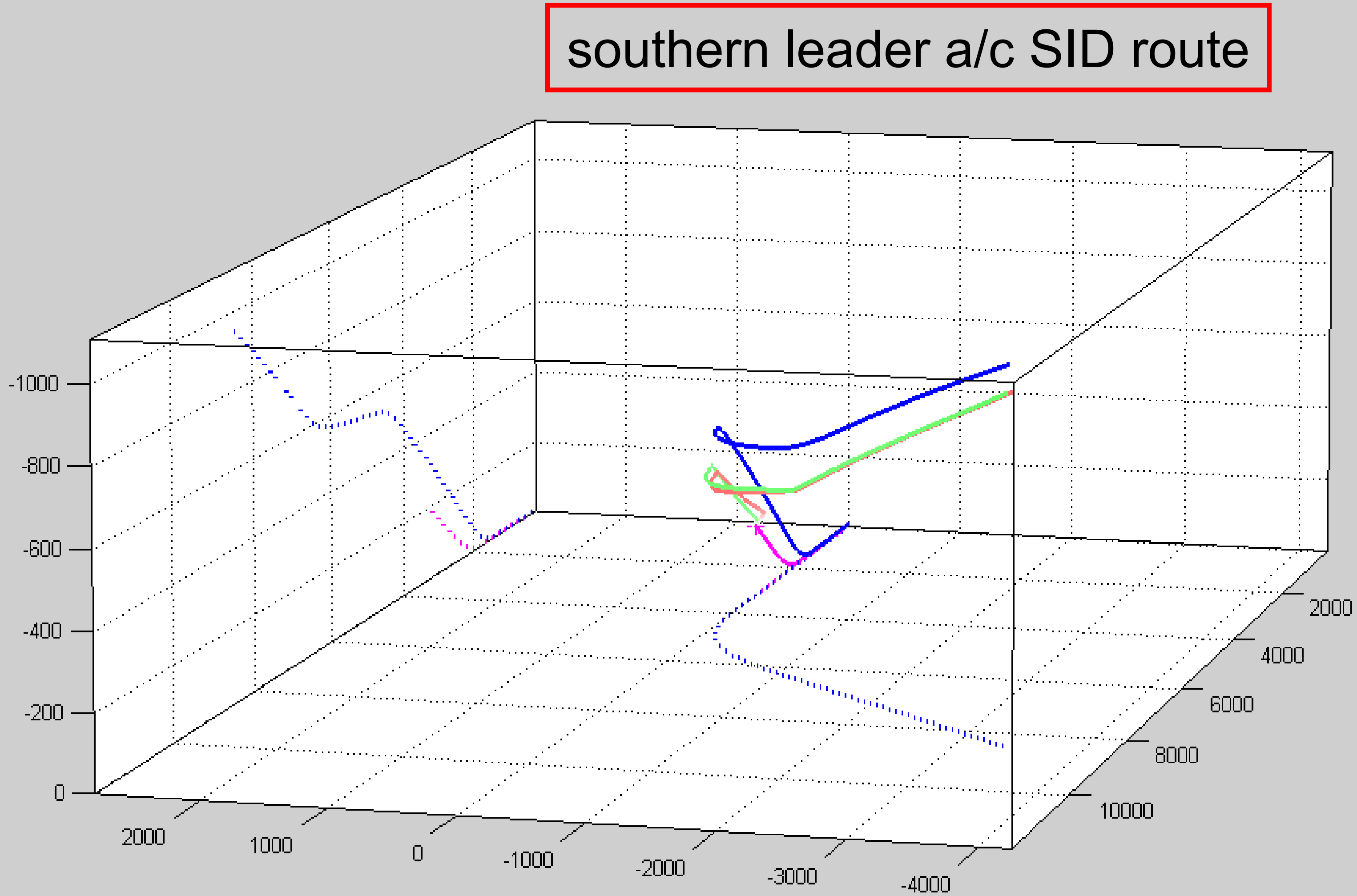


A/C Trajectory Model

- database of
  aircraft parameters,
  nominal departure routes,
  meteo conditions
- (auto) pilot model
- 3DoF point mass model

A306-A320, weak crosswind, late fol take-off

WakeScene-D / 01-Oct-2009 / Nowviv-file: 200311270920, Generator: A306, Follower: A320, WV model: D2P

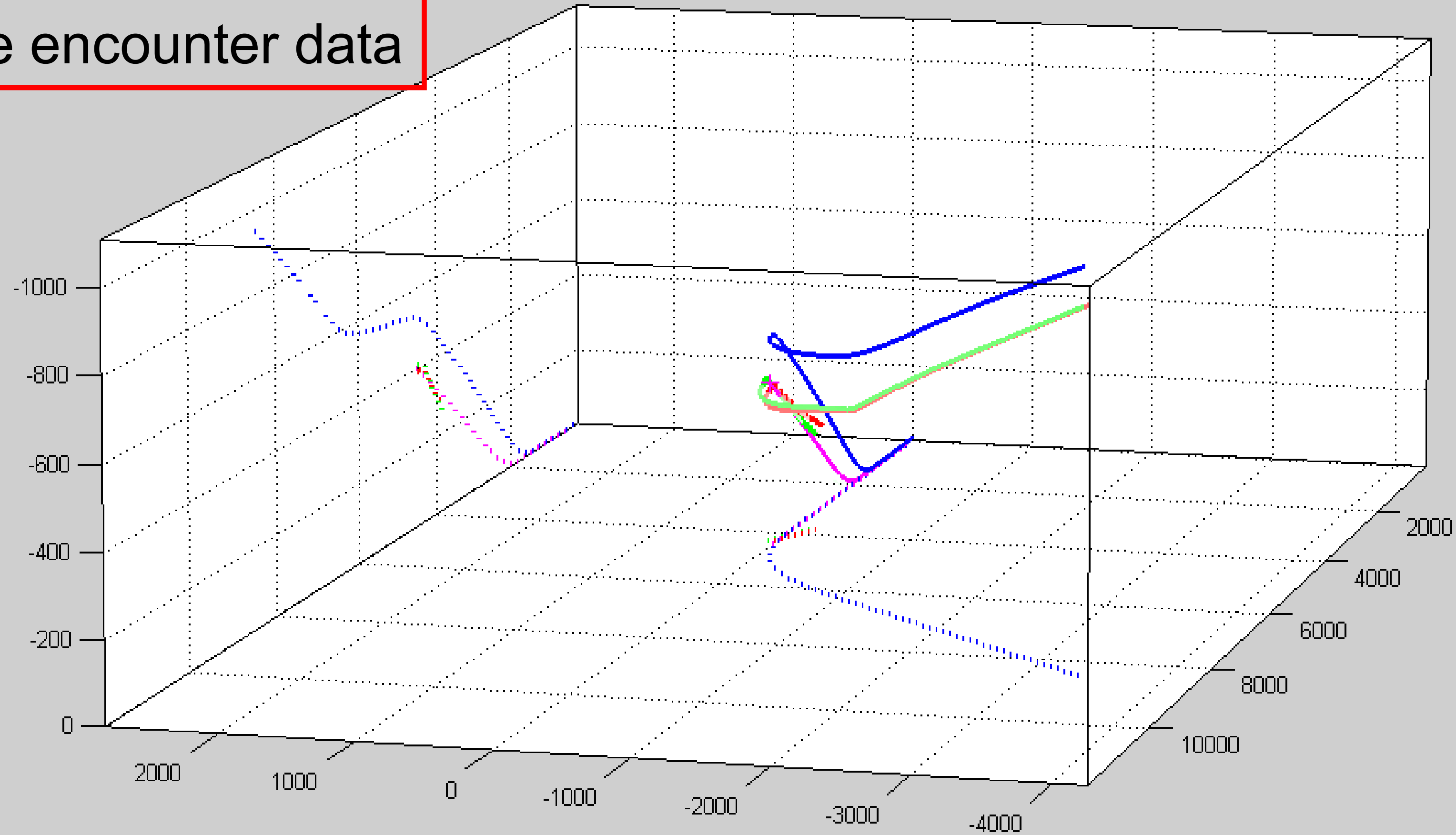


A306-A320, weak crosswind, late fol take-off

WakeScene-D / 01-Oct-2009 / Nowviv-file: 200311270920, Generator: A306, Follower: A320, WV model: D2P

T[s]	Age[s]	Dist[m]	G[m²/s]	/	x[m]	y[m]	z[m]	/	Mf[kg]	Vf[m/s]	Mg[kg]	Vg[m/s]
186.5	119	46.89	-179.35	/	4118	-10	-334	/	71011	83	141450	83
187.2	119	18.69	-188.89	/	4176	-10	-344	/	71009	83	141445	83
187.9	119	12.46	-198.42	/	4234	-10	-353	/	71007	83	141441	83
188.6	119	12.15	207.96	/	4292	-11	-362	/	71005	83	141437	83
188.6	119	12.15	207.96	/	4292	-11	-362	/	71005	83	141437	83
189.3	119	21.41	217.50	/	4350	-11	-371	/	71003	83	141433	84
190.7	119	14.96	212.68	/	4467	-11	-390	/	71000	83	141427	84
191.4	119	13.13	207.39	/	4525	-11	-399	/	70998	83	141424	85
191.4	119	13.13	207.39	/	4525	-11	-399	/	70998	83	141424	85

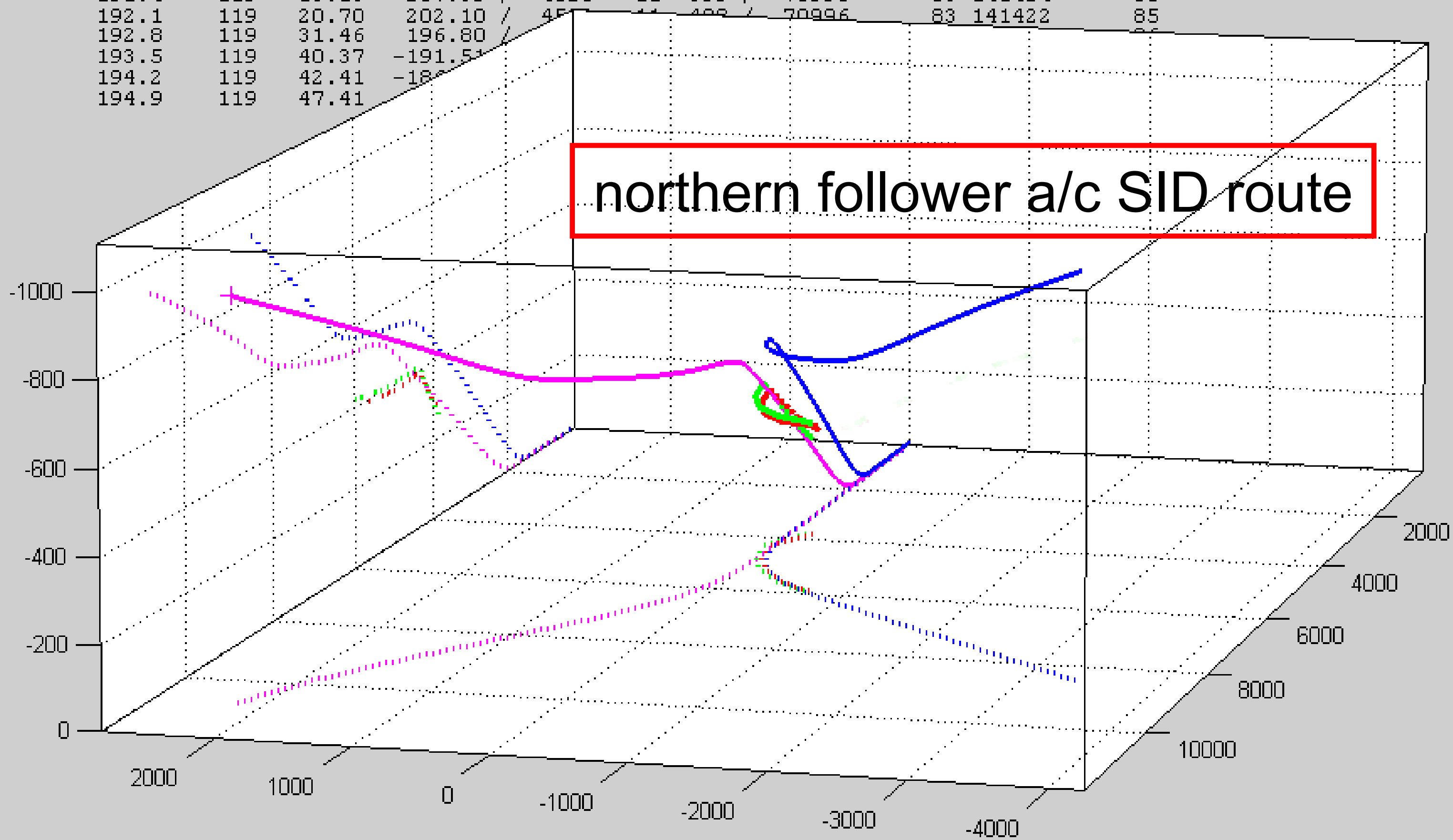
wake encounter data



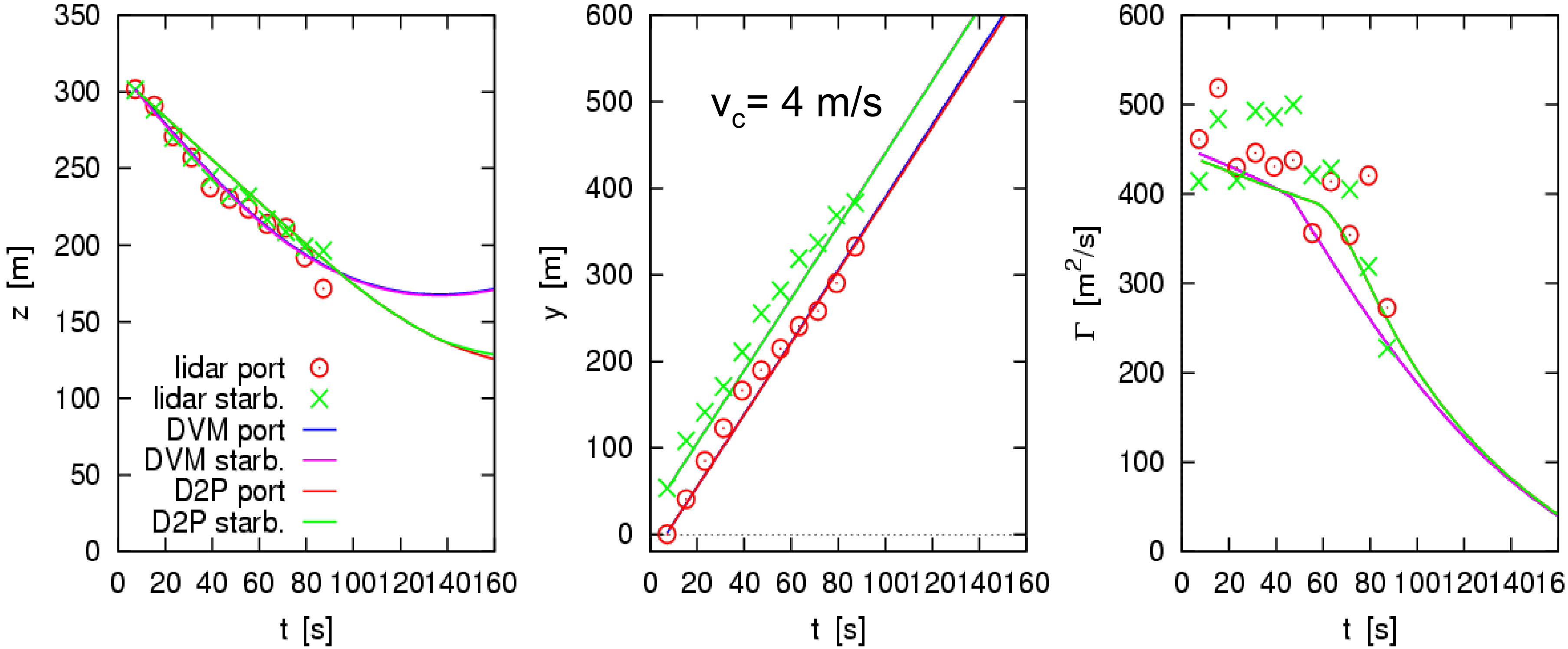
A306-A320, weak crosswind, late fol take-off

WakeScene-D / 01-Oct-2009 / Nowviv-file: 200311270920, Generator: A306, Follower: A320, WV model: D2P

T[s]	Age[s]	Dist[m]	G[m^2/s]	/	x[m]	y[m]	z[m]	/	Mf[kg]	Vf[m/s]	Mg[kg]	Vg[m/s]
186.5	119	46.89	-179.35	/	4118	-10	-334	/	71011	83	141450	83
187.2	119	18.69	-188.89	/	4176	-10	-344	/	71009	83	141445	83
187.9	119	12.46	-198.42	/	4234	-10	-353	/	71007	83	141441	83
188.6	119	12.15	207.96	/	4292	-11	-362	/	71005	83	141437	83
188.6	119	12.15	207.96	/	4292	-11	-362	/	71005	83	141437	83
189.3	119	21.41	217.50	/	4350	-11	-371	/	71003	83	141433	84
190.7	119	14.96	212.68	/	4467	-11	-390	/	71000	83	141427	84
191.4	119	13.13	207.39	/	4525	-11	-399	/	70998	83	141424	85
191.4	119	13.13	207.39	/	4525	-11	-399	/	70998	83	141424	85
192.1	119	20.70	202.10	/	[illegible]	[illegible]	[illegible]	/	[illegible]	83	141422	85
192.8	119	31.46	196.80	/	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
193.5	119	40.37	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
194.2	119	42.41	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
194.9	119	47.41	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]



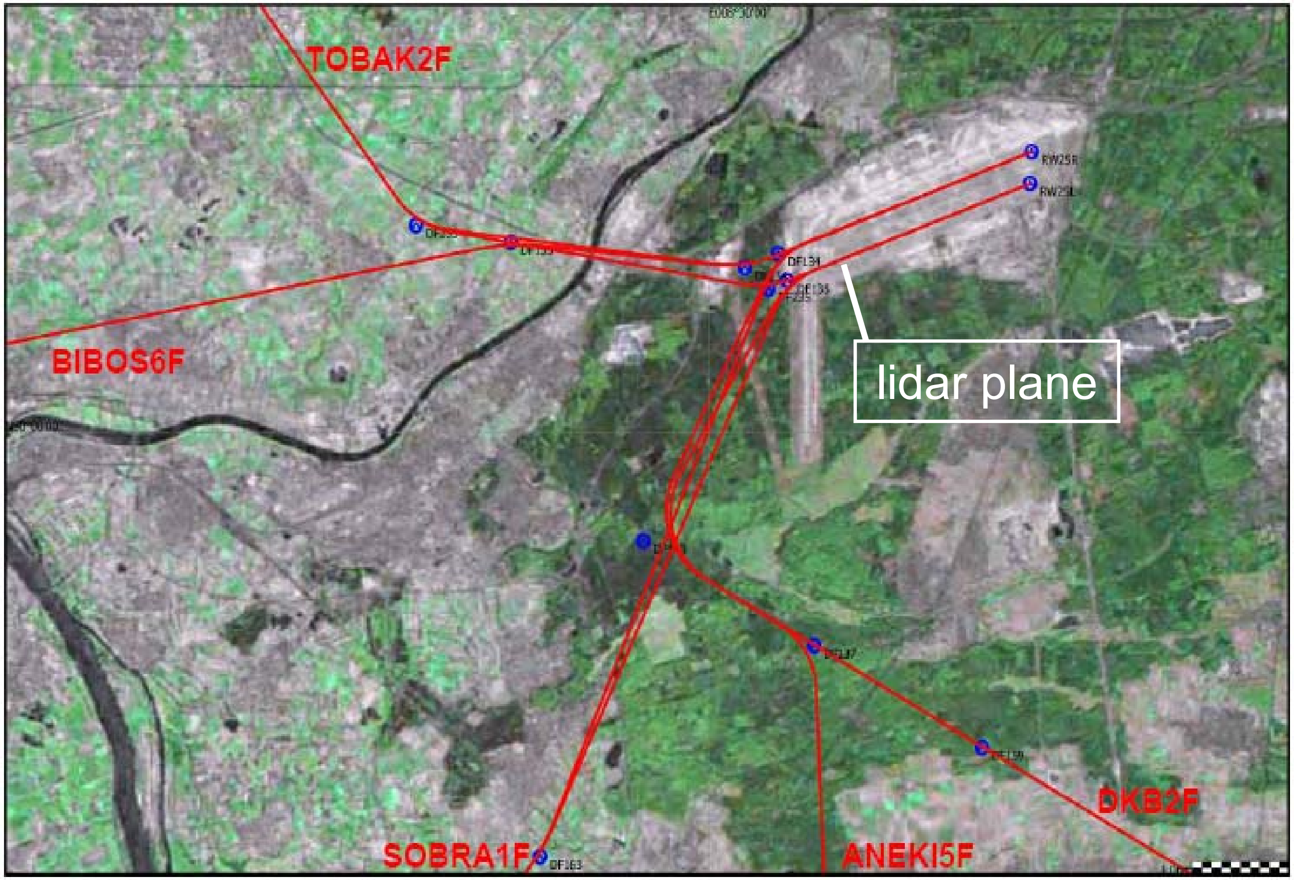
Wake Vortex Models – D2P & DVM (in CREDOS)



input data: • **a/c:** $x_0, y_0, z_0, \gamma, \Phi, V, L, b$

• **meteo:** $u(z), v(z), w(z), \rho(z), q(z), \varepsilon(z), \theta(z)$

departure routes



control gates

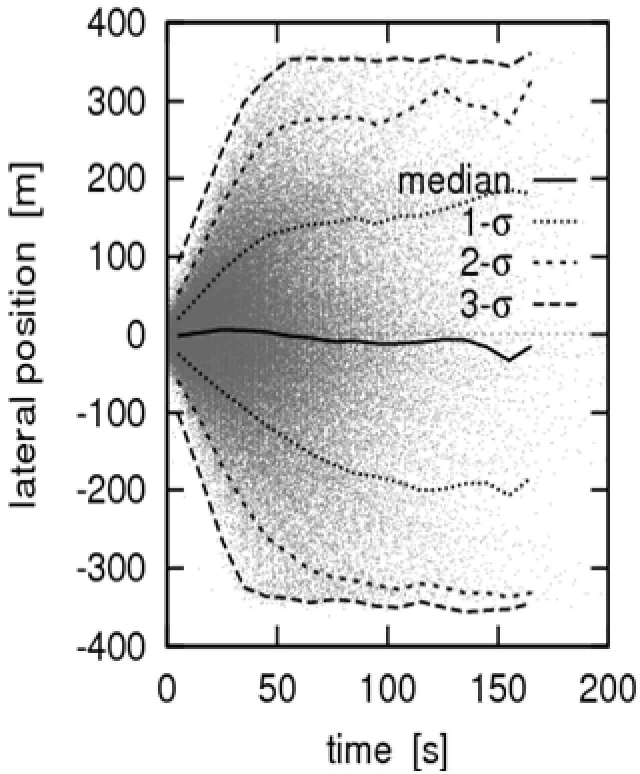
inclined and moving gates released along flight path in time increments of e.g. 5 s

WakeScene-D ⇔ field measurements EDDF-2

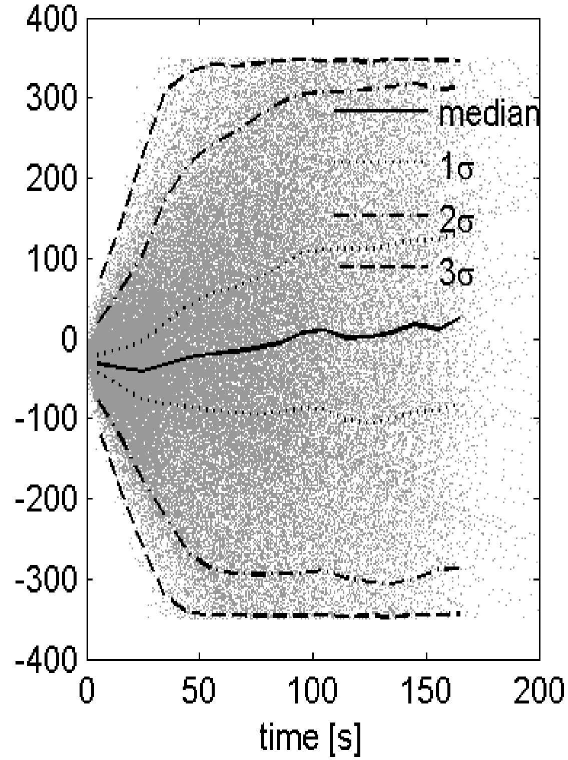
lateral WV transport in Lidar plane (~10.000 departures)

EDDF-2

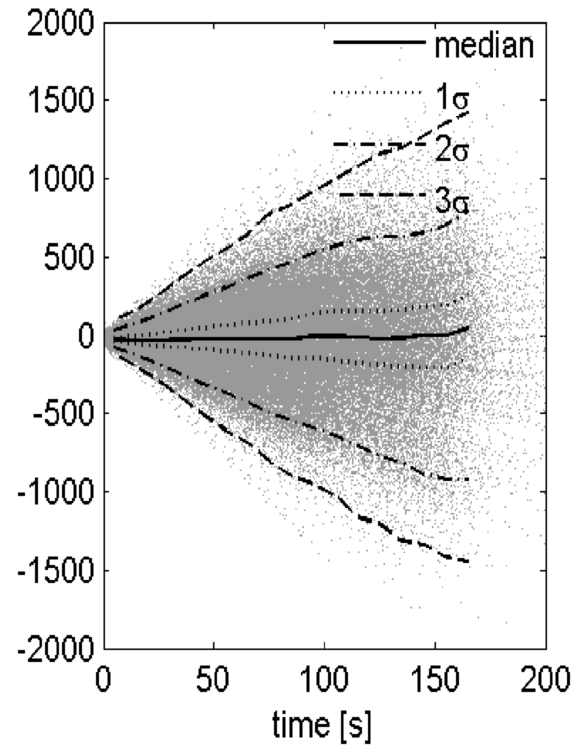
WakeScene-D



measurement domain



zoom on lidar domain

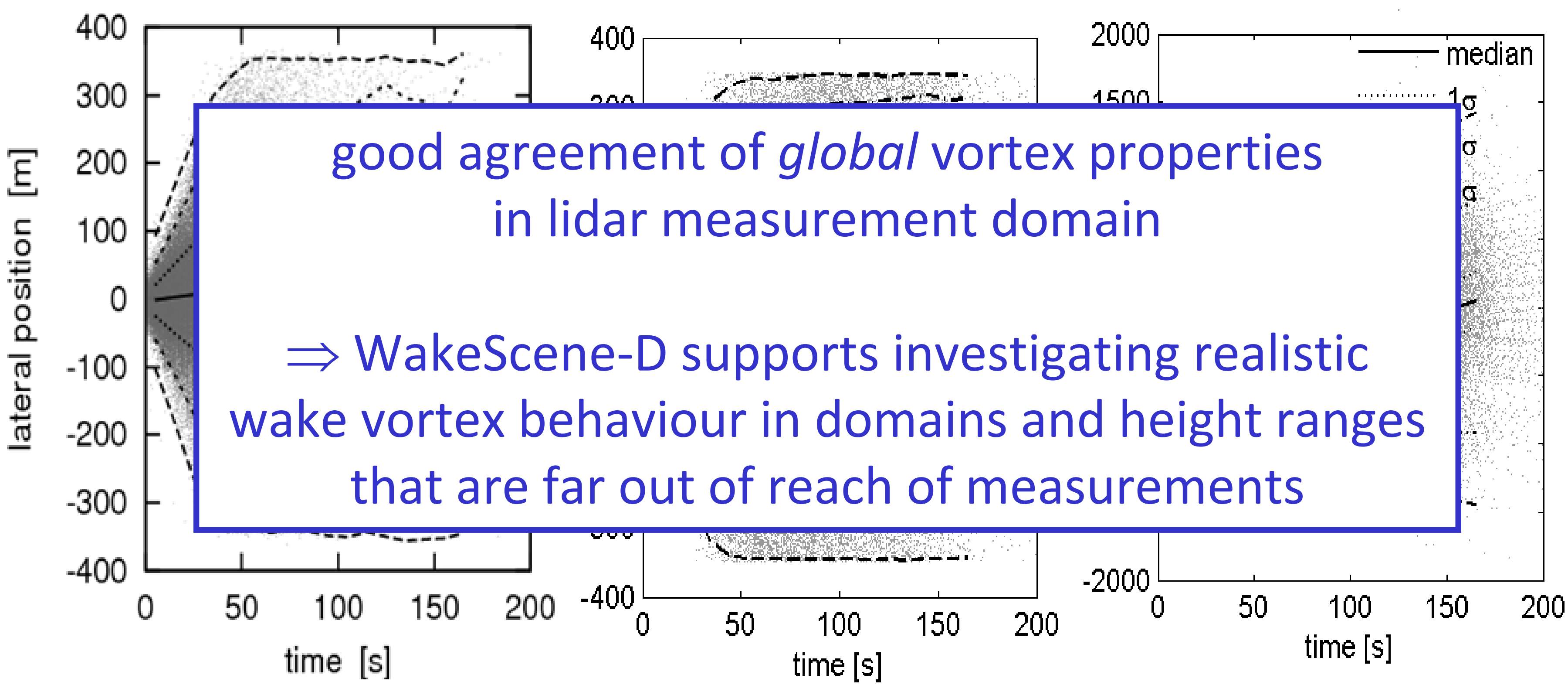


full domain

WakeScene-D ⇔ field measurements EDDF-2

lateral WV transport in Lidar plane (~10.000 departures)

EDDF-2 WakeScene-D

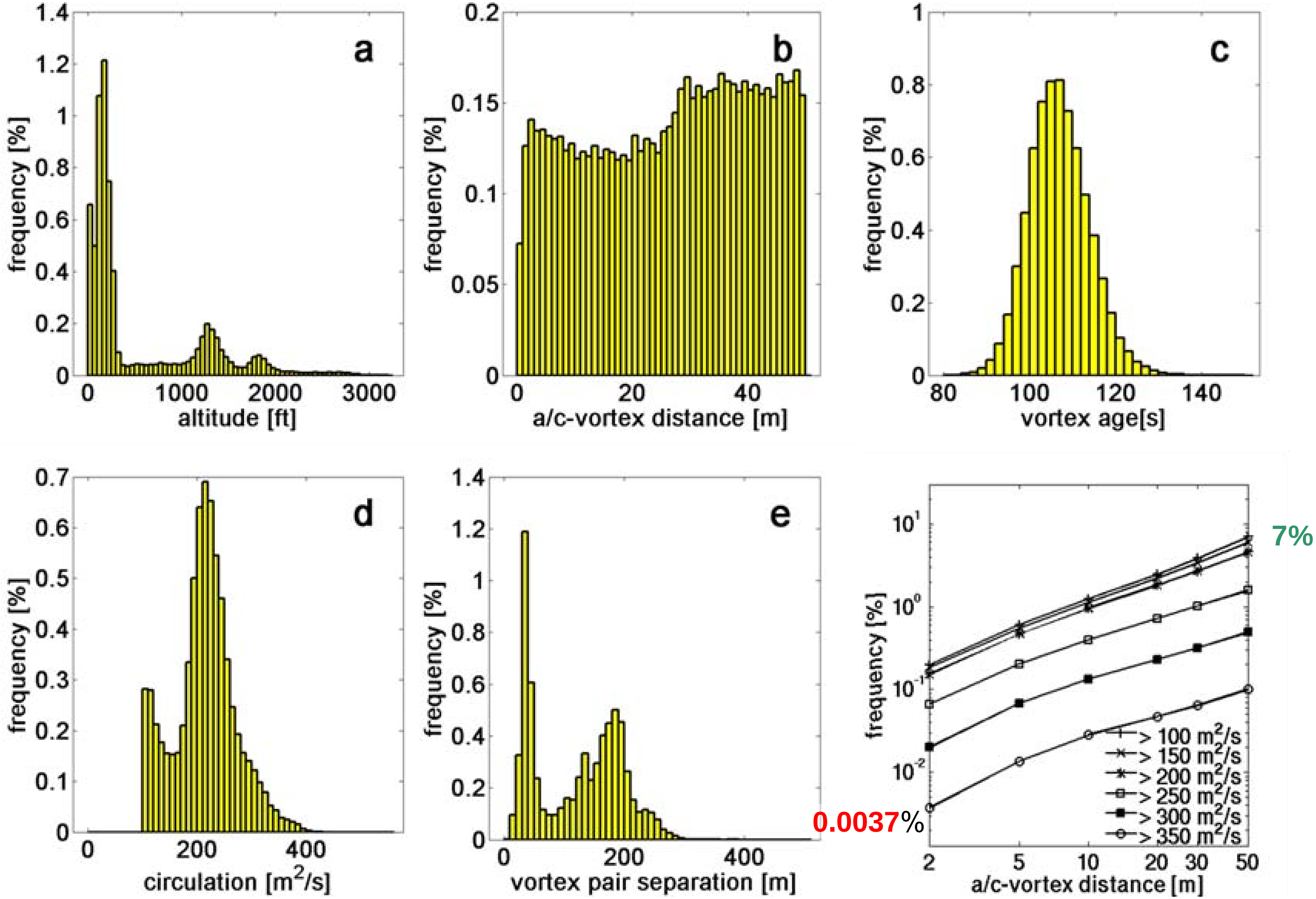


good agreement of *global* vortex properties
in lidar measurement domain

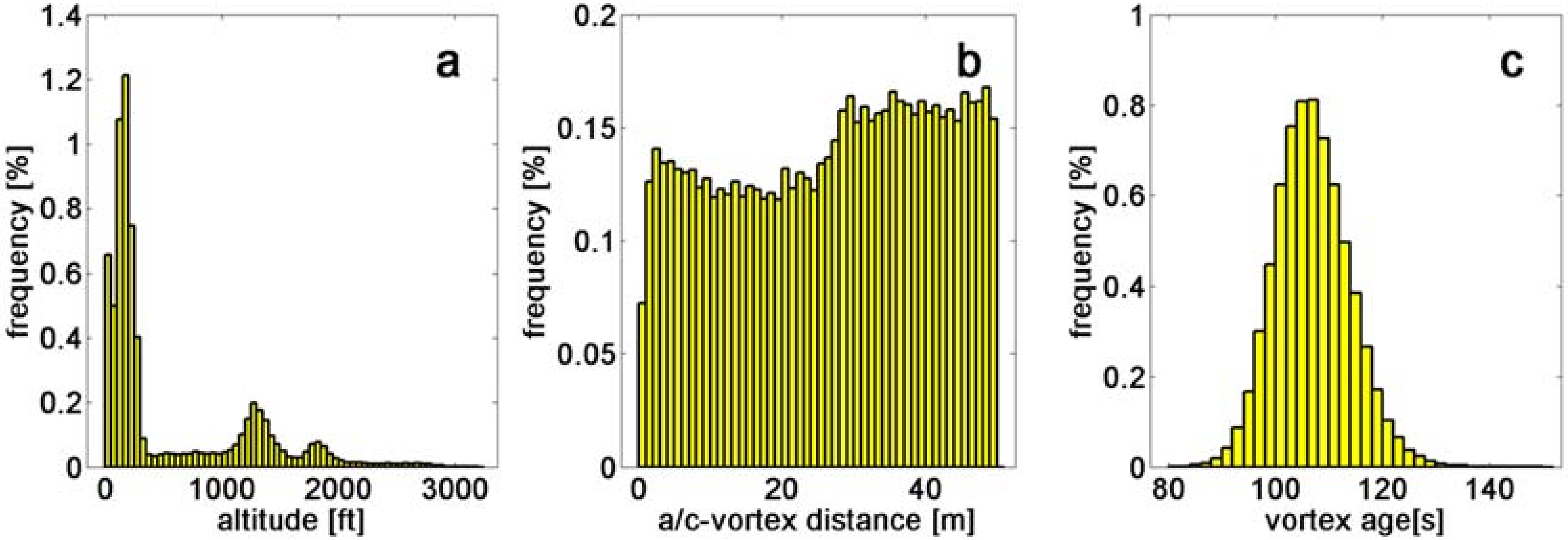
⇒ WakeScene-D supports investigating realistic
wake vortex behaviour in domains and height ranges
that are far out of reach of measurements

measurement domain zoom on lidar domain full domain

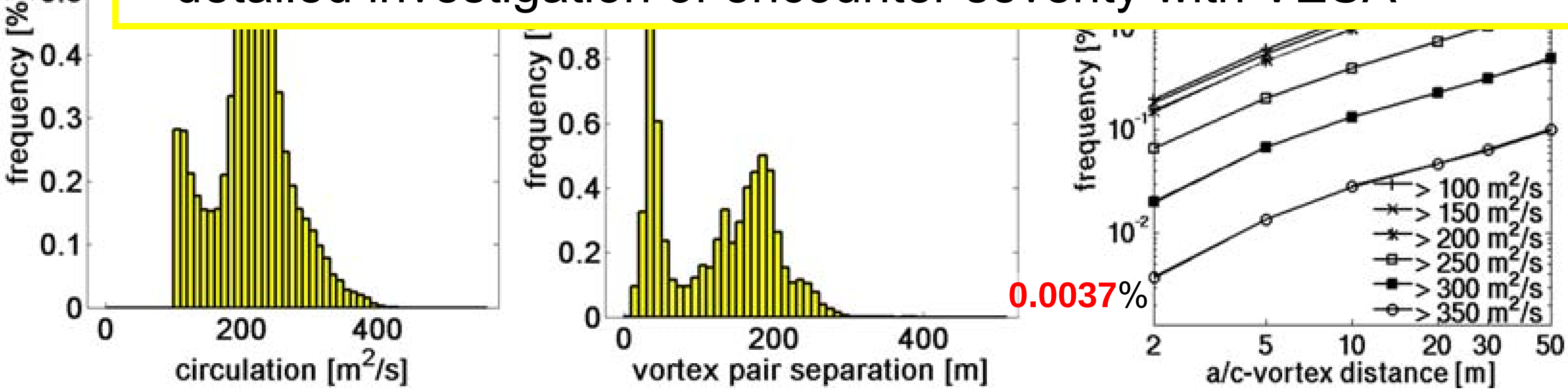
CREDOS reference scenario (120 s separation)



CREDOS reference scenario (120 s separation)

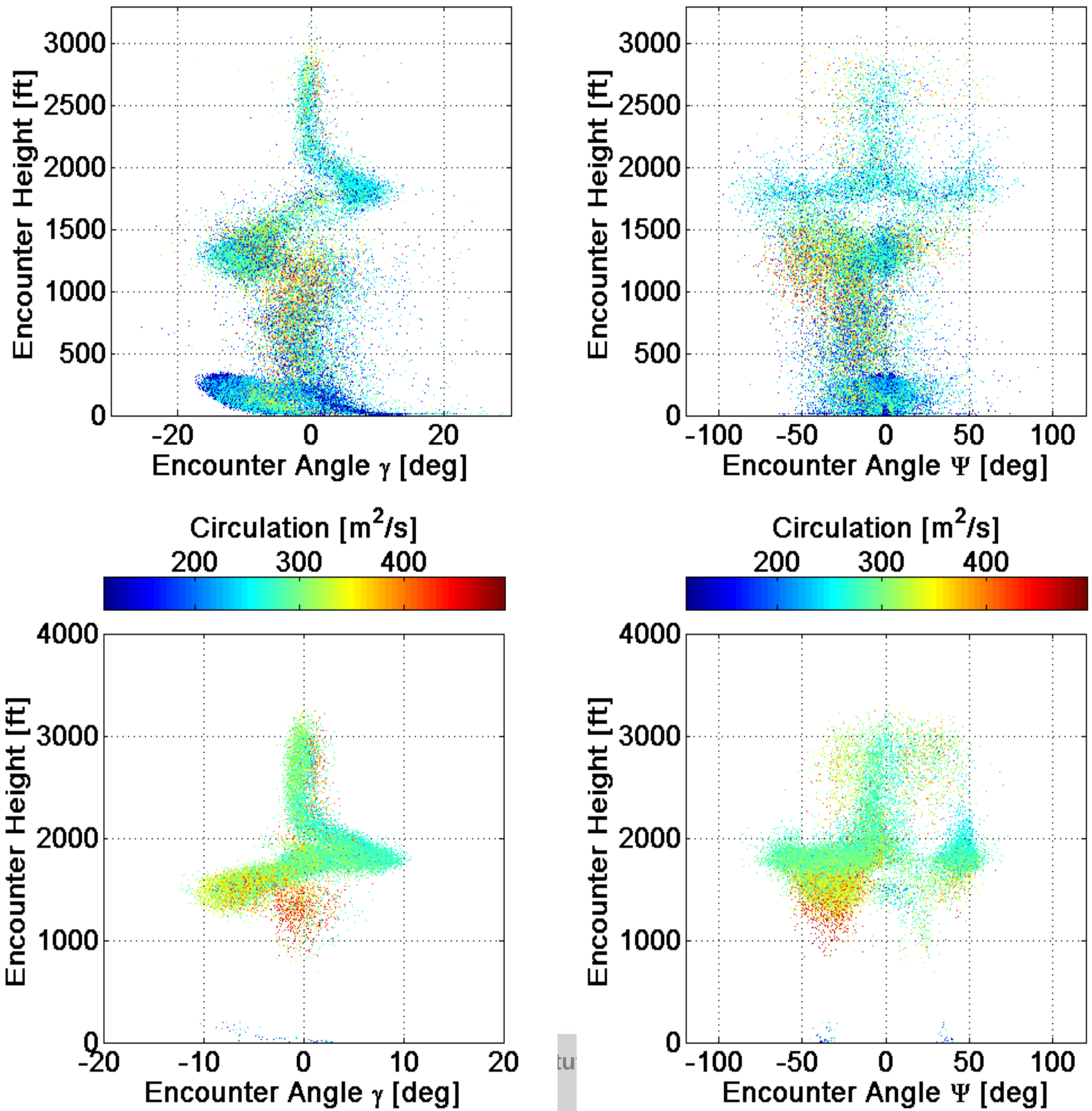


- scenario is considered safe when the frequencies of all circulation/distance-combinations are below reference scenario
- detailed investigation of encounter severity with VESA



inclination angle

azimuth angle



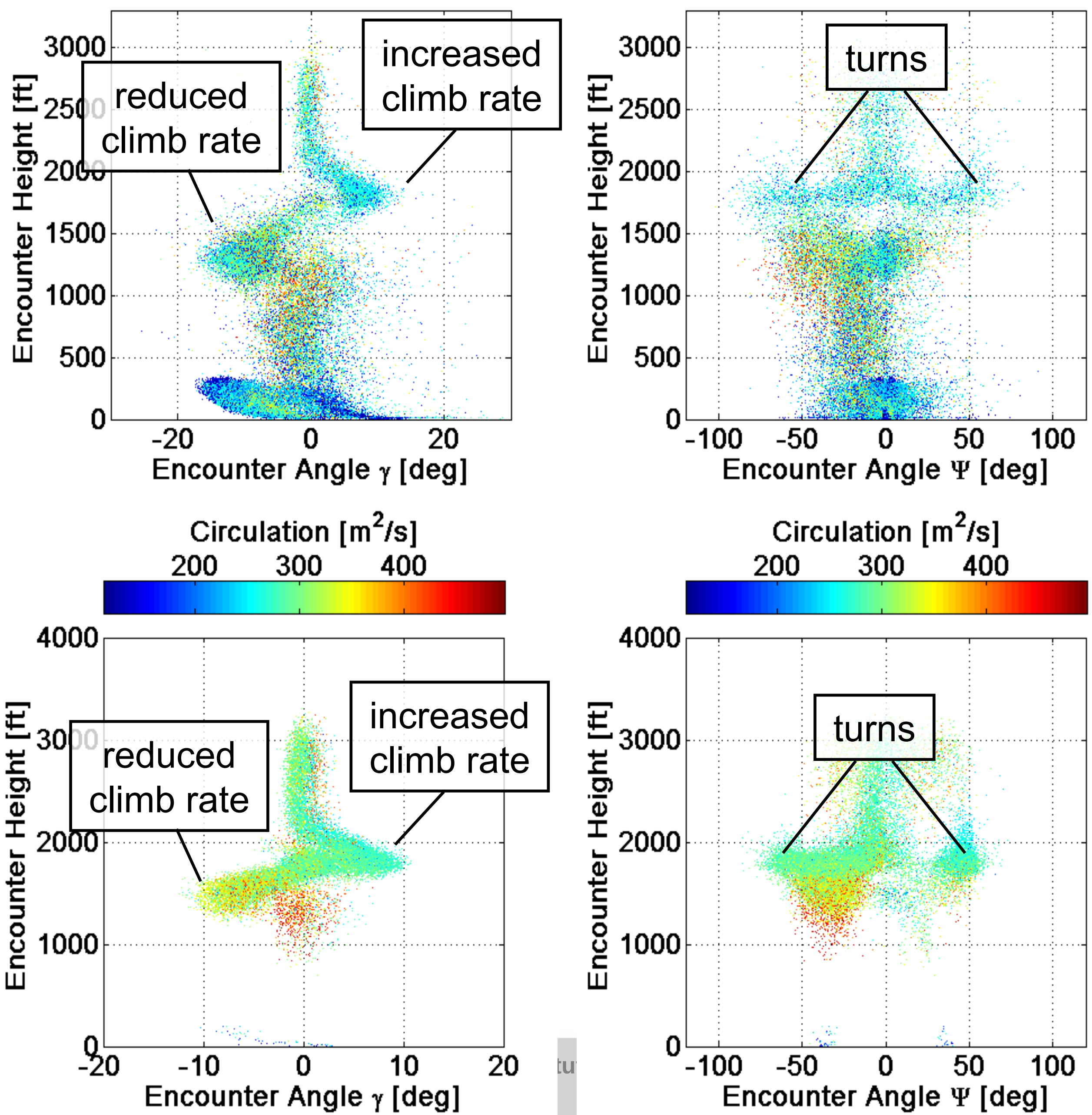
encounter angles – circulation – altitude

reference
scenario
120 s

60 s
CW > 8 knots

inclination angle

azimuth angle



encounter angles – circulation – altitude

reference scenario 120 s

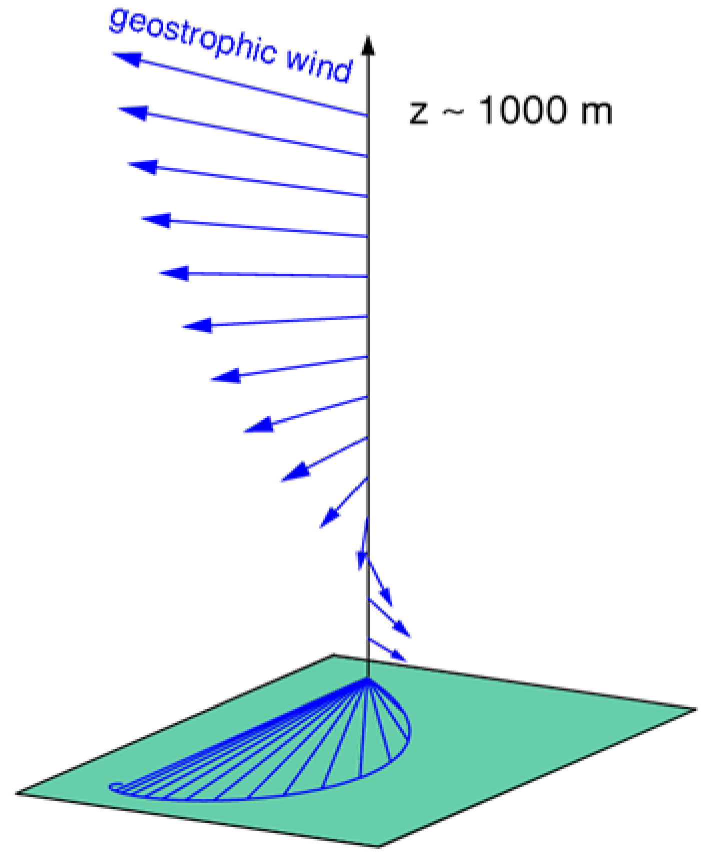
60 s
CW > 8 knots

Wind Direction

ICAO Reference Scenario - 120 s

wind direction	encounter frequency
CW port	5.2%
CW starb.	1.7%
tailwind	2.5%
headwind	13.3%

Ekman spiral: equilibrium of pressure gradient force, Coriolis force, and friction force

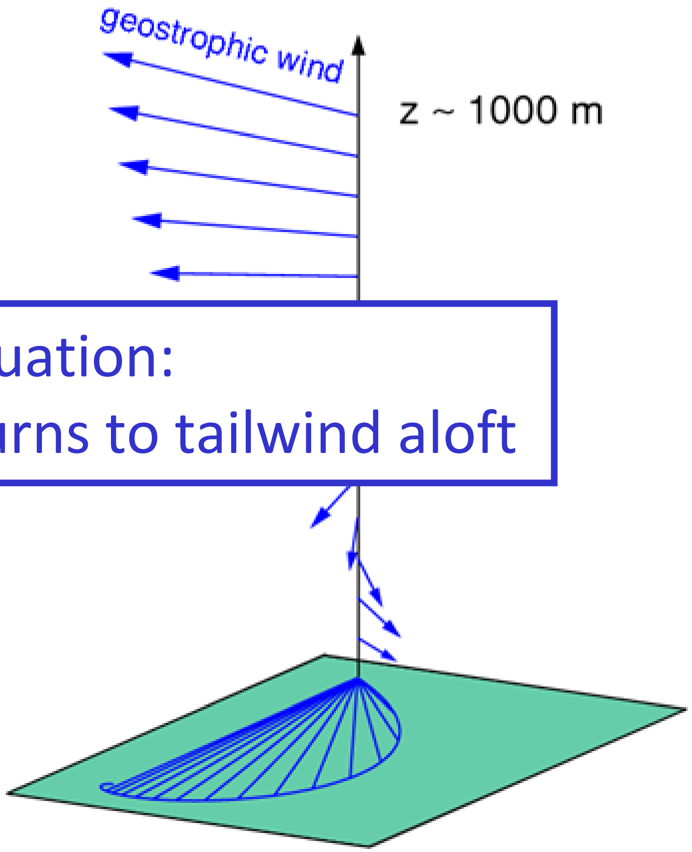


Wind Direction

ICAO Reference Scenario - 120 s

wind direction	encounter frequency
CW port	5.2%
CW starb.	
tailwind	2.5%
headwind	13.3%

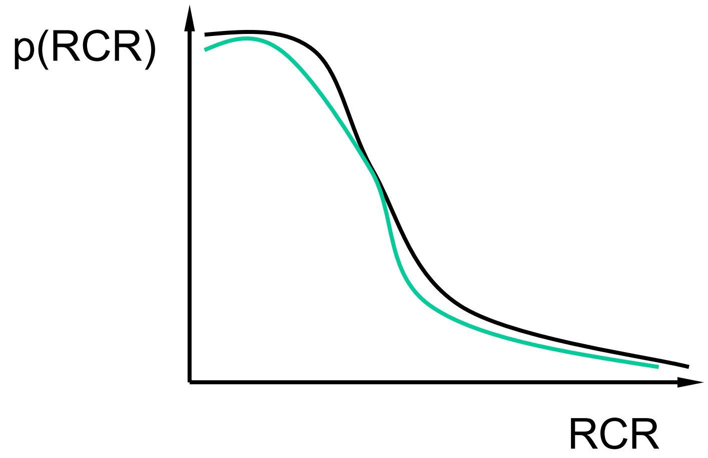
Ekman spiral: equilibrium of pressure gradient force, Coriolis force, and friction force



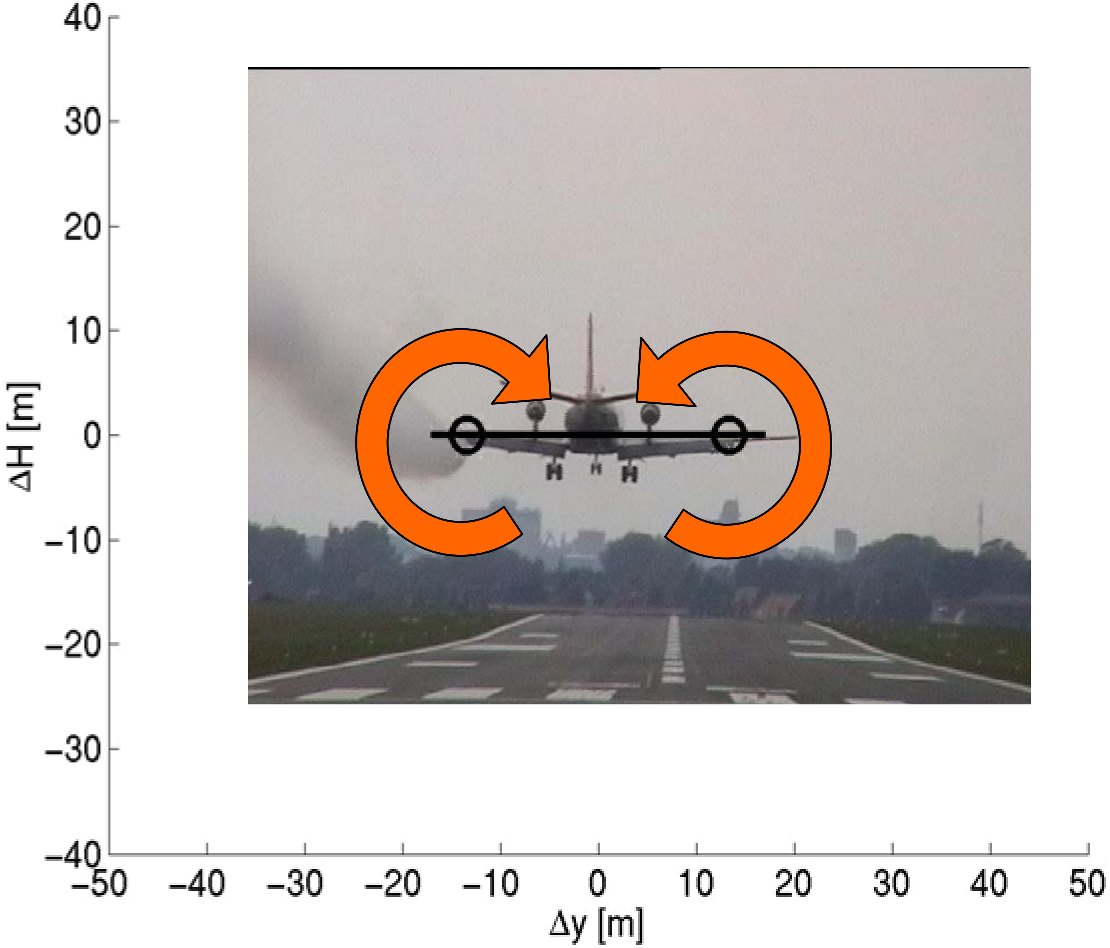
beneficial situation:
CW from starboard side turns to tailwind aloft

RECAT – DLR's approach

- **RECAT Phase II** ⇒ WakeScene for static pairwise separation
  - WakeScene-A – Monte Carlo simulations
  - approach; a/c installed on glide slope
  - trajectory model for 29 most frequent a/c types from Frankfurt traffic mix (BADA, FMS)
  - one year weather data base
  - reference scenario: ICAO separations ⇒ $pdf_{ref}(RCR)$
  - target scenario: optimized separations with $pdf_{targ}(RCR) < pdf_{ref}(RCR)$

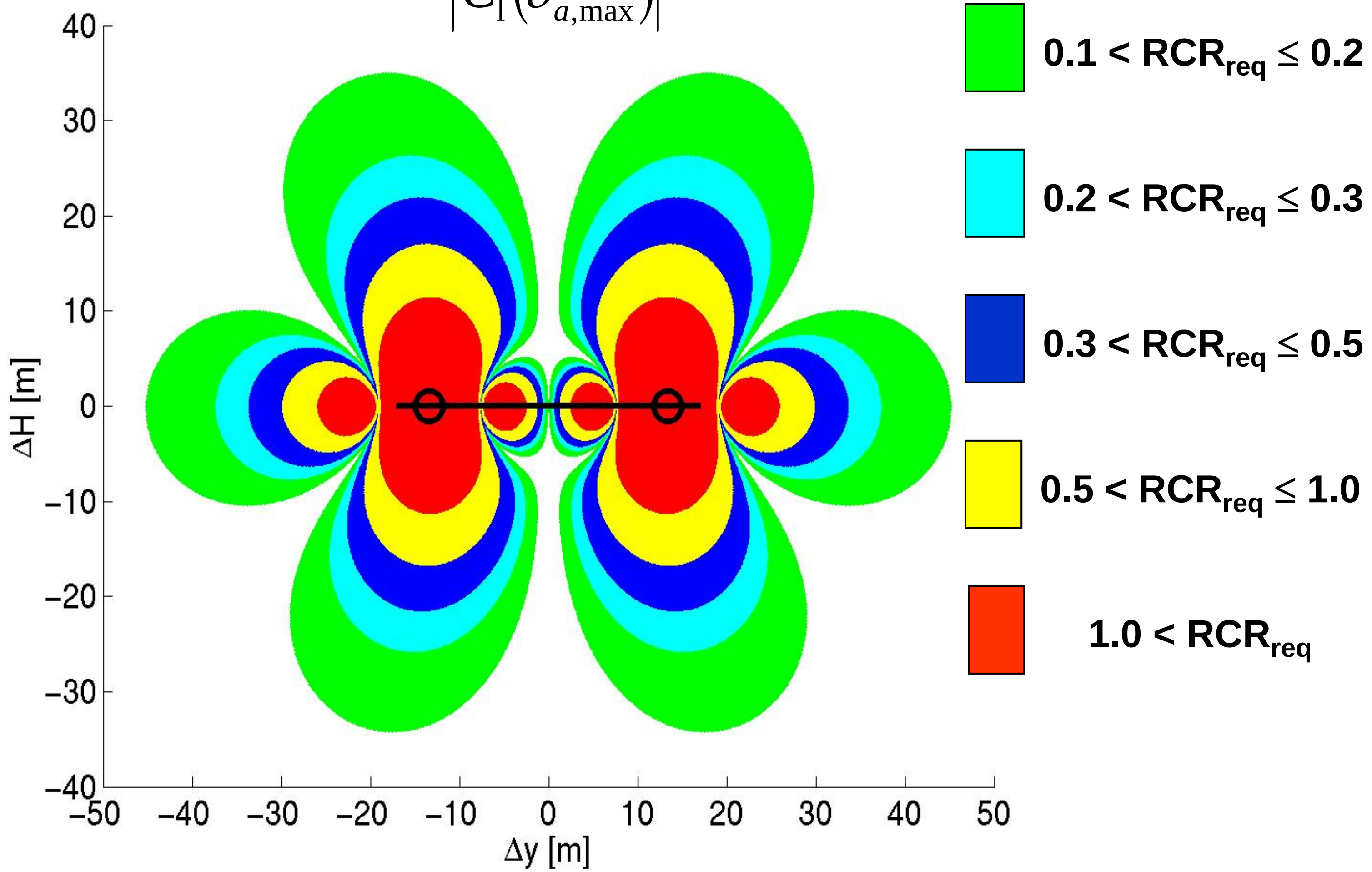


Roll Control Ratio - RCR



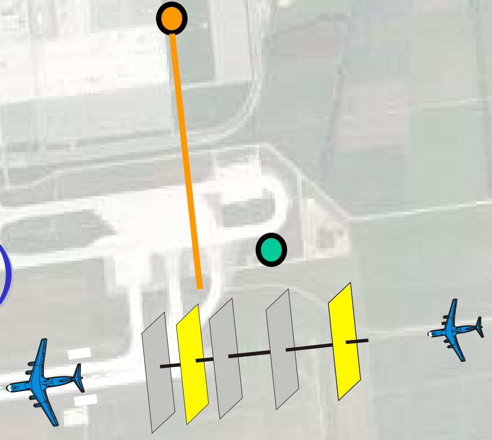
Roll Control Ratio - RCR

roll control ratio $$RCR_{req} = \left| \frac{C_{l,WV}}{C_l\left(\delta_{a,\max}\right)} \right|$$



WV prediction & monitoring system – **WSVBS**

- provides weather dependent dynamic separations
  - on closely-spaced parallel runways
  - and single runways
  - for weight class combinations
  - or *dynamic pairwise separations*
  - demonstration campaigns at
    - Frankfurt airport (winter 06/07)
    - Munich airport (summer 10, spring 11)



DLR

RECAT – DLR's approach

- **RECAT Phase III** ⇒ WSVBS for dynamic pairwise separations

WSVBS

meteo measurements
SODAR/RASS USA
3 gates, 0.3 - 1 NM

numerical weather pred.
COSMO-Airport
10 gates, 2 - 11 NM

optionally a/c type comb.
Flight Plan
a/c type, arrival time

wake-vortex prediction
P2P
envelopes for y(t), z(t), Γ(t) in 13 gates
for (individual) heavy/medium pairings

glide path adherence statistics
FLIP
standard deviations in 13 gates

safety area prediction
SHAPe
ellipses for (individual) medium followers

wake-vortex monitoring
LIDAR
3 planes, 0.3 - 1 NM

temporal a/c separations
for (individual) heavy/medium pairings

conflict detection
validation of WV predictions

procedures
AMAN
STG, MSR, MSL, ICAO

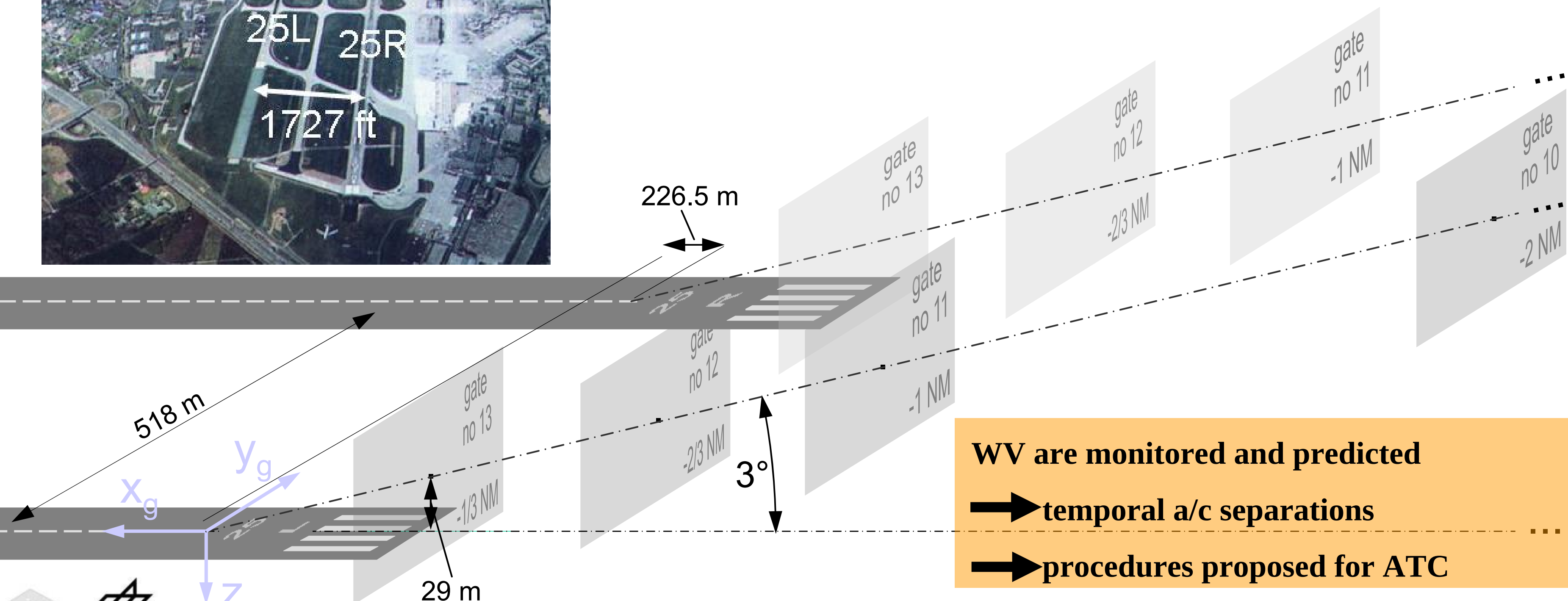
WSVBS at Frankfurt Airport, FRA

Frankfurt Airport

13 Gates

along nominal ILS Flight Path

(Δx = 1/3 NM - 1 NM)



WV are monitored and predicted

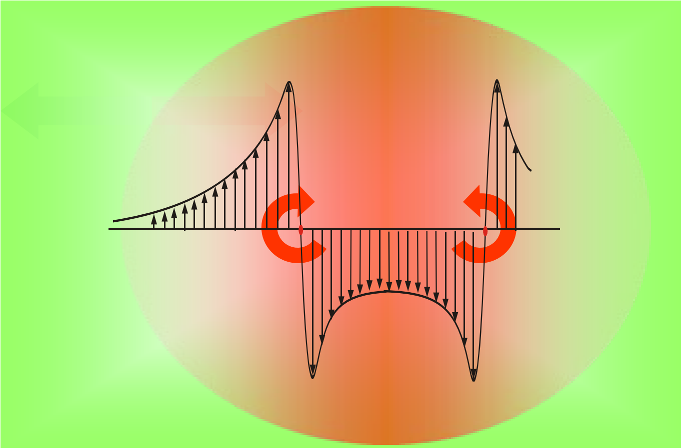
➡ temporal a/c separations

➡ procedures proposed for ATC

Wake encounter severity assessment

Simplified Hazard Area (SHA)/

Simplified Hazard Area Prediction (SHAPe)



„How close can an aircraft
safely approach a wake vortex?“

DLR concept:

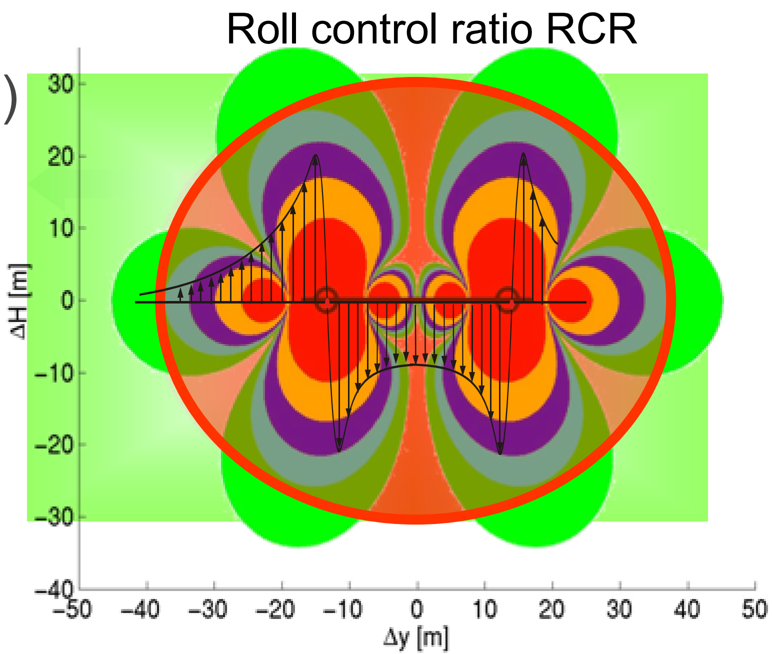
- Simplified Hazard Area (SHA)
  - conservative/ non-hazard approach, safe and undisturbed operations possible outside the hazard area, no go-arounds
  - simple, robust severity criterion
  - roll control ratio: one parameter to cover complete A/C reaction
  - validated with pilot-in-the loop simulator & flight tests
  - dynamic (vortex decay, weather)
  - A/C categories and individual/ pairwise (Recat III !)
- Simplified Hazard Area Prediction (SHAPe) based on MTOW

Wake encounter severity assessment

Simplified Hazard Area (SHA)/

Simplified Hazard Area Prediction (SHAPe)

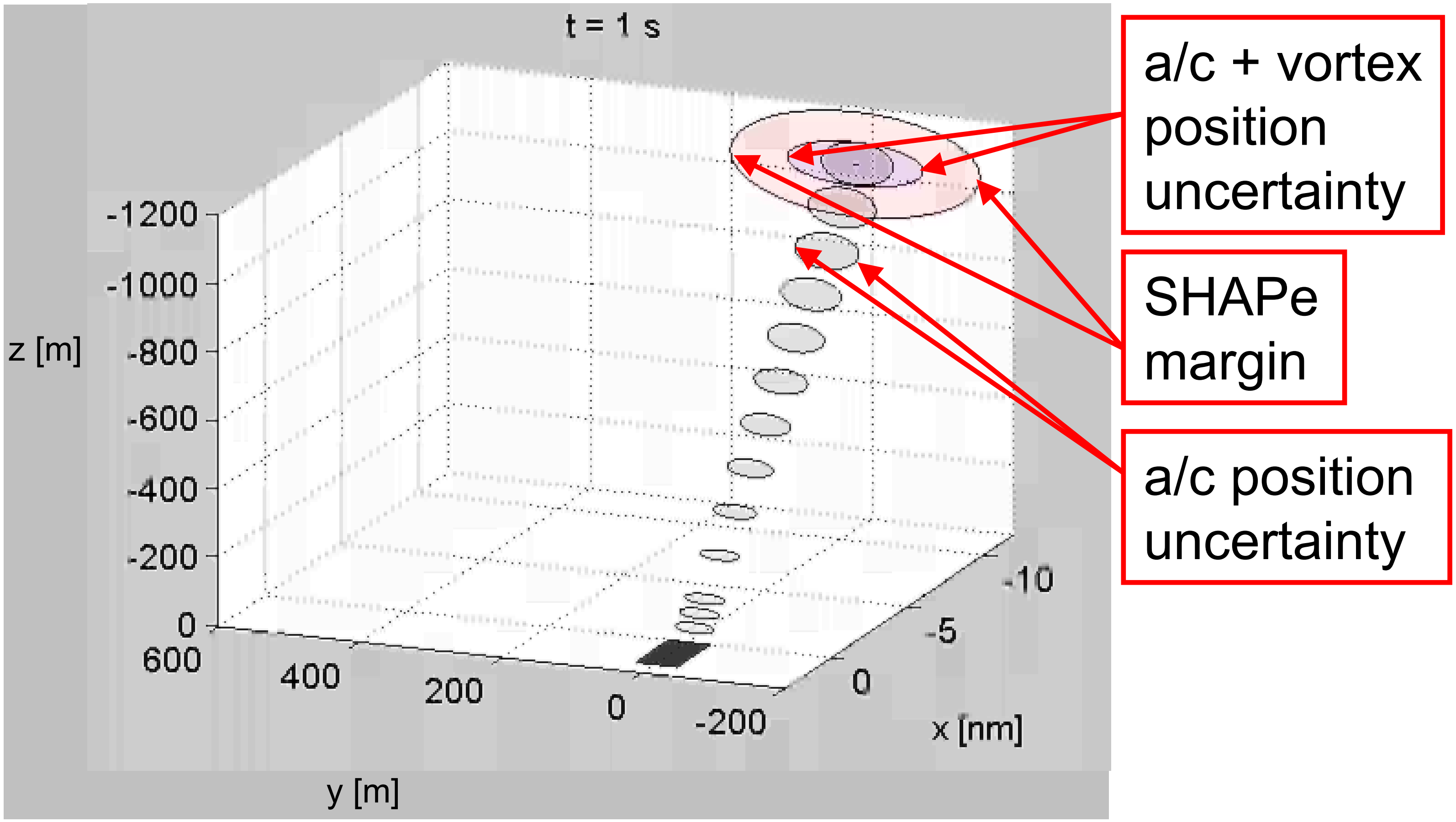
„How close can an aircraft safely approach a wake vortex?“



DLR concept:

- Simplified Hazard Area (SHA)
  - conservative/ non-hazard approach,
    - safe and undisturbed operations possible outside the hazard area, no go-arounds
  - simple, robust severity criterion
  - roll control ratio: one parameter to cover complete A/C reaction
  - validated with pilot-in-the loop simulator & flight tests
  - dynamic (vortex decay, weather)
  - A/C categories and individual/ pairwise (Recat III !)
- Simplified Hazard Area Prediction (SHAPe) based on MTOW

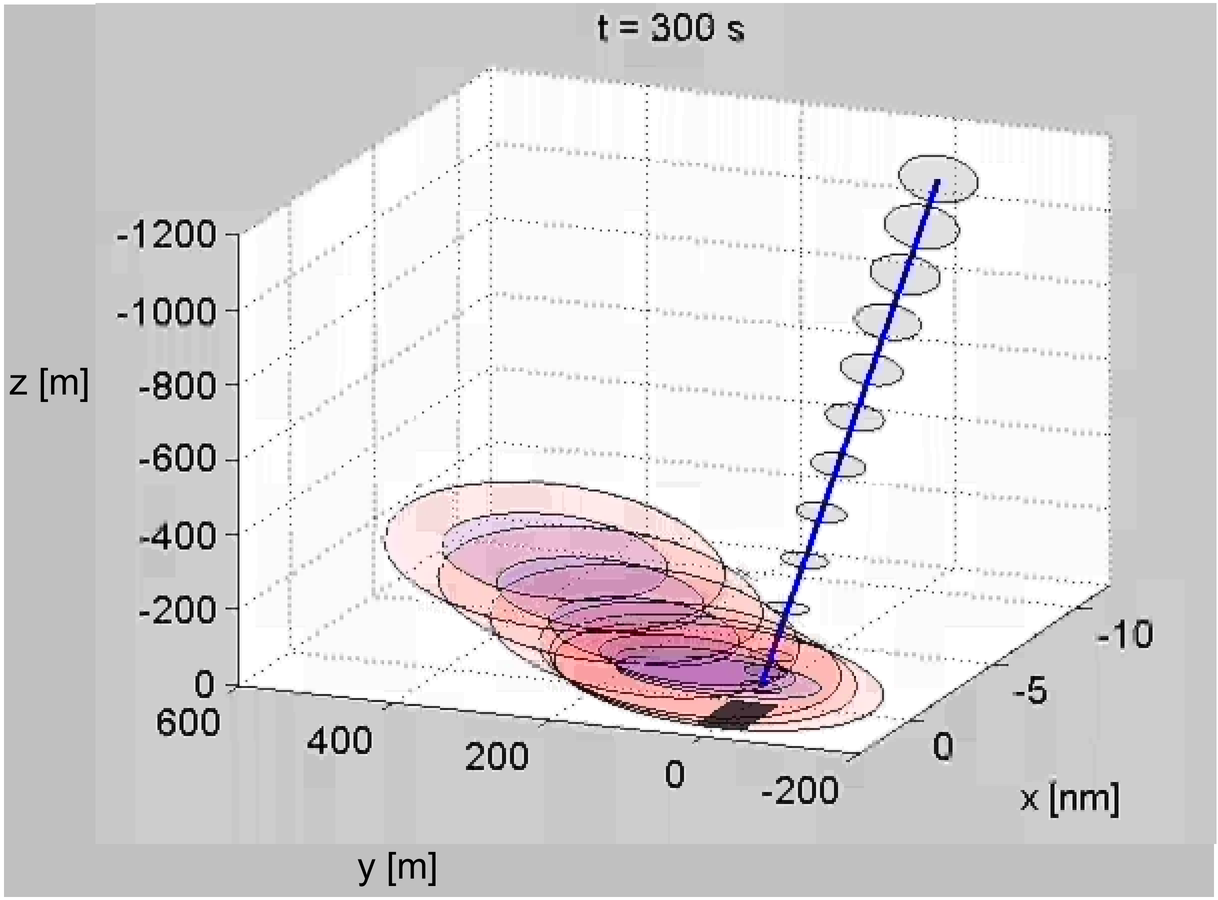
Dynamic wake vortex separation advisory



‘medium‘ behind ‘heavy‘: cross wind 3 m/s

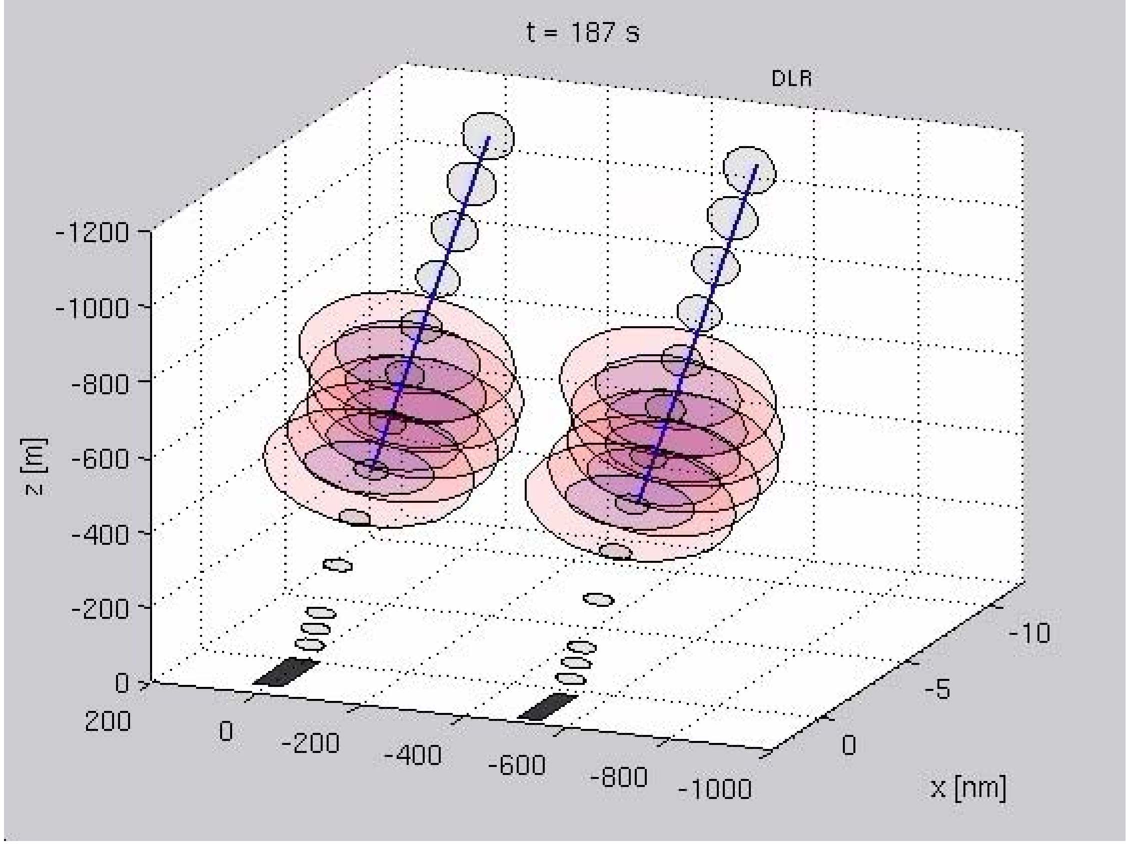
weak turbulence

Dynamic wake vortex separation advisory



'medium' behind 'heavy': cross wind 3 m/s

weak turbulence

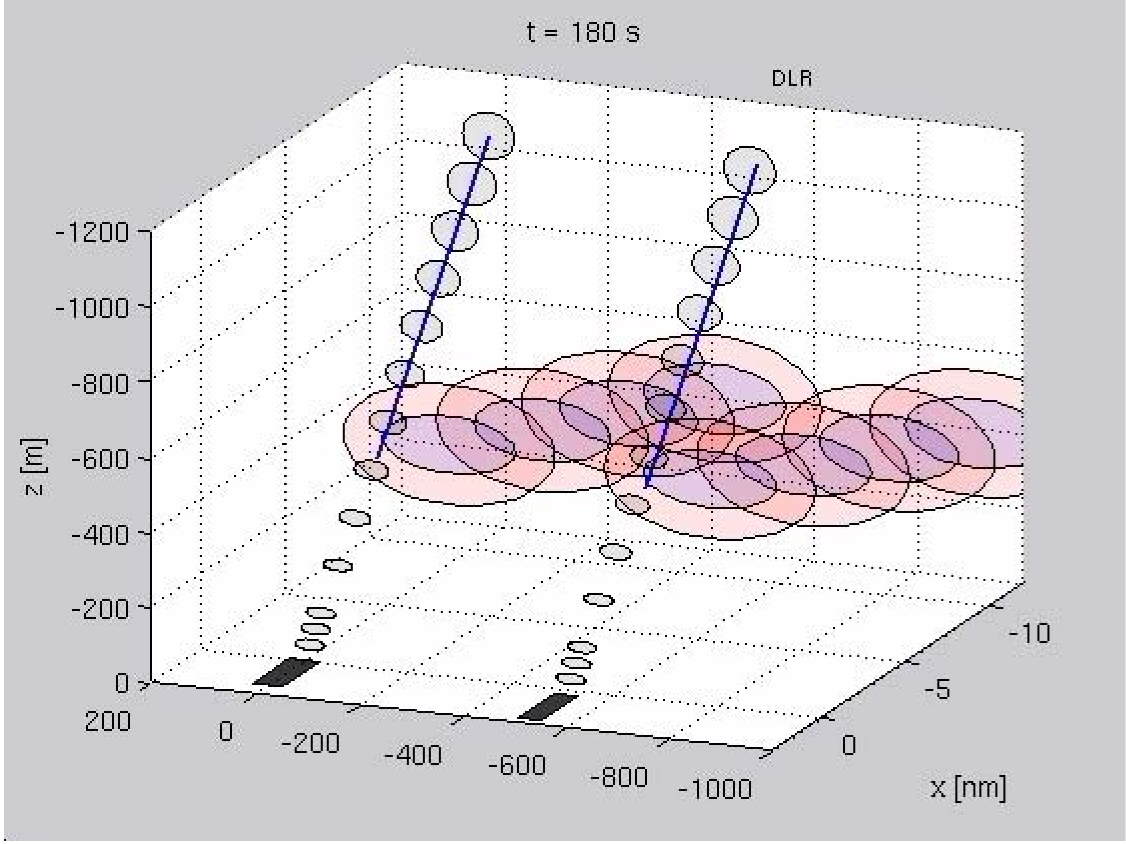


WSV Strategy
Animated
veering light winds

- 2004/09/01 08:10
- heavy-medium

25L25L	100	125
25L25R	0	0
25R25L	0	0
25R25R	100	125

staggered approach



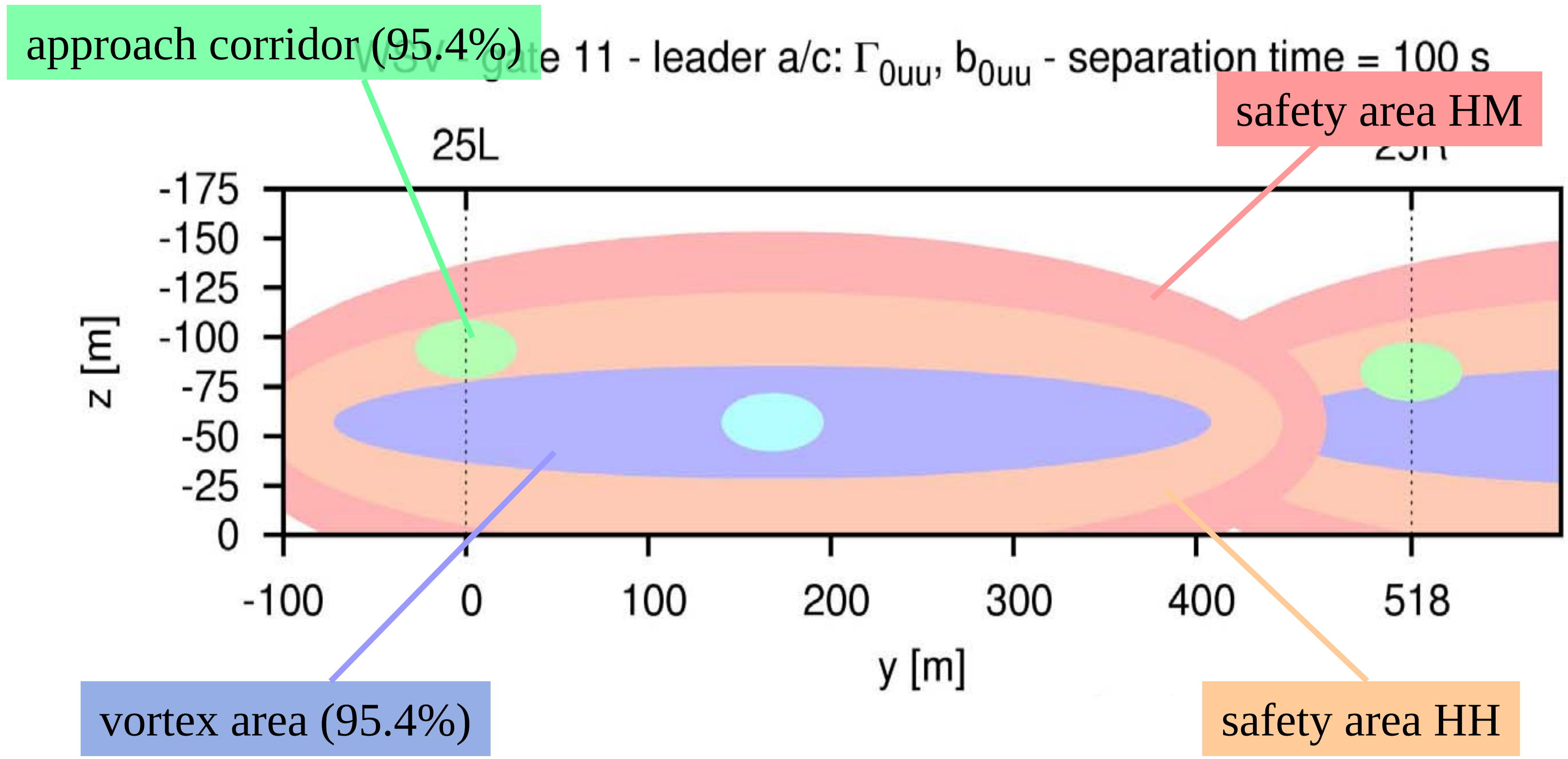
WSV Strategy Animated strong crosswind

- 2004/09/10 19:10
- heavy-medium

25L25L	68	75
25L25R	0	0
25R25L	100	125
25R25R	68	75

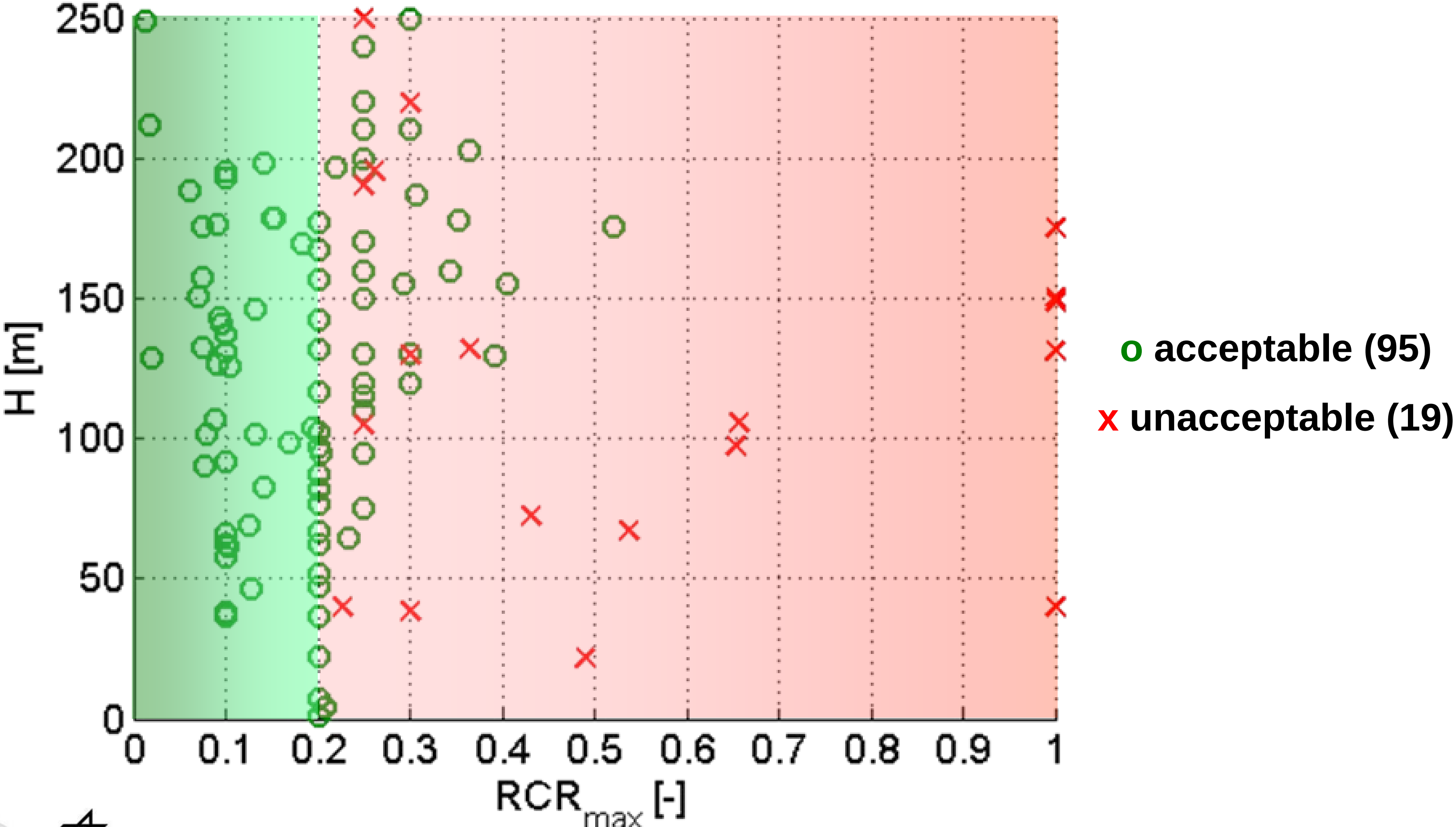
- modified staggered left
- reduced sep. single rwy

WV forecast strategy



Wake encounter hazard area limit results

Manually flown (non fly-by-wire) ILS approach



Wake encounter severity criteria
State of the art

$RCR < 0.5 + 0.006 \cdot H_{RCRmax}$

GA prediction

[2002, Höhne,G., Reinke, A., Verbeek, M.]

RCR < 0.5

acceptable WVE

[1988, Rossow V. J., Tinling, B. E.]

RCR < 0.2-0.3

appropriate limit for acceptable WVE

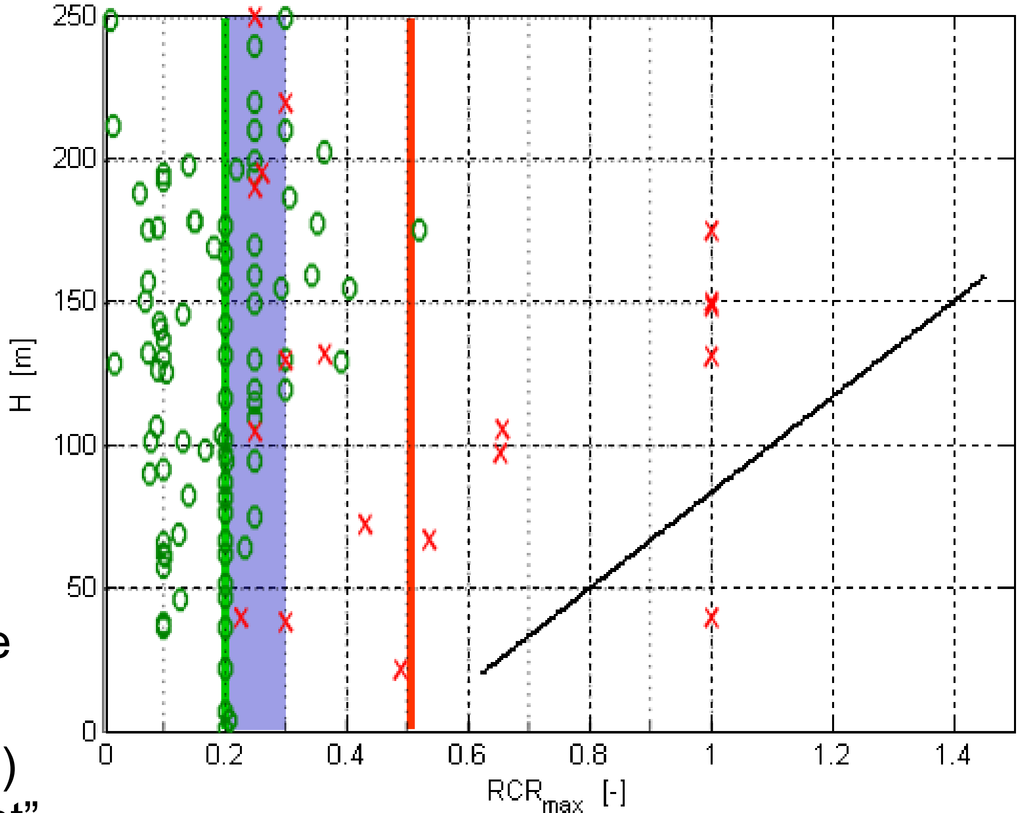
[1998, Stewart E. C.]

RCR < 0.2

operationally safe WVE

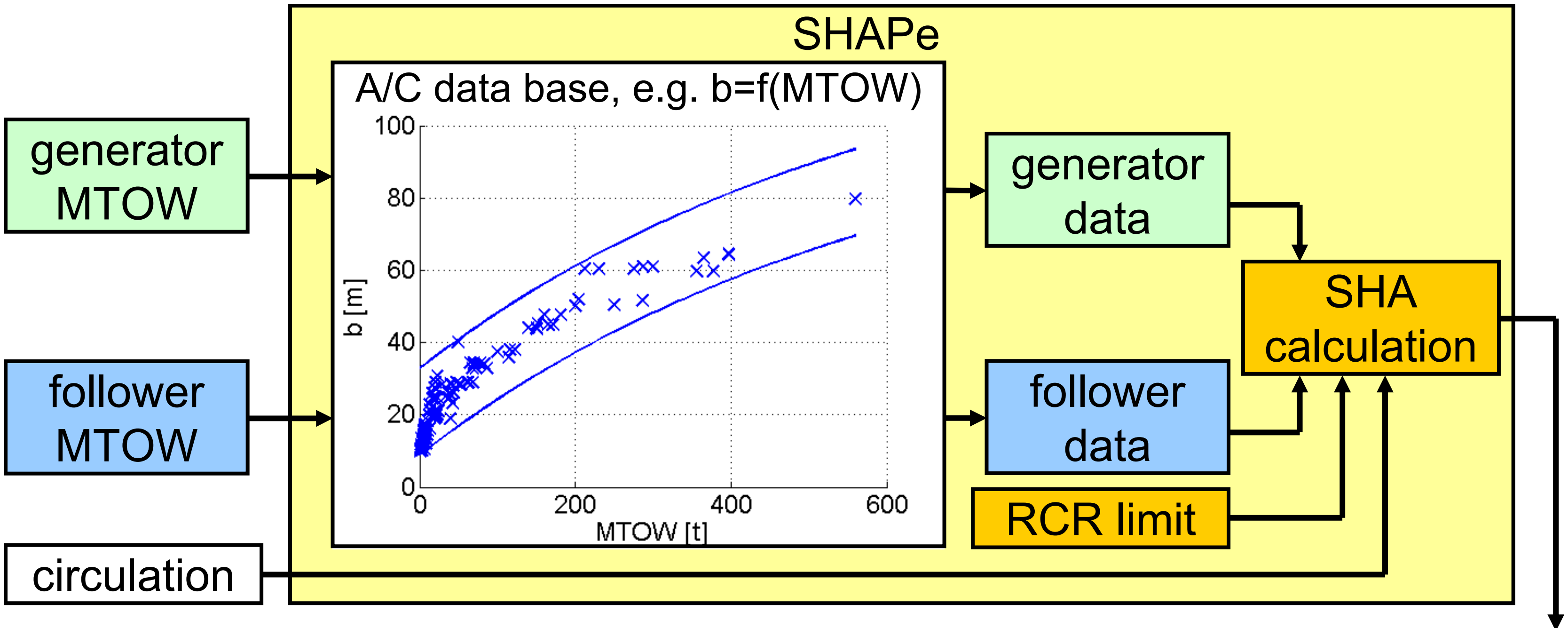
[2006, Hahn, K.-U., Schwarz, C.]

- CREDOS (EU FP 6) multiple severity criteria
- WakeNet3-Europe (EU FP 7) task group “safety assessment”
- RECAT/ SESAR JU
- FAA risk matrix activity



no commonly accepted severity criteria available

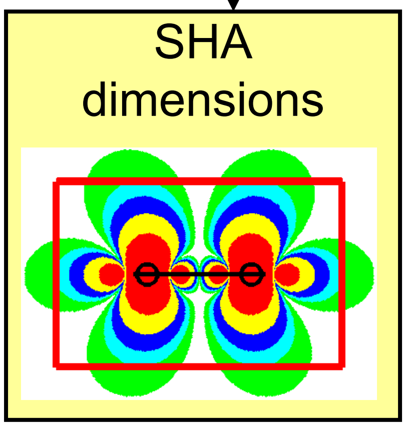
Simplified Hazard Area Prediction (SHAPe)



all relevant wake vortex parameters parameterized based on MTOW with boundary fits

determination of hazard area depending on vortex strength and RCR (worst case approach)

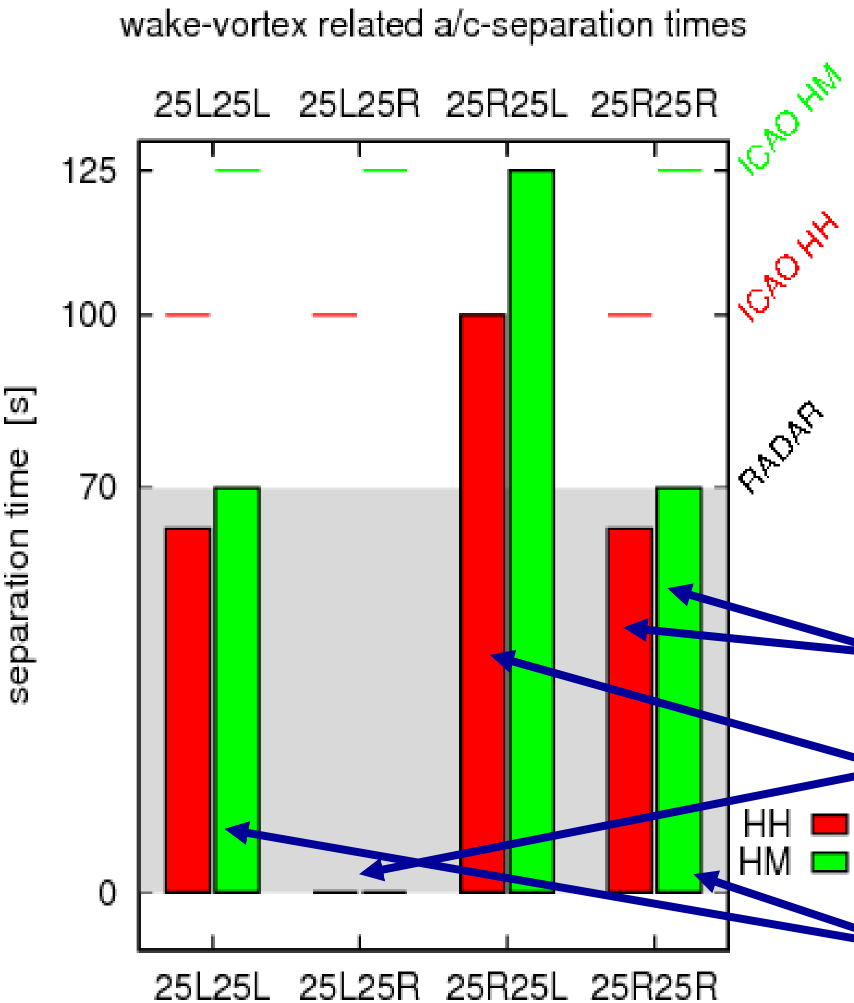
dimension of safety area for any (generic) aircraft pairing



Display for parallel runways

full information and procedures,

example: 2007-Jan-25 15:10 UTC



separate consideration of HH and HM

staggered separation

in-trail separation

WSVBS - Conclusions for Frankfurt Airport

The WSVBS demonstrated its functionality at Frankfurt airport in winter 06/07

- Stable prediction characteristics - no forecast breakdowns
- Potential ("weather-wise") use of new ConOps in 75% of the time
- Potential capacity gain > 3 % (real traffic flow and traffic mix)
- The predictions were correct: no warnings from the LIDAR
  - from a-posteriori analysis of ≈1100 heavy a/c approaches
- The controllers confirmed the benefit of such a system and agreed with the proposed procedures and display layout

- **ATC Quarterly, Vol. 17, No. 4, 2009**

Conclusions – I

P2P – WV transport and decay model:

- fast (~ 10 ms)
- deterministic, probabilistic, and stochastic prediction modes
- all relevant effects considered
- high level of skill (validated in 11 campaigns)
- appropriate uncertainty allowances with known probabilities

WakeScene – WV scenarios simulation package:

- MC Simulation of air traffic & WVs for departures and approaches
- traffic mix, aircraft trajectories, meteorological conditions, WV transport and decay, encounter identification, control & evaluation software
- submodels validated / global comparison encouraging
- **concept for RECAT II**
- (can further be coupled with VESA, encounter severity)

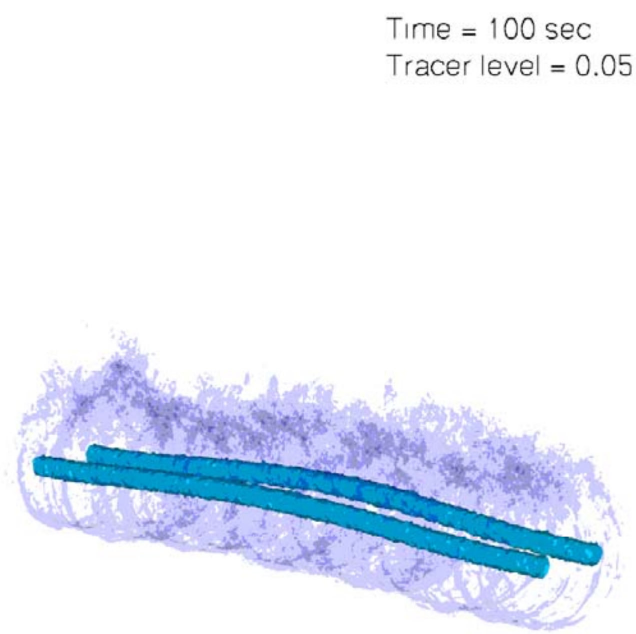
Conclusions – II

WSVBS – WV prediction & monitoring system

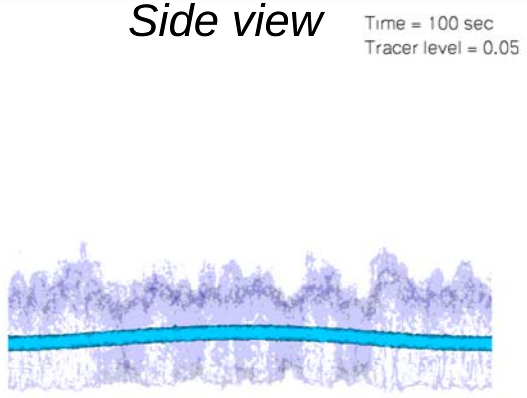
- supports weather dependent dynamic separations for CSPR & single RWYs
- weight class combinations or dynamic pairwise separations
- demonstration campaigns at Frankfurt and Munich airport
- **system for RECAT III**

Wake vortex structures in neutrally stratified environments

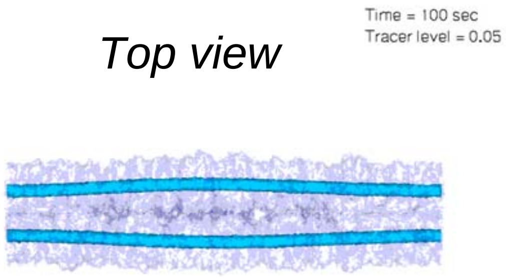
pressure waves – spiral-shaped instabilities – double rings



Side view



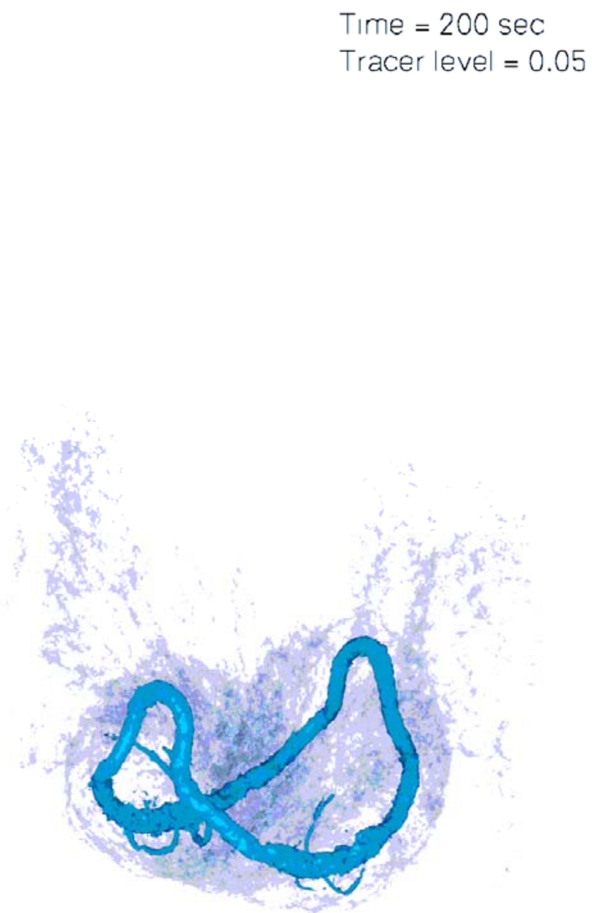
Top view



$\varepsilon^* = 0.01$, $N^* = 0$, $L_t^* = 0.85$, tracer initialized in half oval, domain laterally extended to 512 meshes

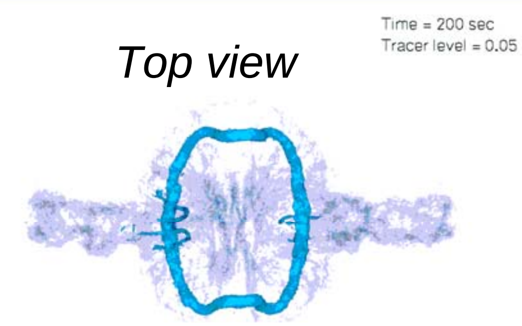
Wake vortex structures in neutrally stratified environments

pressure waves – spiral-shaped instabilities – double rings



Side view

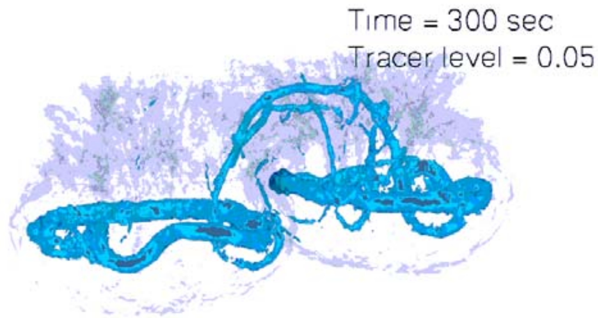
Top view

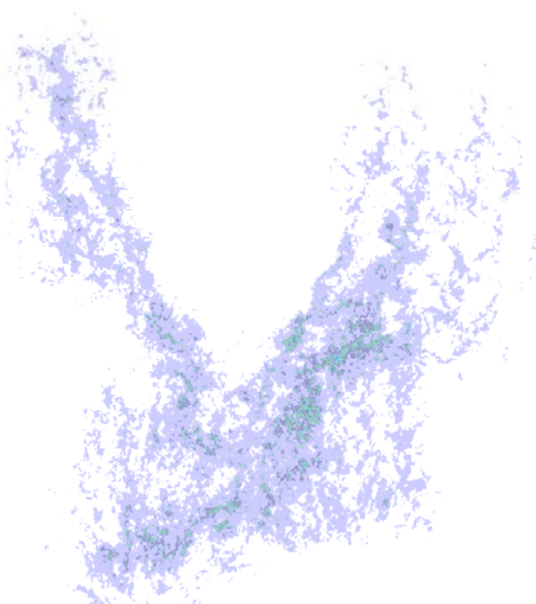


$\varepsilon^* = 0.01$, $N^* = 0$, $L_t^* = 0.85$, tracer initialized in half oval, domain laterally extended to 512 meshes

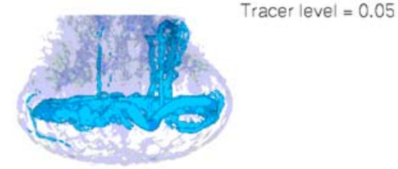
Wake vortex structures in neutrally stratified environments

pressure waves – spiral-shaped instabilities – double rings

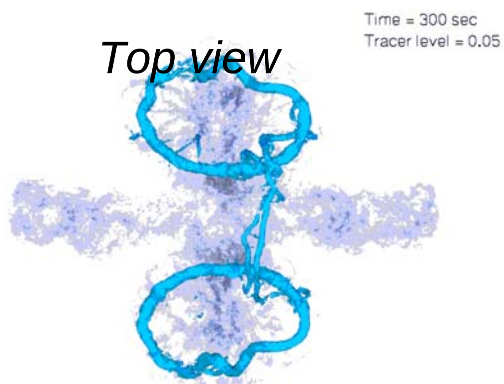




Side view



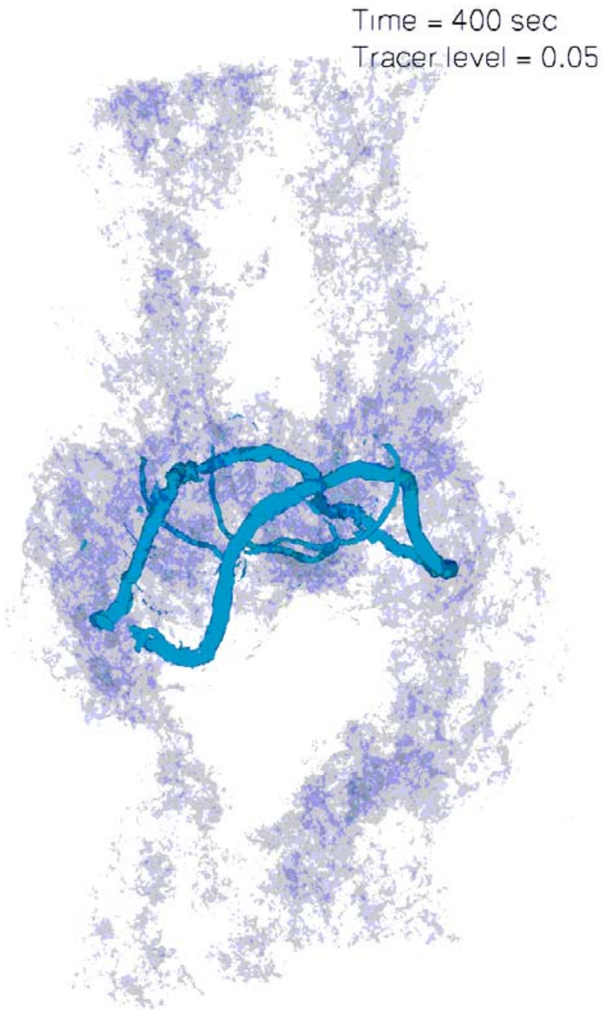
Top view



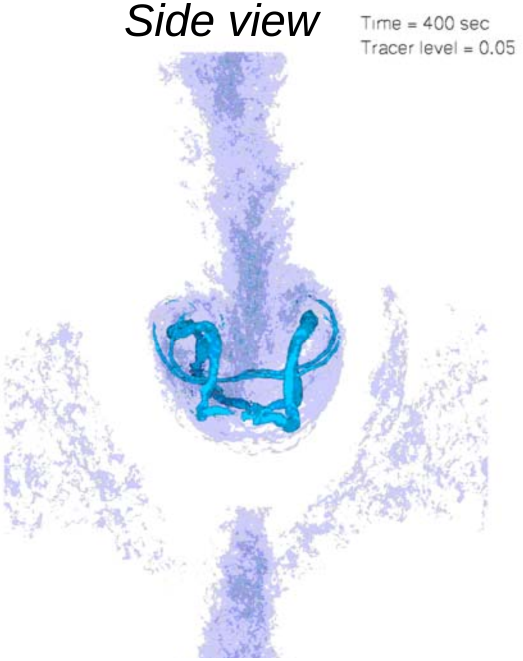
$\varepsilon^* = 0.01$, $N^* = 0$, $L_t^* = 0.85$, tracer initialized in half oval, domain laterally extended to 512 meshes

Wake vortex structures in neutrally stratified environments

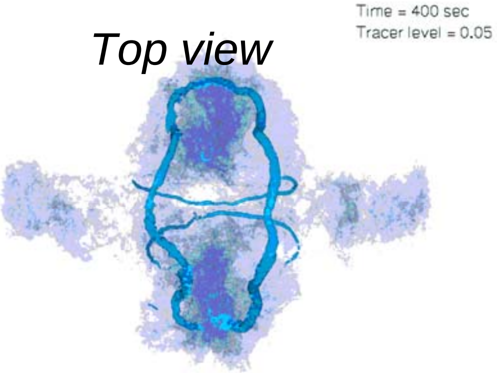
pressure waves – spiral-shaped instabilities – double rings



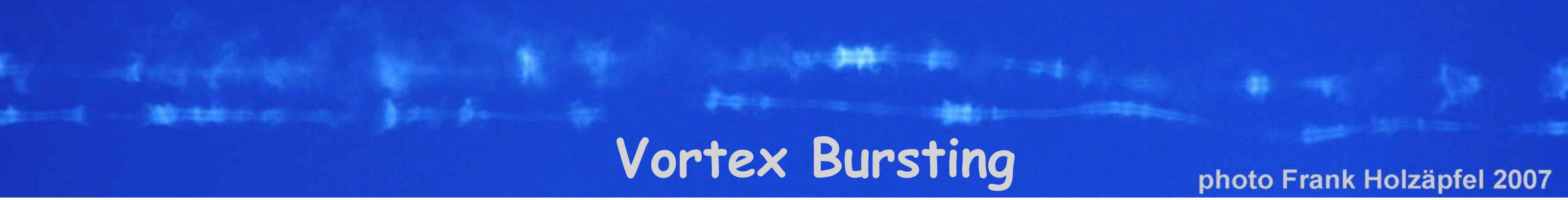
Side view



Top view

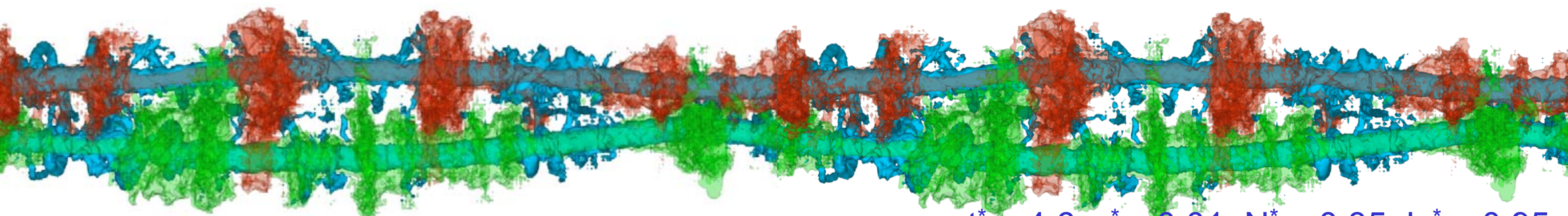


$\varepsilon^* = 0.01$, $N^* = 0$, $L_t^* = 0.85$, tracer initialized in half oval, domain laterally extended to 512 meshes

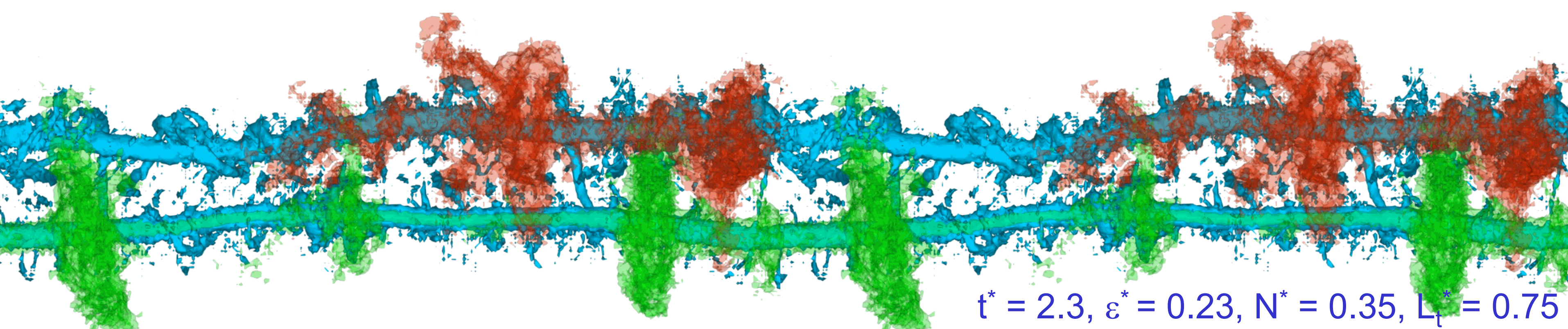


Vortex Bursting

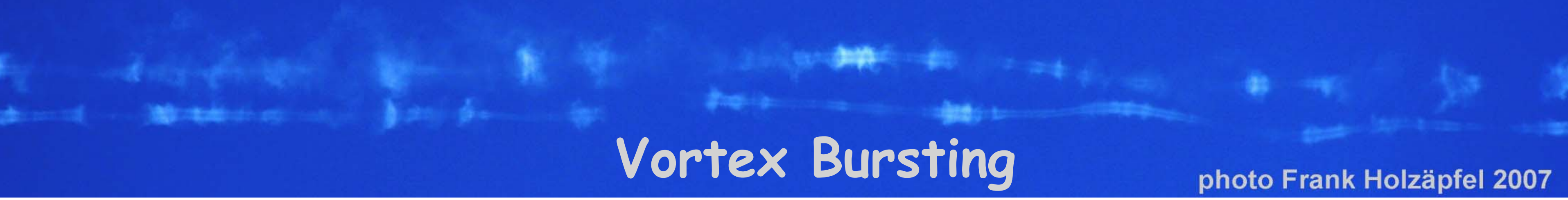
vortex bursting:
- visualized by passive tracer
- caused by collisions of secondary vorticity structures propagating along vortex lines
- not related to local vortex decay



$t^* = 4.6, \varepsilon^* = 0.01, N^* = 0.35, L_t^* = 0.95$

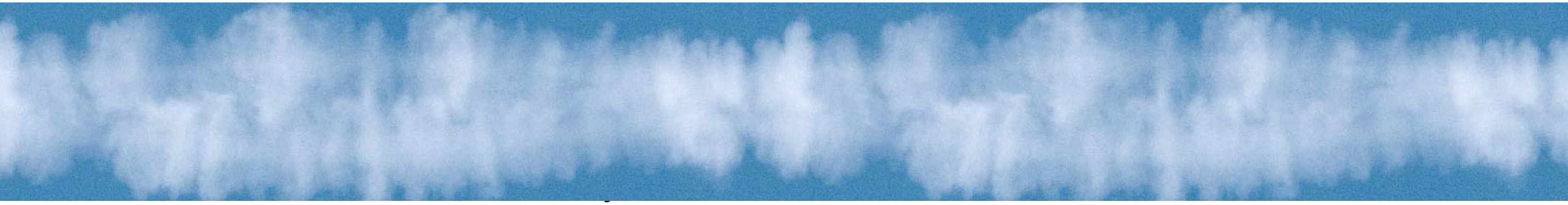


$t^* = 2.3, \varepsilon^* = 0.23, N^* = 0.35, L_t^* = 0.75$

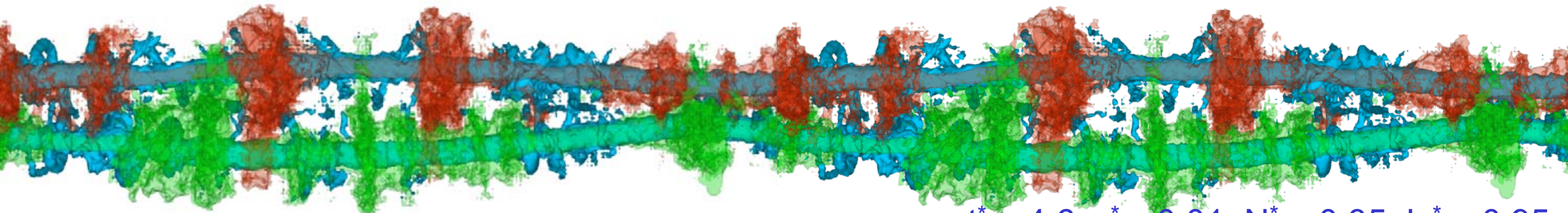


Vortex Bursting

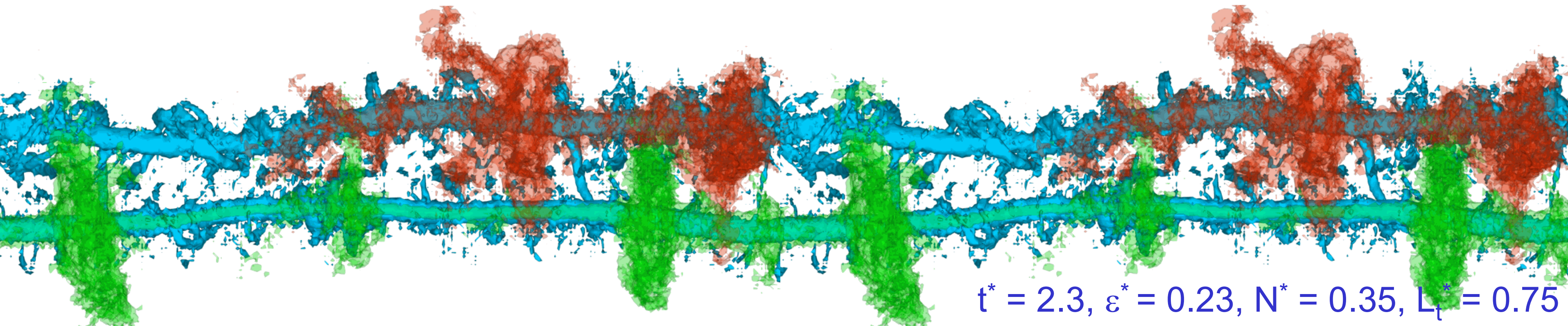
Radiative Transfer Simulation with libRadtran/MYSTIC T. Zinner, M. Schönegg, MIM



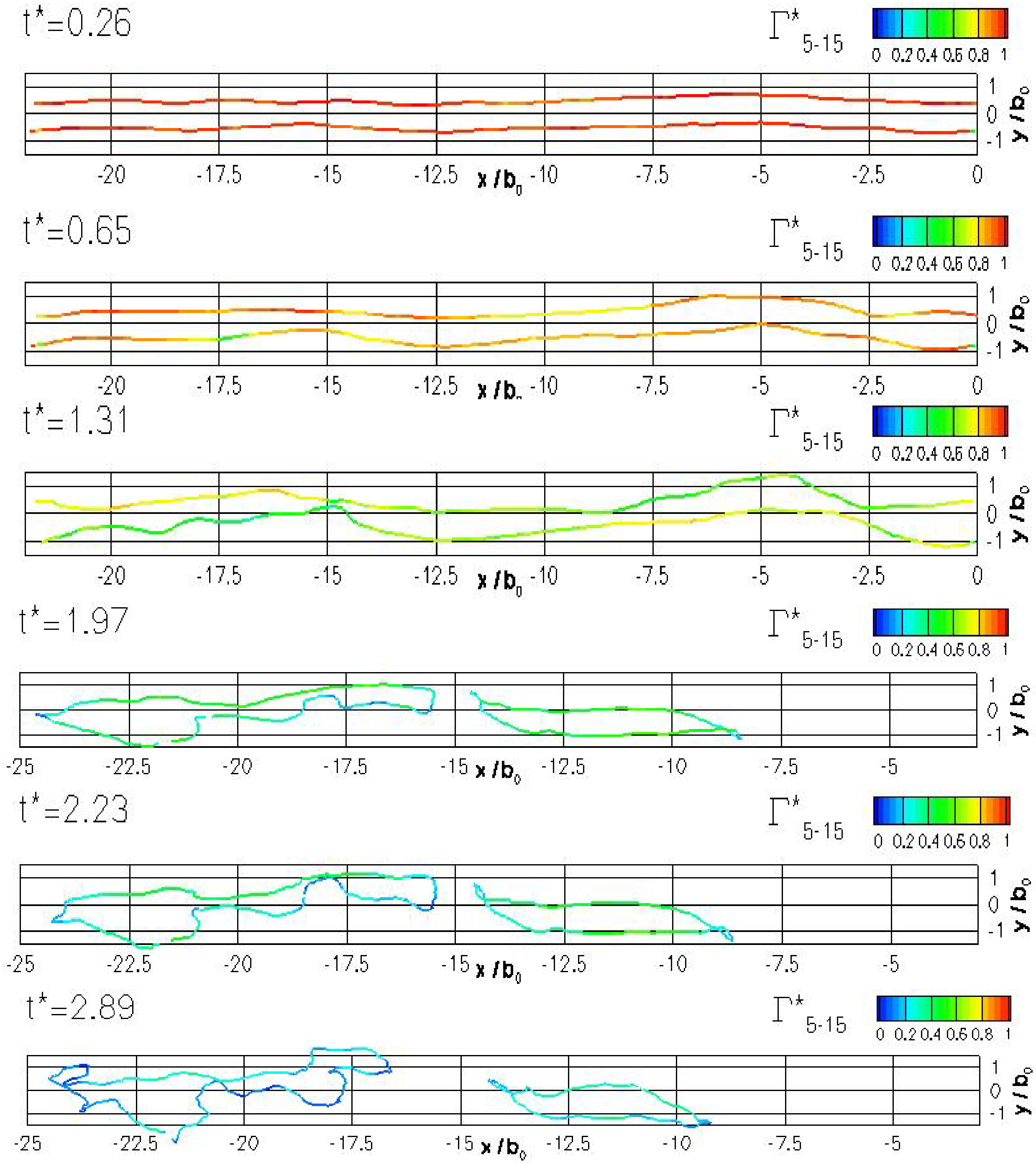
max. ice water content 0.2 g/m³, eff. radius 25 μm



$t^* = 4.6$, $\varepsilon^* = 0.01$, $N^* = 0.35$, $L_t^* = 0.95$



$t^* = 2.3$, $\varepsilon^* = 0.23$, $N^* = 0.35$, $L_t^* = 0.75$



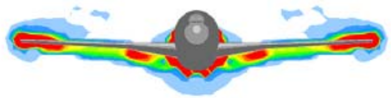
complex structures in increased turbulence

$1024 \times 1024 \times 1024$ m³

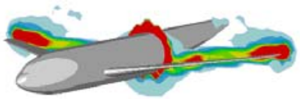
$\varepsilon^* = 0.23$, $N^* = 0$, $L_t^* = 2.22$

current work
flying through LES domain ...

Front view



Perspective view



Time = 1.184 sec

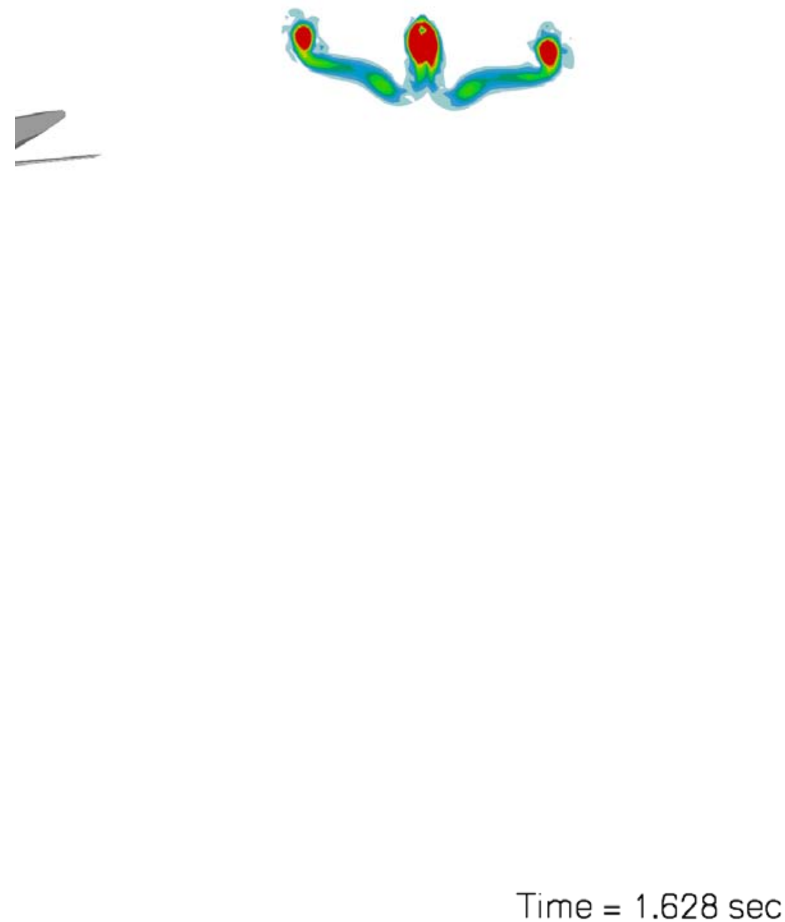
Time = 1.184 sec

current work

flying through LES domain ...

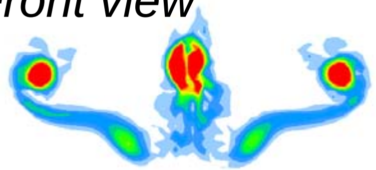
Front view

Perspective view

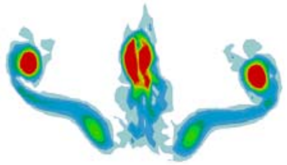


current work
flying through LES domain ...

Front view



Perspective view

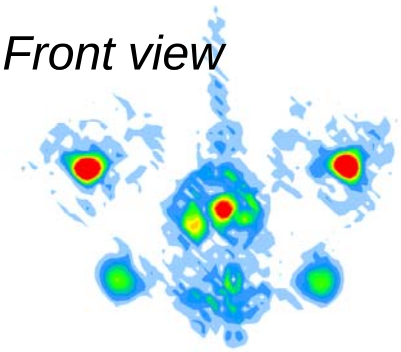


Time = 2.8512 sec

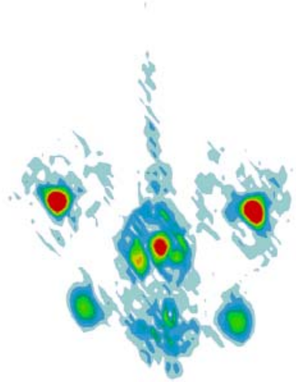
Time = 2.8512 sec

current work
flying through LES domain ...

Front view



Perspective view

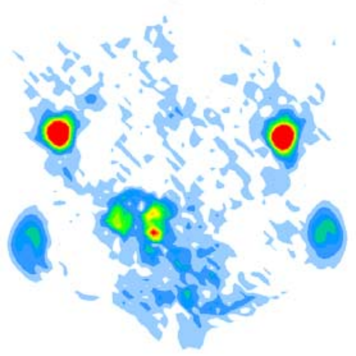


Time = 5.8512 sec

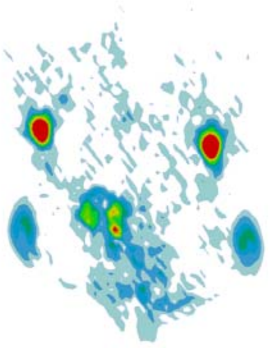
Time = 5.8512 sec

current work
flying through LES domain ...

Front view



Perspective view

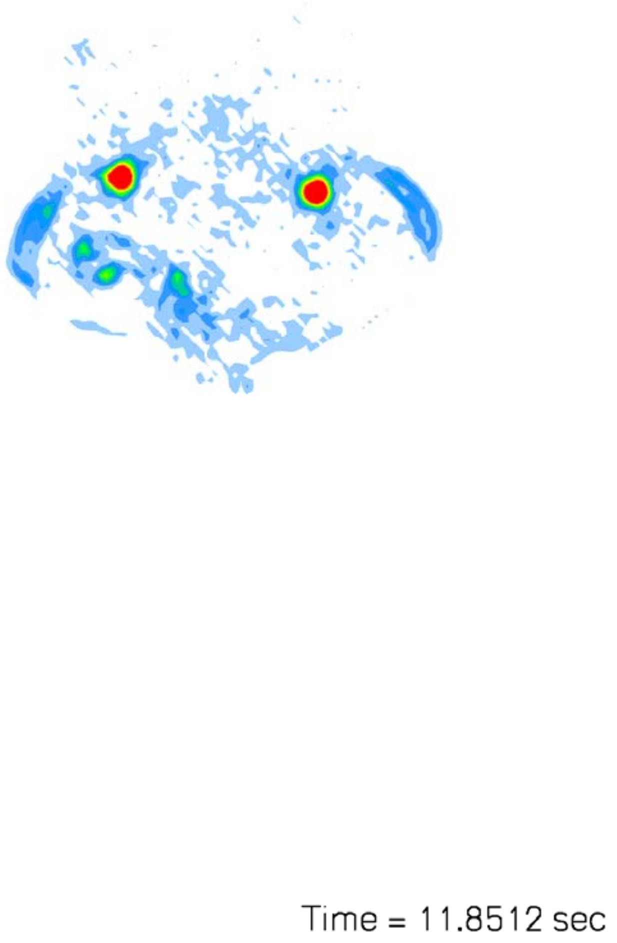


Time = 8.8512 sec

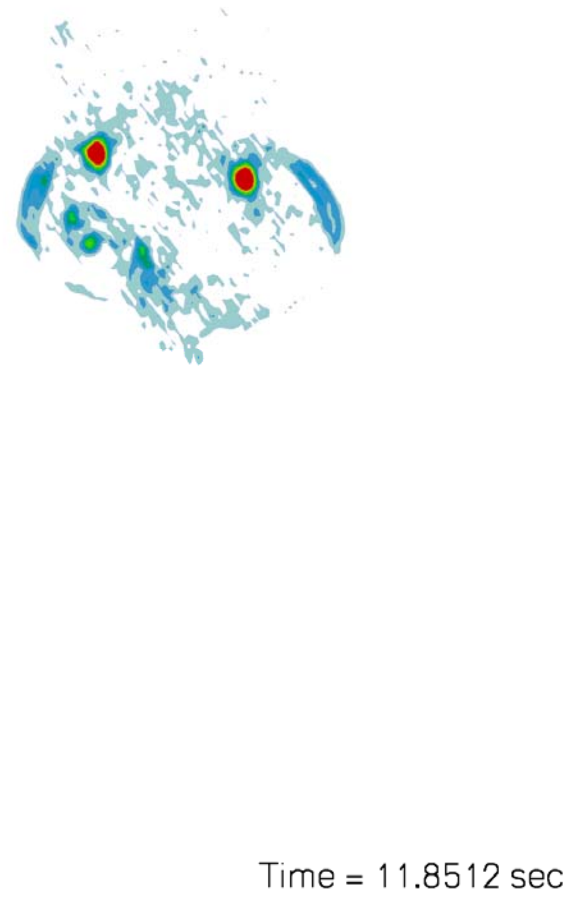
Time = 8.8512 sec

current work
flying through LES domain ...

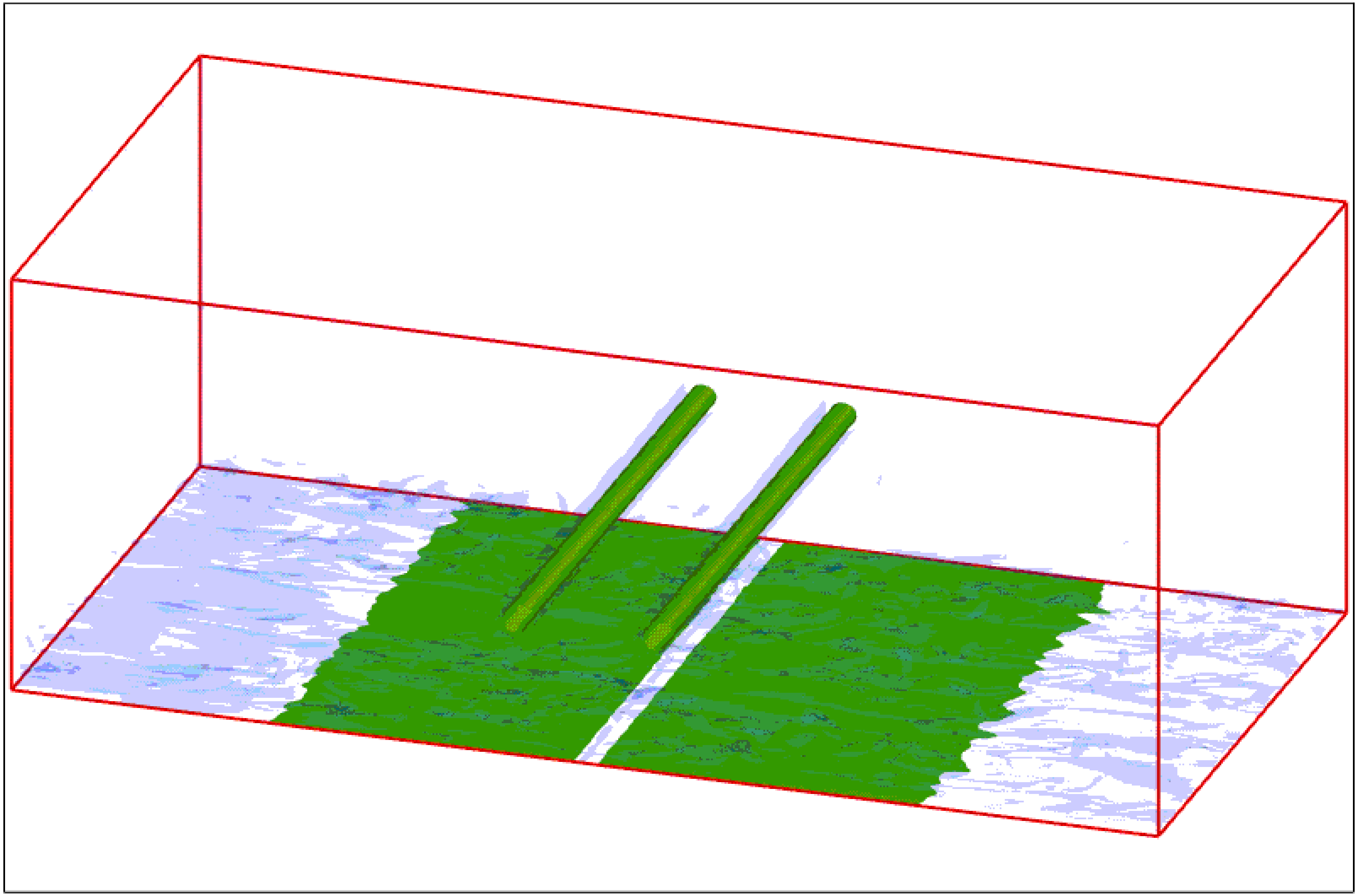
Front view



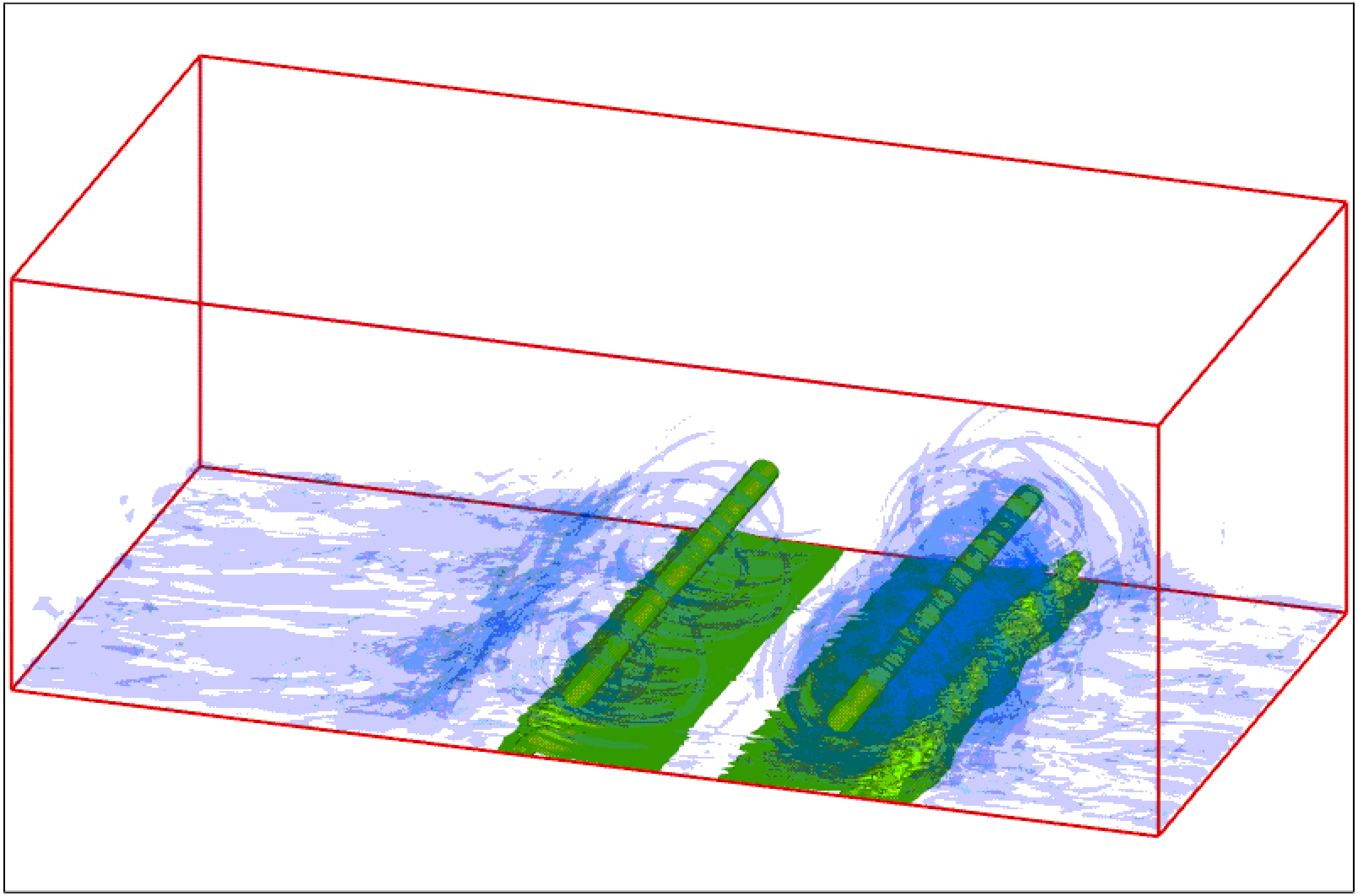
Perspective view



WV evolution in ground proximity with crosswind – LES



WV evolution in ground proximity with crosswind – LES



WV evolution in ground proximity with crosswind – LES