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Wake vortex models, and the associated 3-D velocity fields, for real-time and fast-time WVE simulations

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WakeNet3-Europe Specific Workshop

Models and Methods for Wake Vortex Encounter Simulations

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Institute of Mechanics, Materials and Civil Engineering

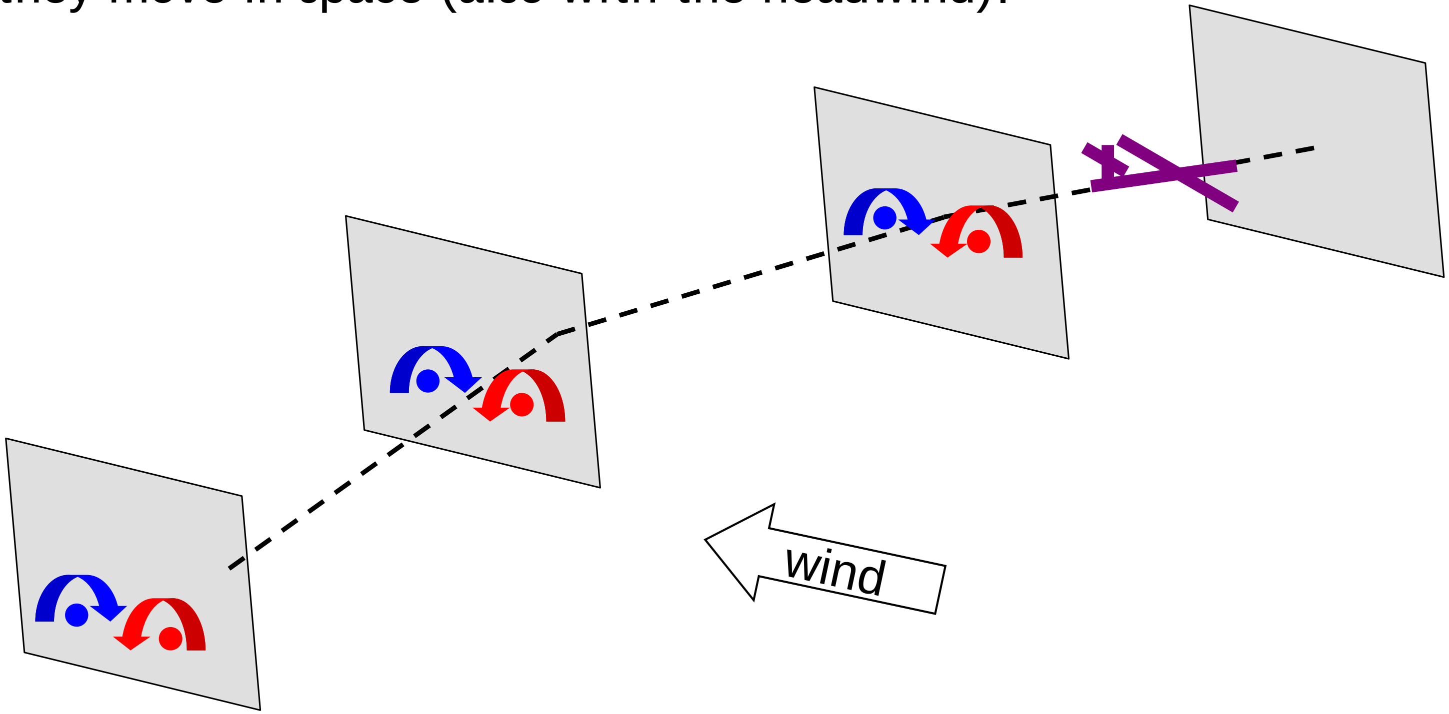
ÉCOLE POLYTECHNIQUE DE LOUVAIN

Outline

- Presentation of the WAKE4D platform
- Vortex circulation distribution models
- Velocity field evaluation using the WAKE4D results
  - Case OGE with Crow instability
  - Case of a typical take-off also with IGE
- Near velocity field induced by a refueling aircraft (2004 project with R. Luckner, Airbus)
- Velocity field computed from LES results
  - Case of a vortex pair evolving in a weakly turbulent atmosphere (with Crow instability)
  - Case of a vortex pair in stratified and weakly turbulent atmosphere
  - Case of a vortex pair in ground proximity with crosswind

WAKE4D platform

- The WAKE4D is a « 3-D space + time » wake vortex prediction platform software.
- It uses as input:
  - the aircraft trajectory
  - the met conditions.
- The computational domain is divided in different “computational” gates crossing the flight path.
- The aircraft crossing one of the gates generates a pair of vortices that are transported and also decay. The gates follow the evolution of the vortices; thus they move in space (also with the headwind).



WAKE4D-DVM and WAKE4D-PVM

- The platform can be run deterministically (using the DVM in each gate) or probabilistically (using the PVM in each gate).

- The Deterministic wake Vortex Model (DVM) forecasts, in real-time, the behaviour (transport and decay) of the wake vortices in one computational gate, using simplified physical models. It takes into account the influences of the a/c characteristics, the wind, the ground proximity, the turbulence and the stratification.

- The Probabilistic wake Vortex Model (PVM) uses the DVM as subtool in a Monte-Carlo approach with variation of the impact parameters (inputs and model coefficients). This enables to obtain the PDF's (and thus the statistics) of the results (positions and circulation) in one computational gate.

- From the 3-D "gate by gate" DVM (resp. PVM) computations, one can rebuild the 3-D wake (resp. envelope of the wake).

- The results can then be interpolated in a fixed control gate (similar to a LIDAR scanning plane).

- In PVM mode, one can also count the vortex present in a given box as a function of time. This is useful for potential encounter analyses (for instance for CSPR) .

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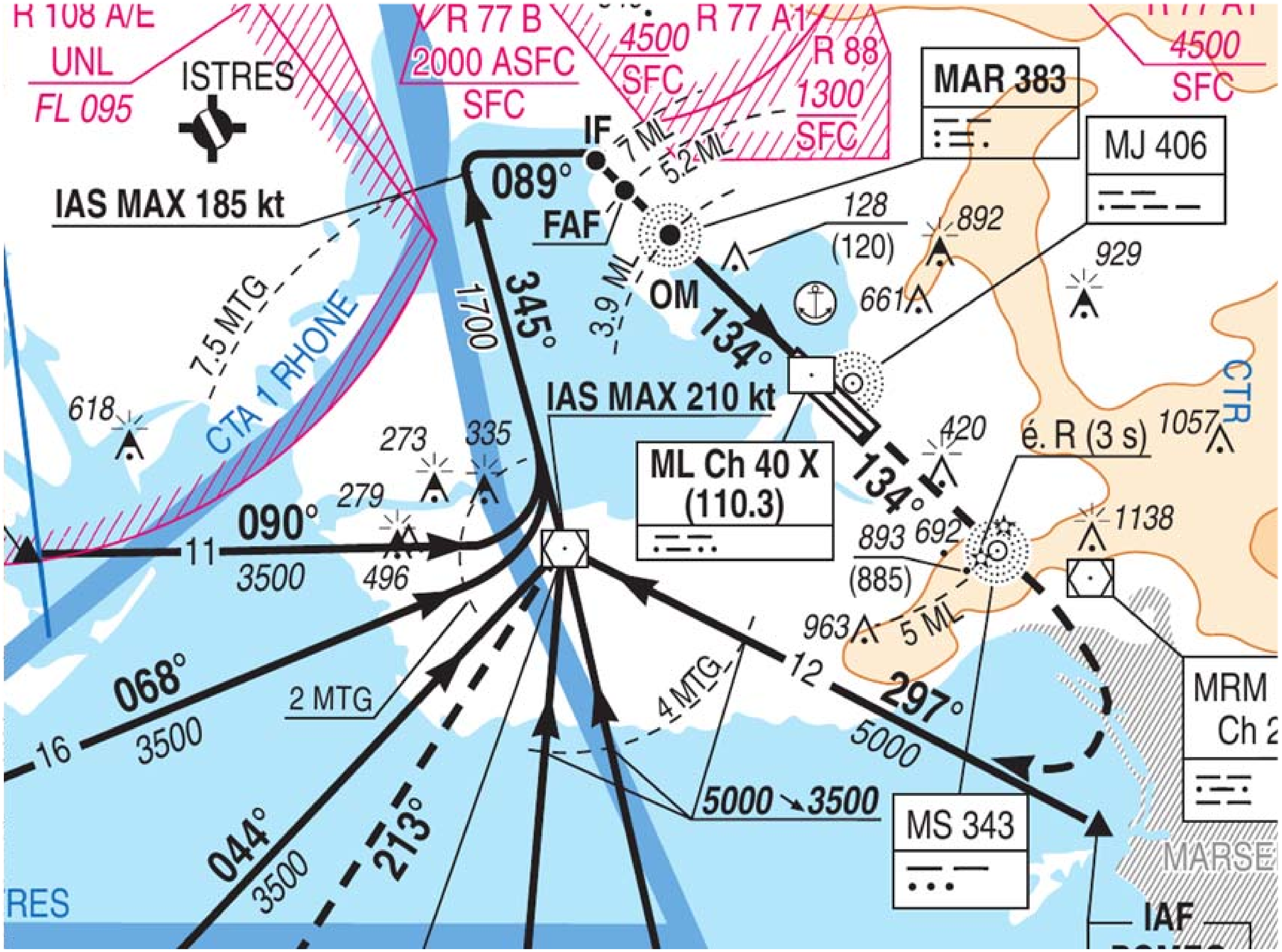
Example of use of WAKE4D : approach to Marseille-Provence

- Aircraft : B747- 400
  - MLW : 285,000 kg
  - b=64.4 m
  - s= 0.75 [-]

- Met. conditions :
  - Southern wind profile (log profile)
  - Turbulence (EDR=10^{-4} m^2/s^3 OGE, then log law)
  - No stratification



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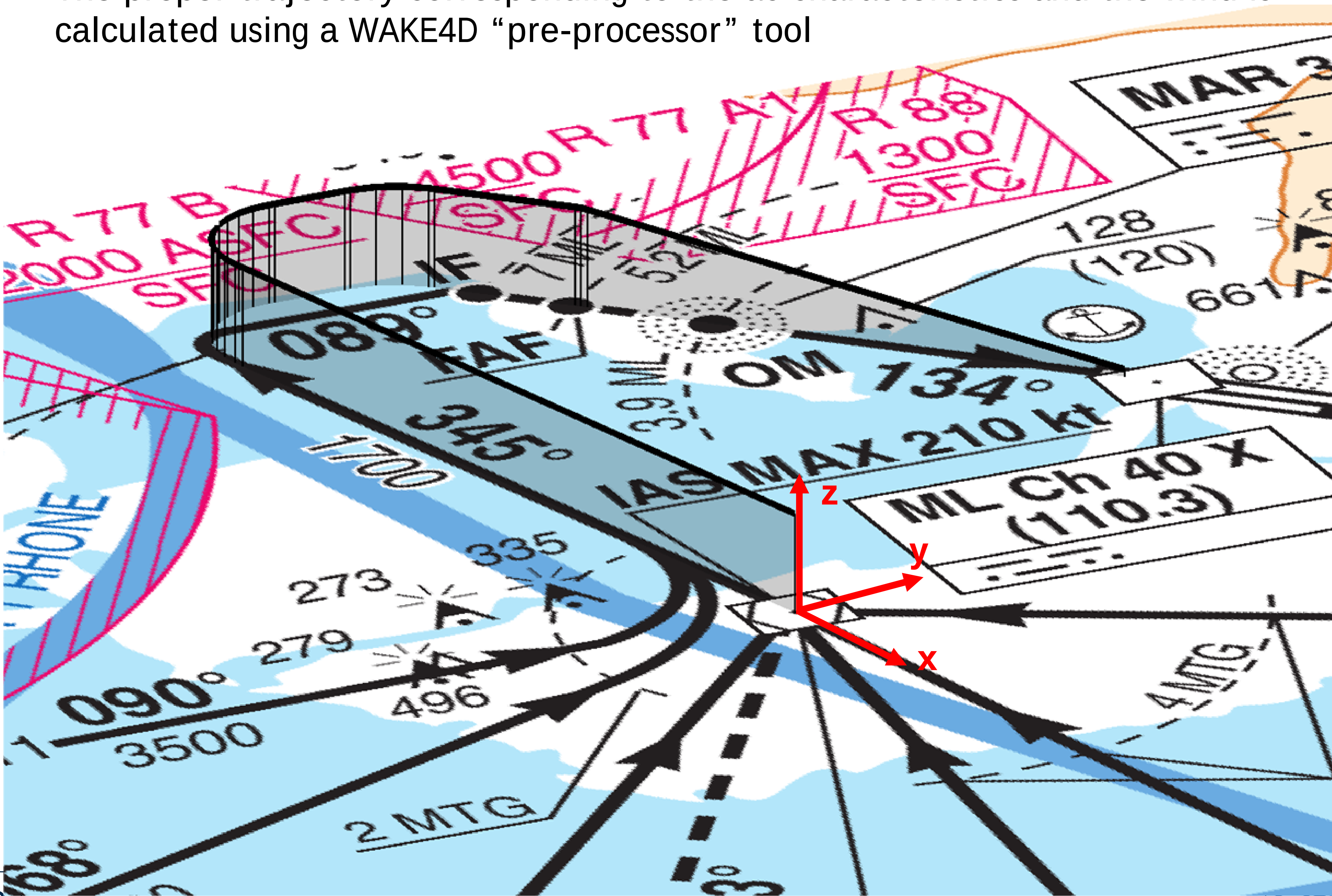
Aircraft trajectory

- The proper trajectory corresponding to the ac characteristics and the wind is calculated using a WAKE4D “pre-processor” tool



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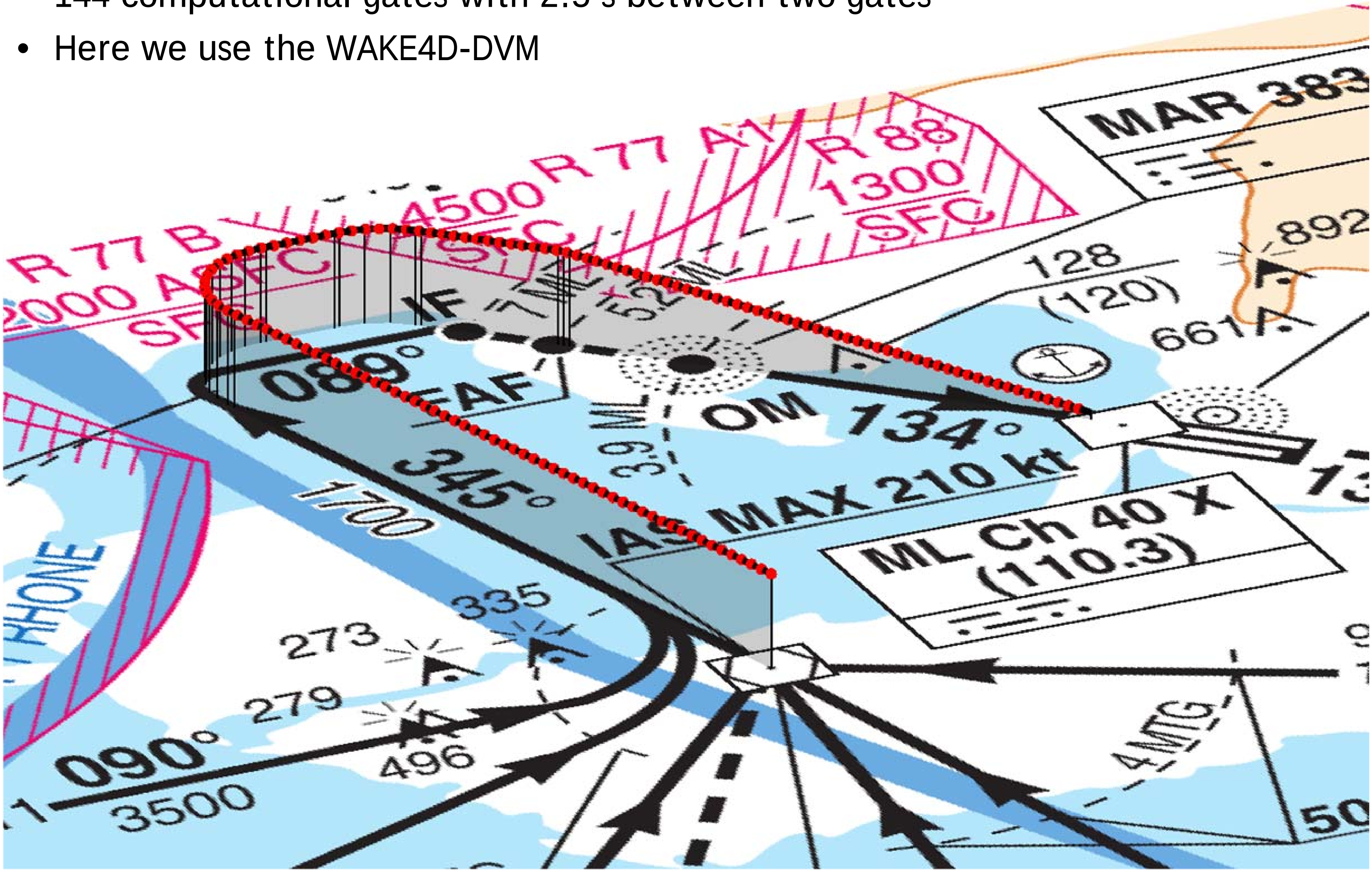
Computational gate locations

- 144 computational gates with 2.5 s between two gates
- Here we use the WAKE4D-DVM



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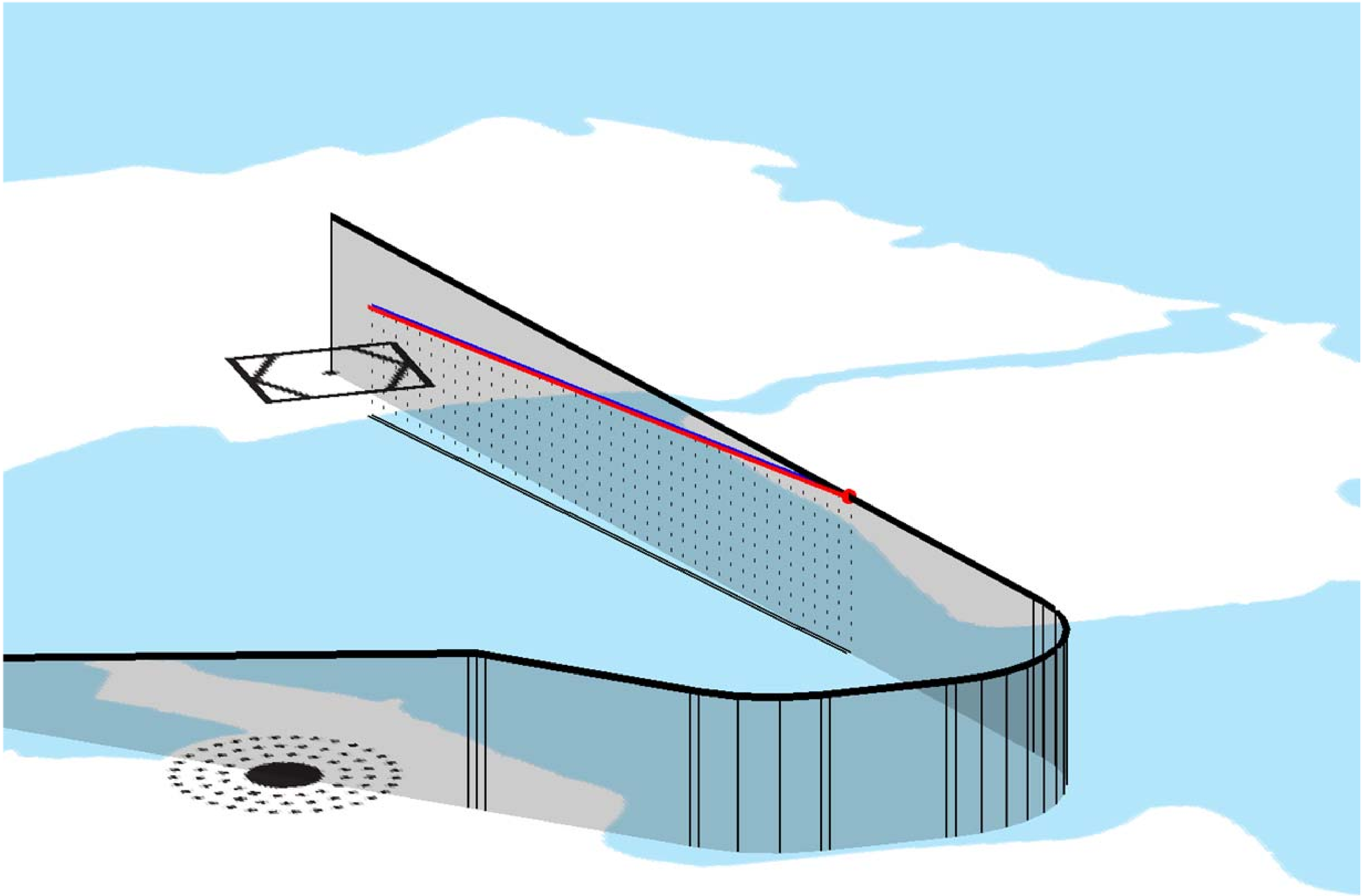
Wake at time t= 100 s



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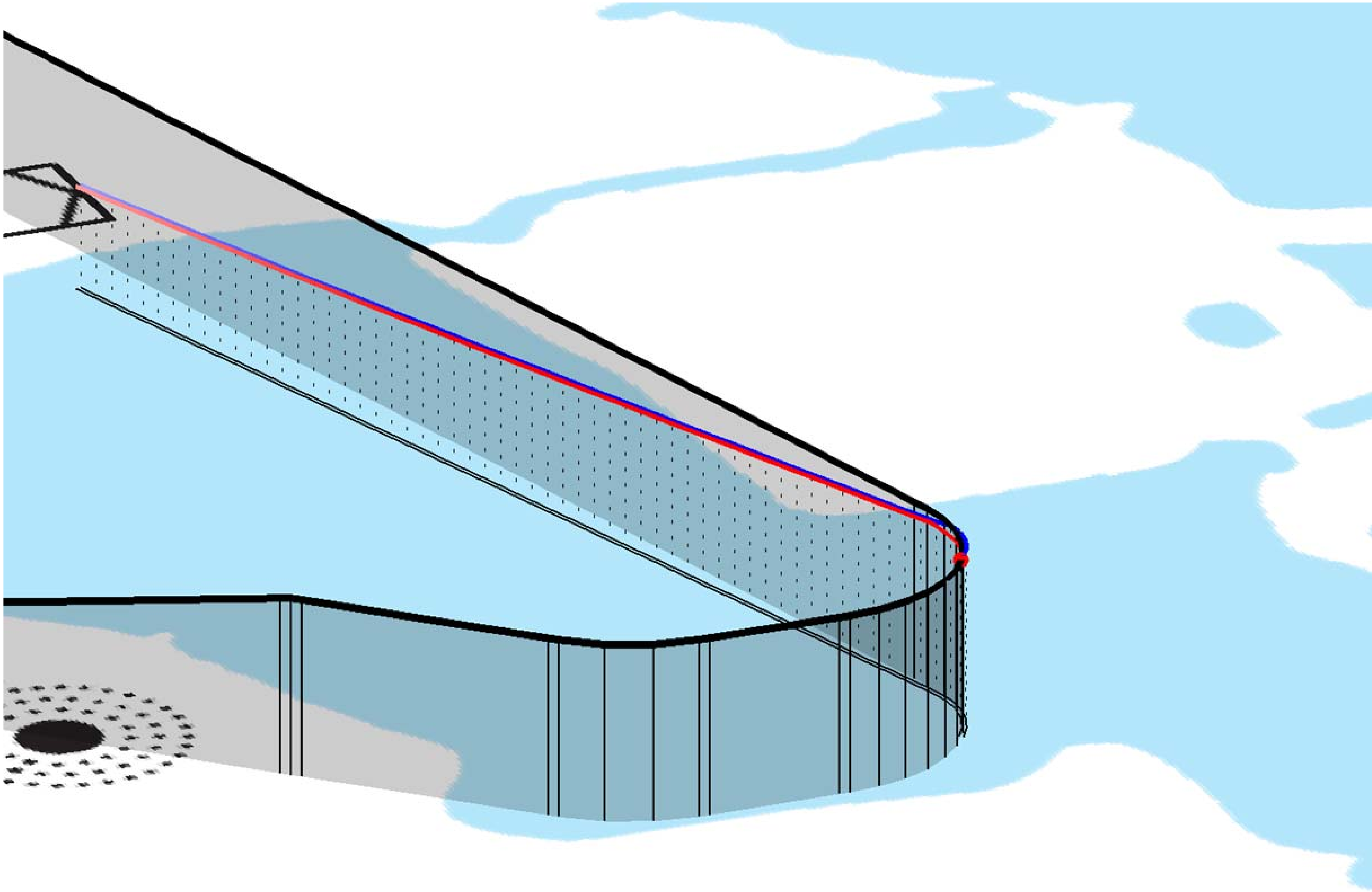
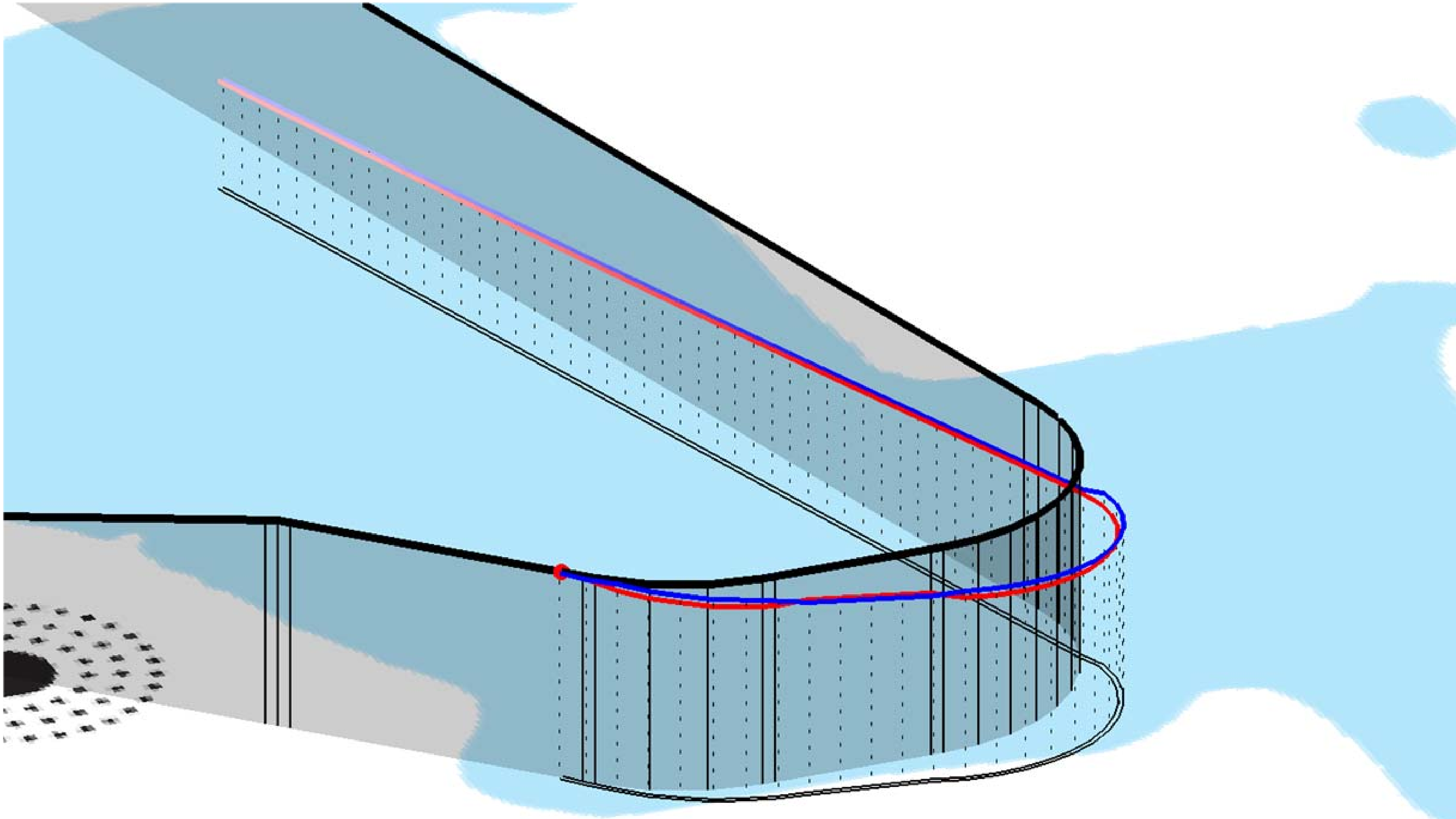
Wake at time t= 150 s



Wake at time t= 200 s



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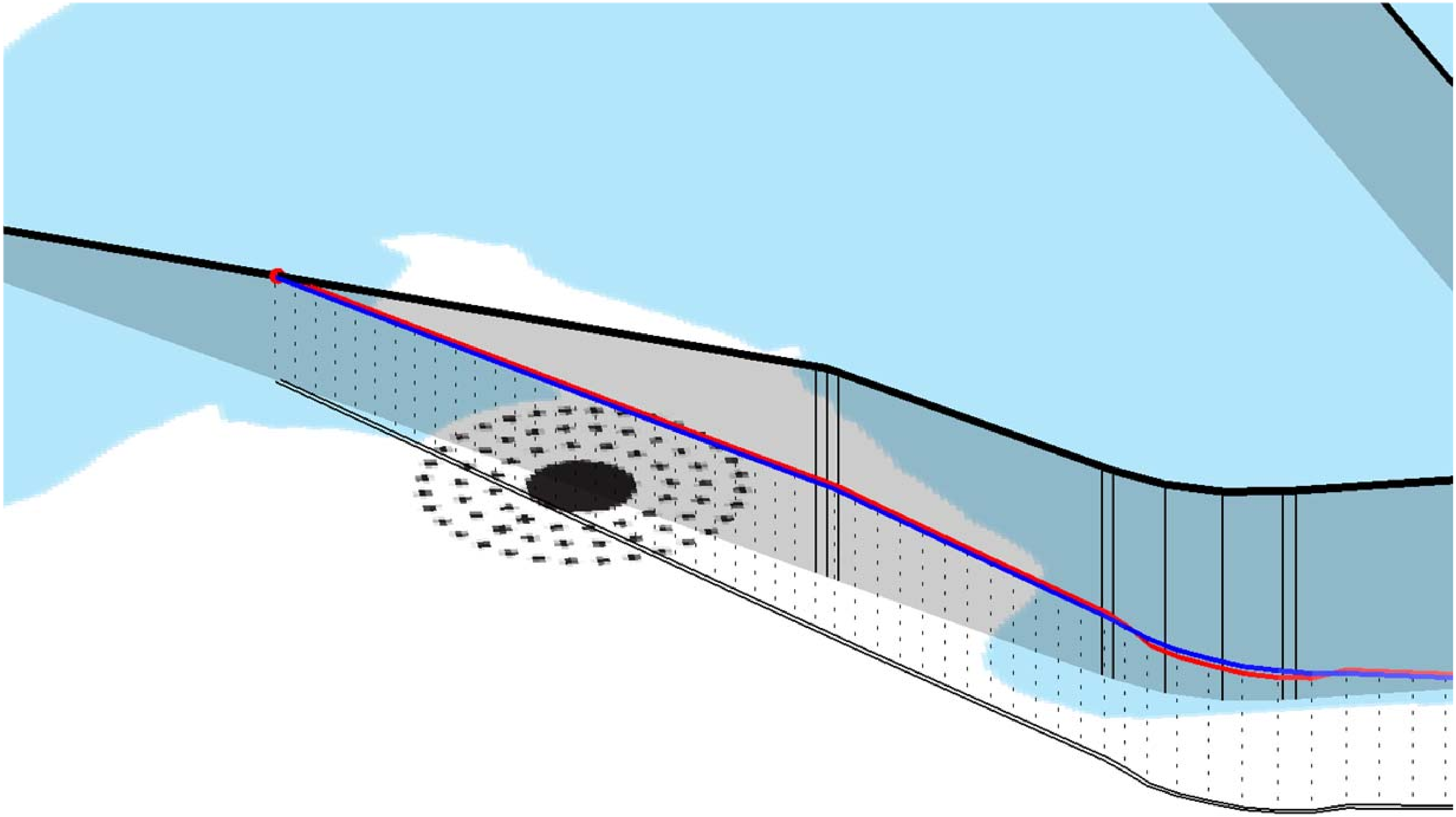
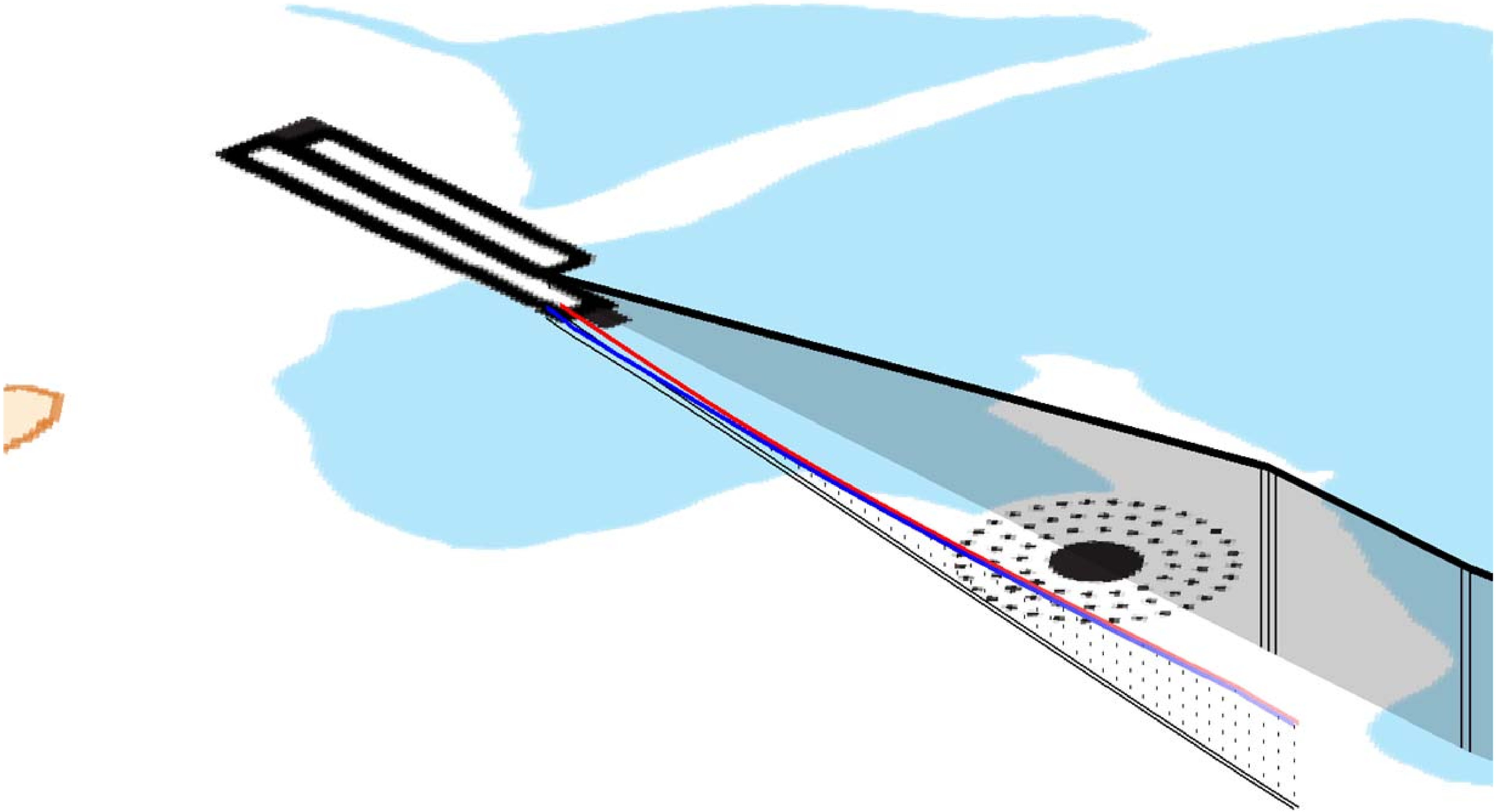
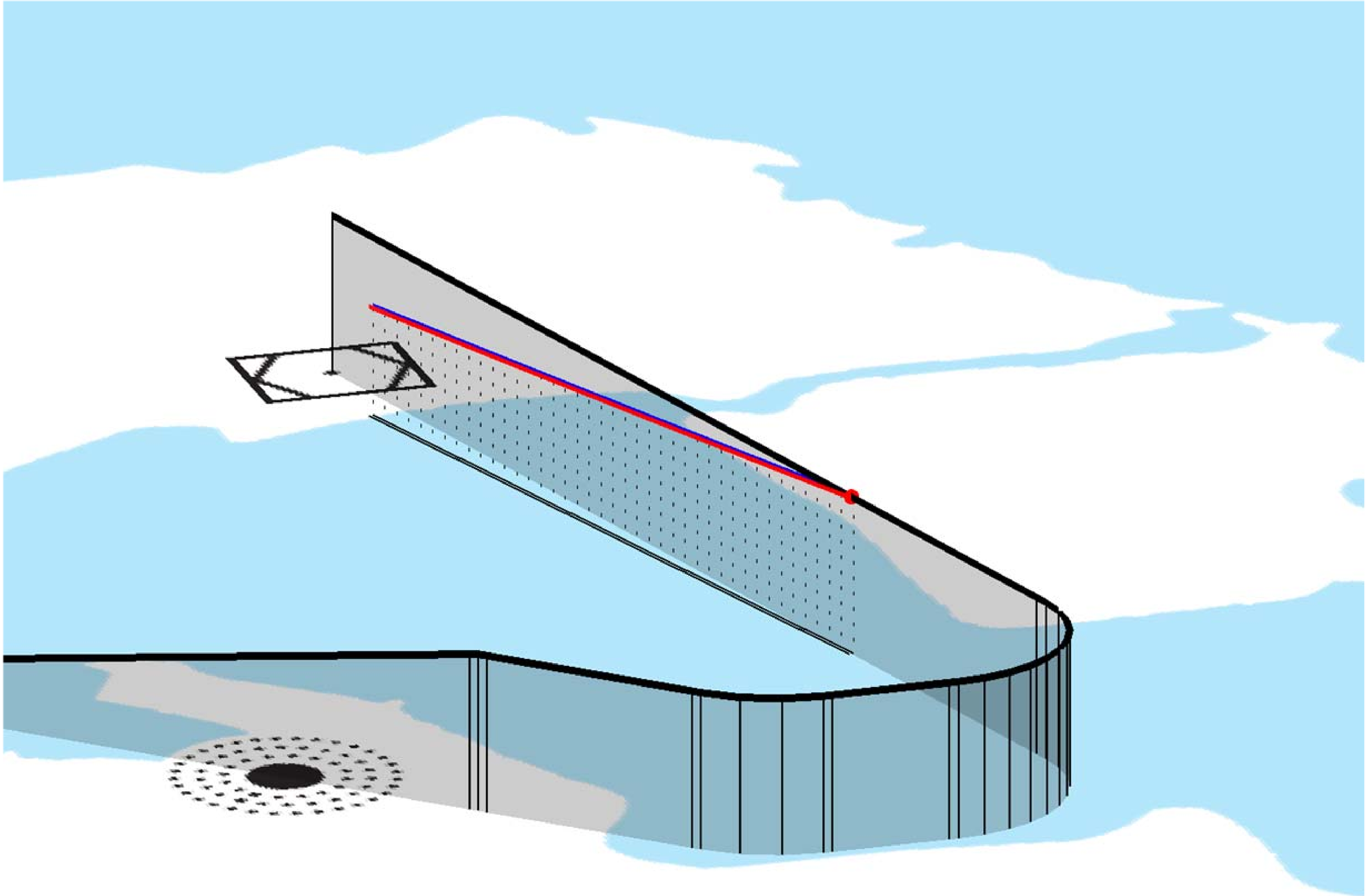
Wake at time t= 300 s



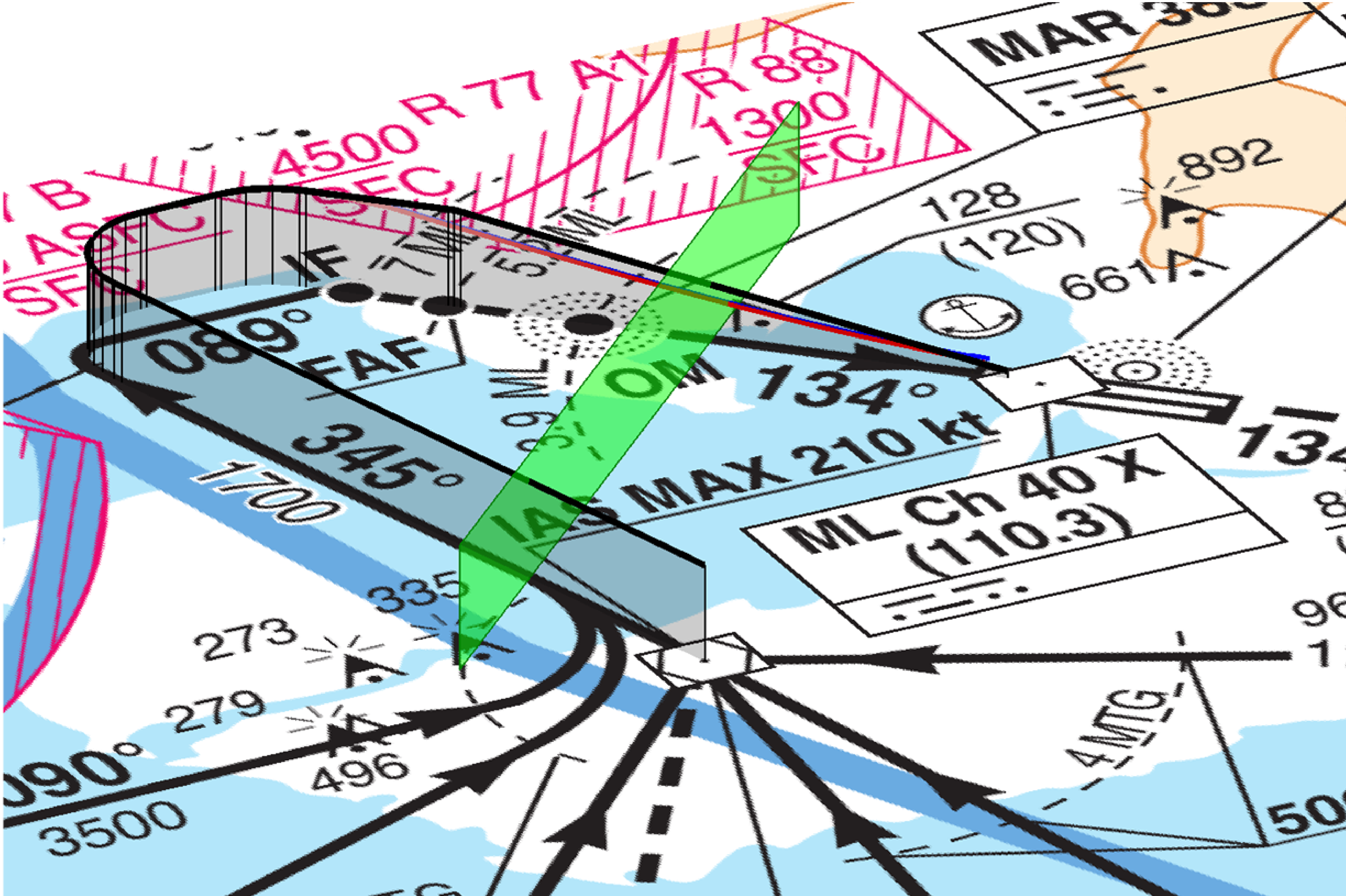
Wake at time t= 400 s



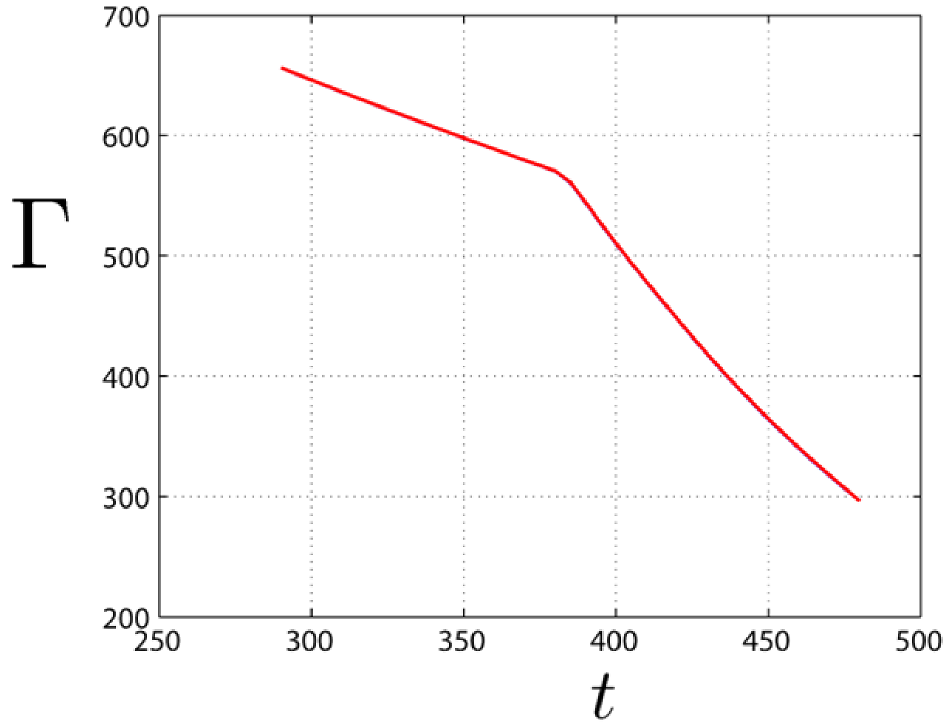
Animation

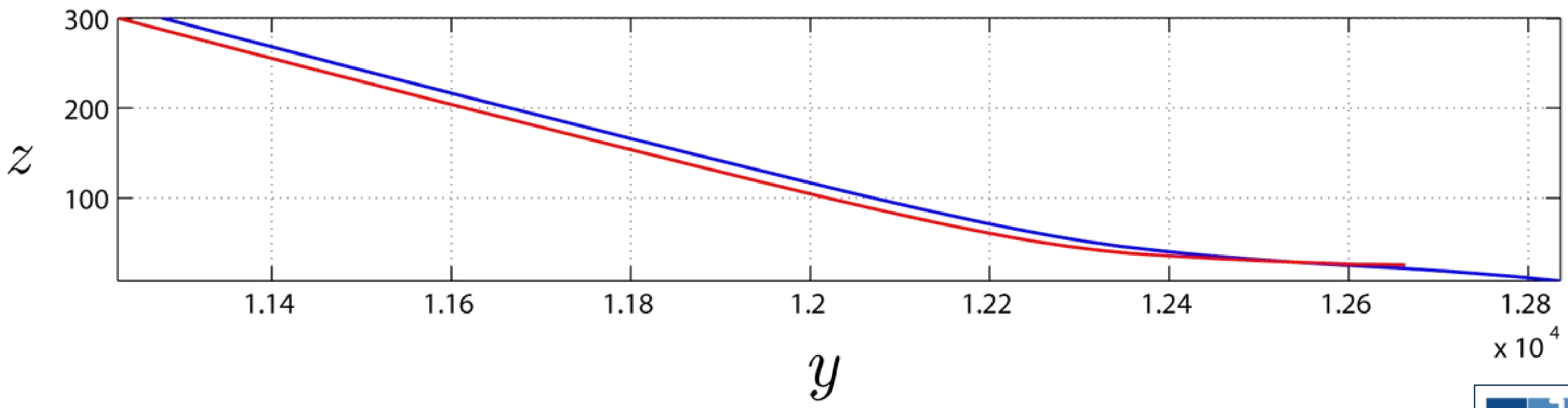


Example of postprocessing: interpolation in a scanning plane



Example of postprocessing: interpolation in a scanning plane





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“One-scale” vortex circulation distribution models

- Definitions :

$$u_\theta(r_c) = \max\left(u_\theta(r)\right) \qquad \Rightarrow \tilde{r} = r/r_c$$

$$\widetilde{\Gamma} = \Gamma/\Gamma_0 \qquad \widetilde{u}_\theta = \frac{u_\theta}{\Gamma_0/(2\pi\, r_c)} \qquad \widetilde{\omega} = \frac{\omega}{\Gamma_0/(\pi\, r_c^2)}$$

	$\widetilde{\Gamma}\,(\tilde{r})$	$\widetilde{u}_\theta\,(\tilde{r})$	$\widetilde{\omega}\,(\tilde{r})$
Gaussian ($\beta = 1.256$)	$1 - \exp\left(-\beta\,\tilde{r}^2\right)$	$\frac{1}{\tilde{r}}\left(1 - \exp\left(-\beta\,\tilde{r}^2\right)\right)$	$\beta \exp\left(-\beta\,\tilde{r}^2\right)$
Low Order Algebraic	$\frac{\tilde{r}^2}{(\tilde{r}^2+1)}$	$\frac{\tilde{r}}{(\tilde{r}^2+1)}$	$\frac{1}{(\tilde{r}^2+1)^2}$
High Order Algebraic ($\gamma = 1.781$)	$\frac{\tilde{r}^2\left(\tilde{r}^2+2\,\gamma\right)}{(\tilde{r}^2+\gamma)^2}$	$\frac{\tilde{r}\left(\tilde{r}^2+2\,\gamma\right)}{(\tilde{r}^2+\gamma)^2}$	$\frac{2\,\gamma^2}{(\tilde{r}^2+\gamma)^3}$
Top Hat $0 \leq \tilde{r} < 1$	$\tilde{r}^2$	$\tilde{r}$	1
$\tilde{r} \geq 1$	1	$\frac{1}{\tilde{r}}$	0

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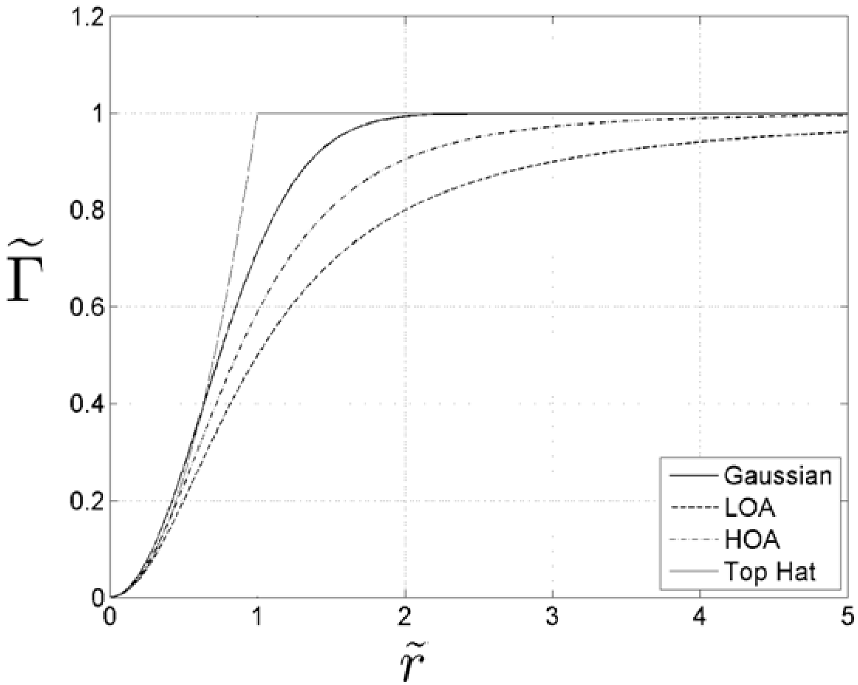
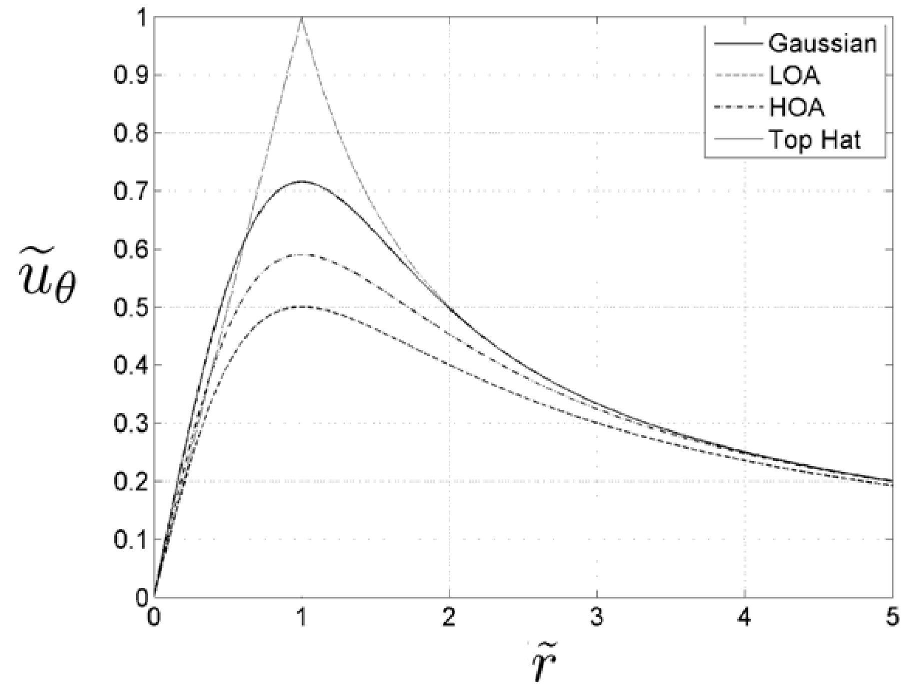
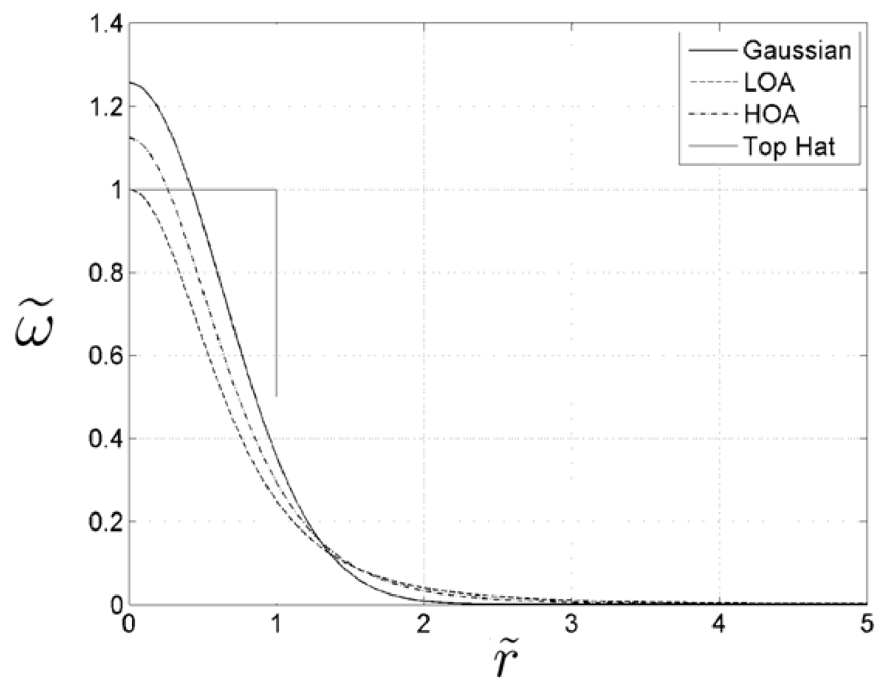
“One-scale” vortex circulation distribution models







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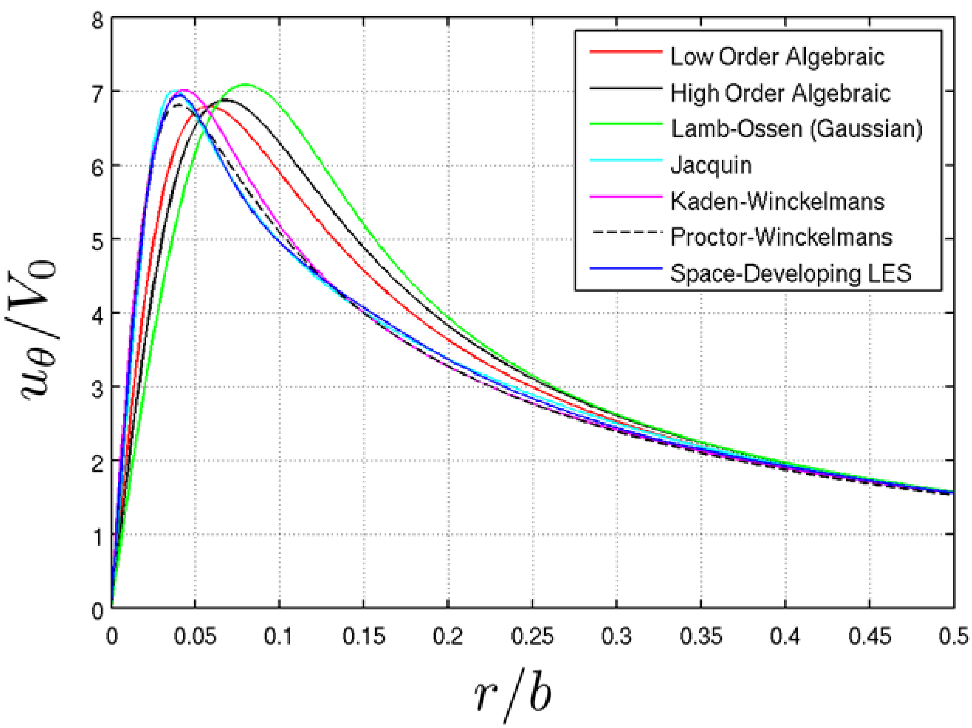
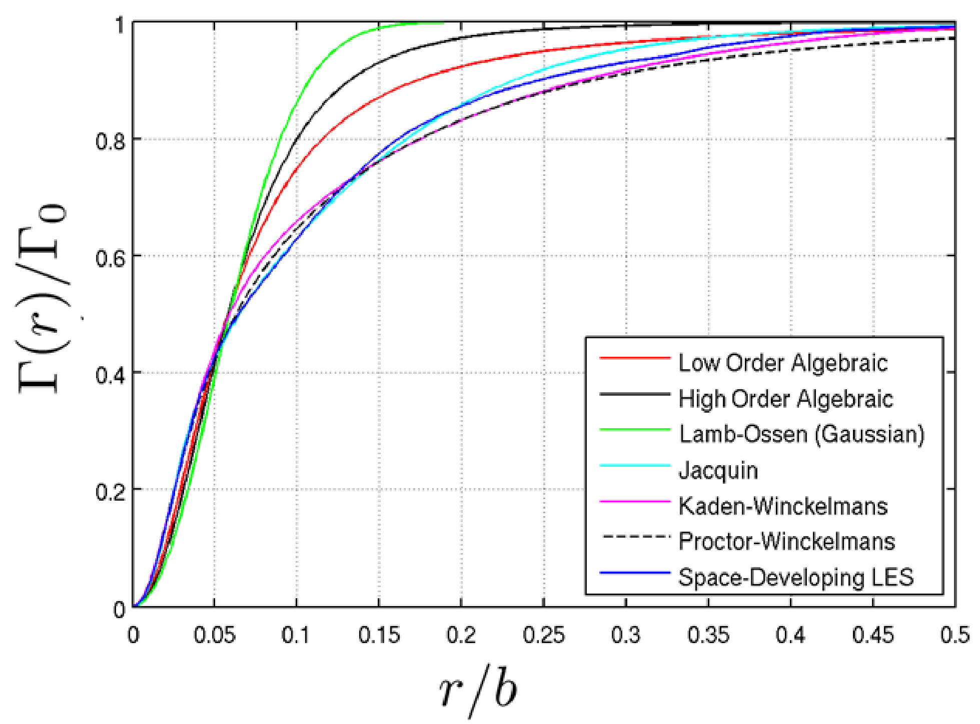
“Two-scales” vortex circulation distribution models

- Those models have 2 DOF (e.g., Jacquin, Proctor-Winckelmans, Kaden-Winckelmans)
- Example: Proctor-Winckelmans model $$\frac{\Gamma(r)}{\Gamma_0} = 1 - \exp\left(- \frac{\beta_i \left(\frac{r}{b}\right)^2}{\left(1 + \left(\frac{\beta_i}{\beta_o}\left(\frac{r}{b}\right)^{5/4}\right)^p\right)^{1/p}} \right)$$

  with $\beta_o = 10$, $p = 3 \ldots 5$, and β_o/β_i determined by r_c/b

- Based on the LES results of a rollup at very high Re, the two-scales models appear to be superior in term of azimuthal velocity and circulation profiles

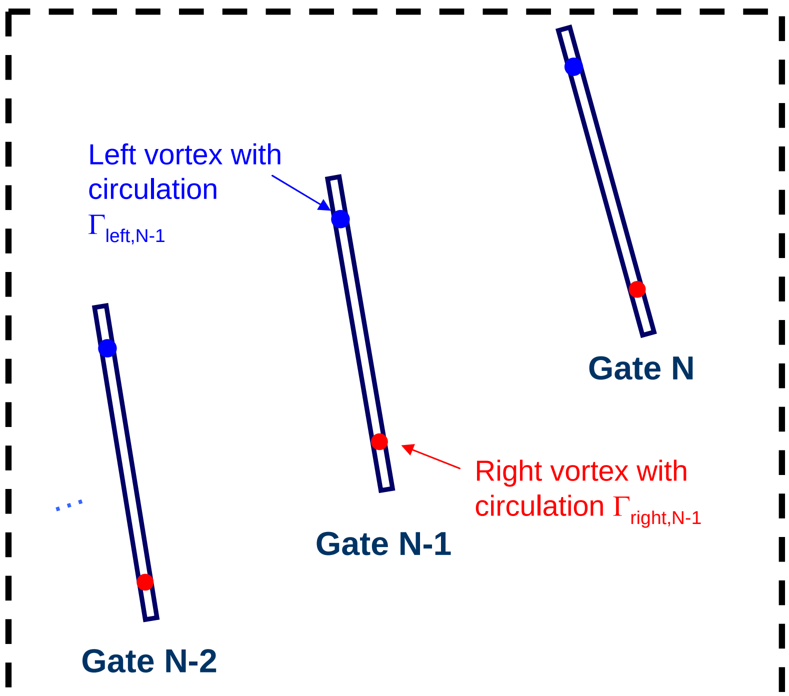




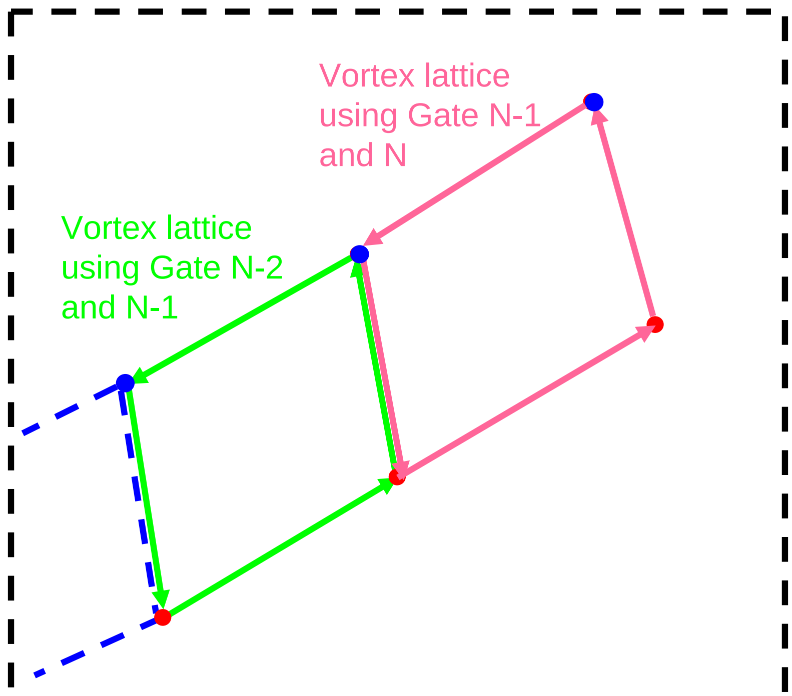
Jackson et al., TP 13629E, 2001
de Bruin and Winckelmans, AW-114-25, Awiator, 2005
Lonfils et al., TR1.1.2-6, Far-Wake, 2008

Induced velocity field evaluation using the WAKE4D results

- Using the “gate by gate” computation, the whole velocity field can be rebuild, as post-processing, using a vortex tube segment approach.
- Between each pair of computational gates, an equivalent vortex lattice (i.e., vortex closed loop) is calculated with an average circulation.
- The total velocity field is calculated by summing the induced velocity of all “active” vortex lattices at a certain point and at a given time.
- If the vortices are close to the ground, the velocity induced by the secondary vorticity is interpolated and added.



WAKE4D outputs at time t



Vortex lattice representation for velocity field evaluation at time t

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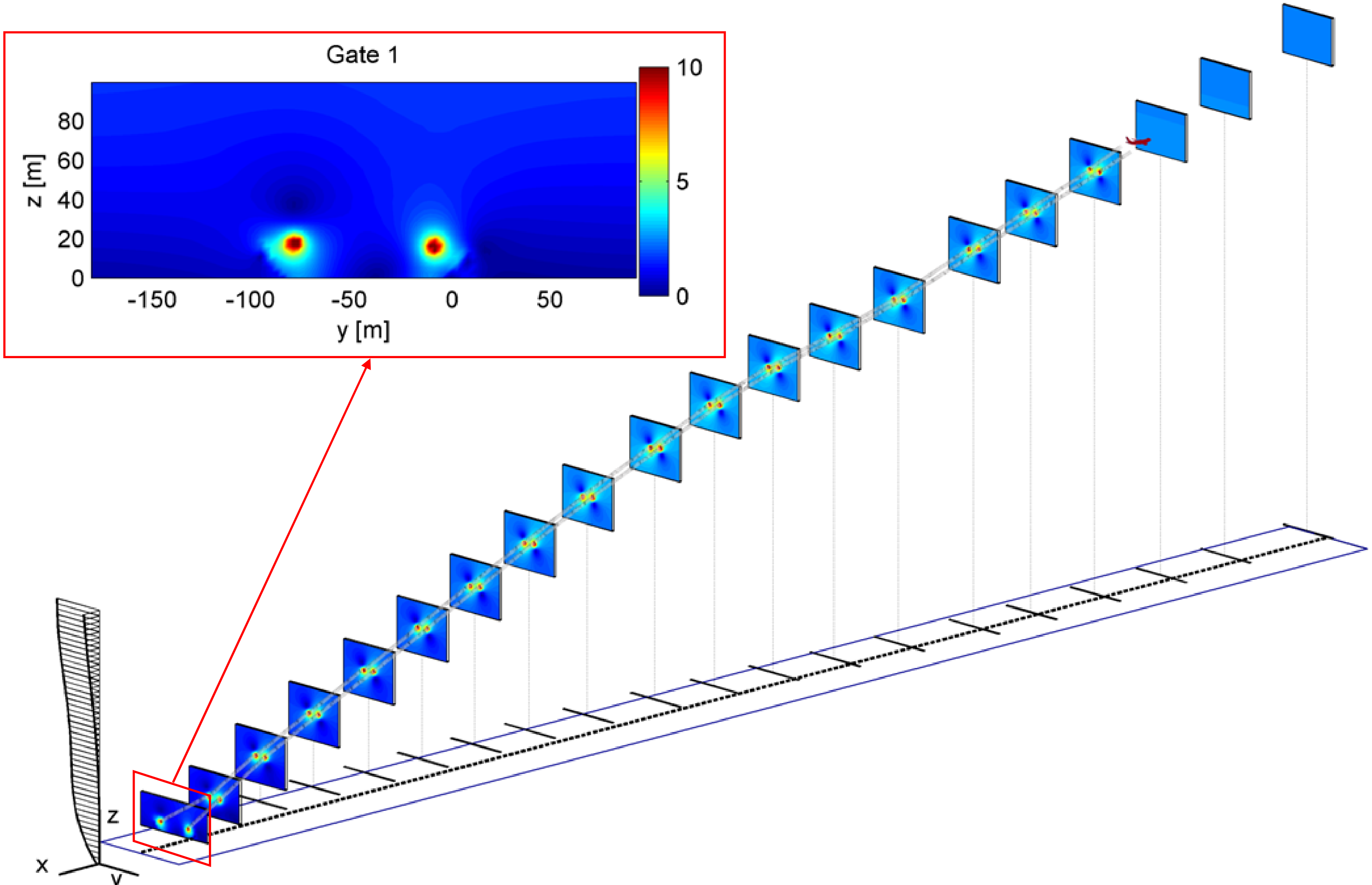
Induced velocity field evaluation using the WAKE4D results

- This approach enables the evaluation of the velocity for complex aircraft trajectory scenarios (e.g., take-off, landing, turns, …)
- This approach was also used in the CREDOS project (WP3)



Velocity norm field computed in several gates along the flight trajectory

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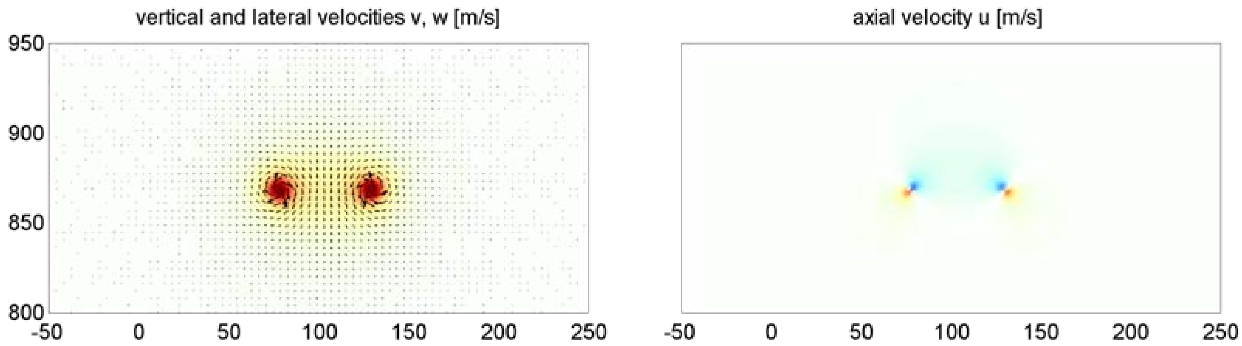
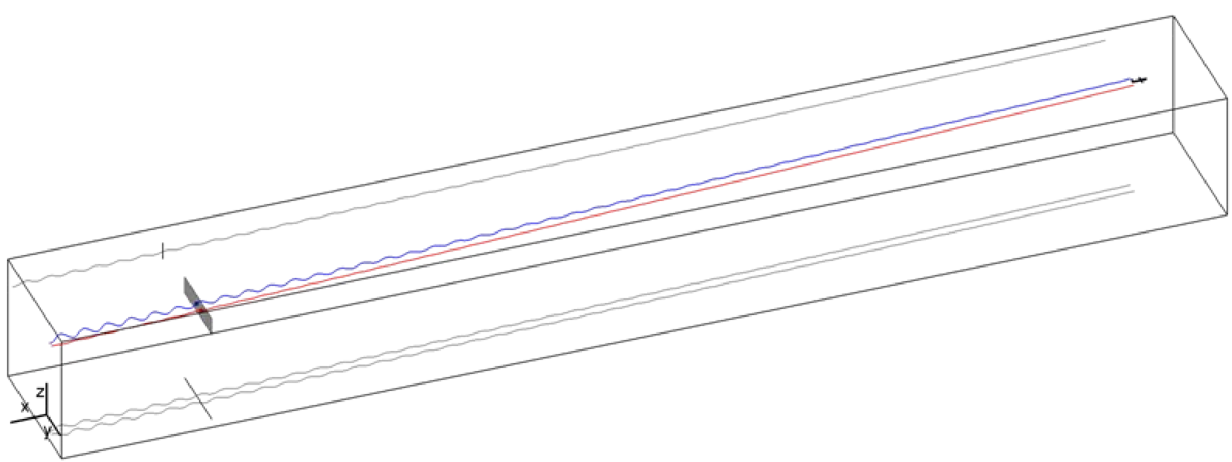
Induced velocity field evaluation using the WAKE4D results with Crow instability effect

- The Wake4D contains a simplified model for the Crow instability that depends on the turbulence level (and thus the time-to-demise)
- As post-processing, the velocity field induced by the deformed vortices can be evaluated, in real-time, using a vortex filaments approach
- This approach is useful for OGE conditions (also cruise), without turns and where Crow effects are important





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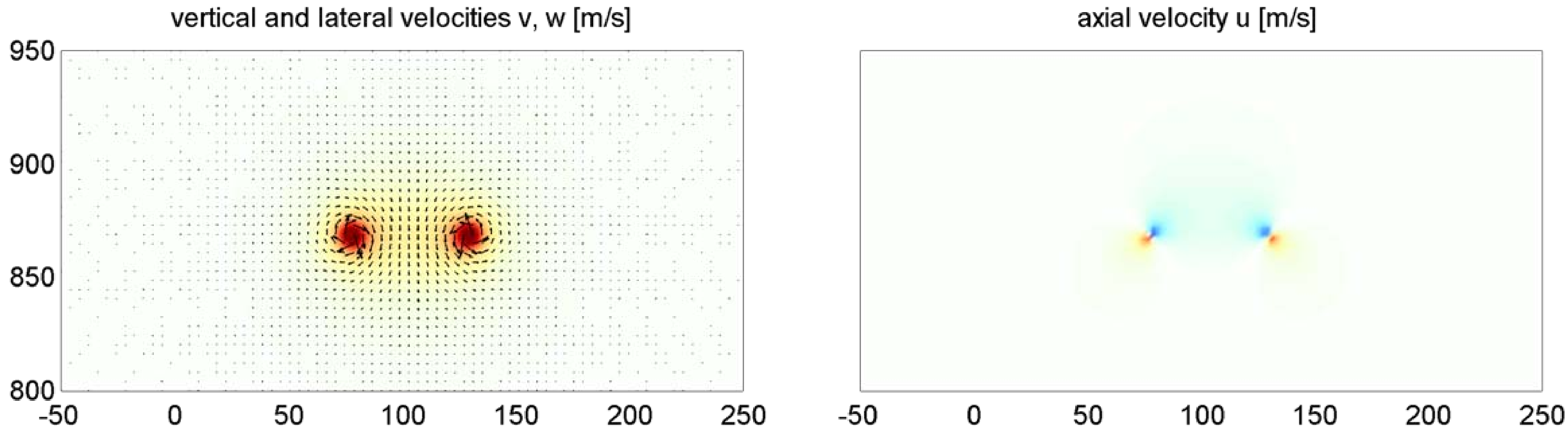
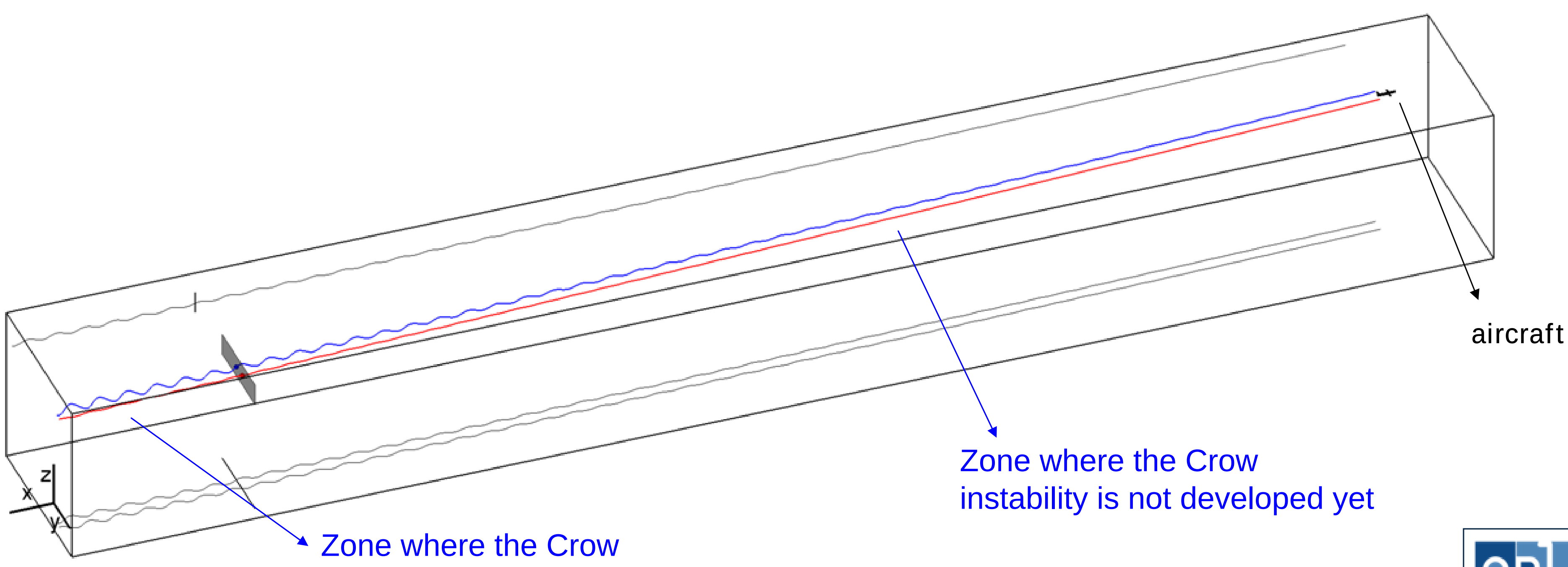
Induced velocity field evaluation using the WAKE4D results with Crow instability effect : example





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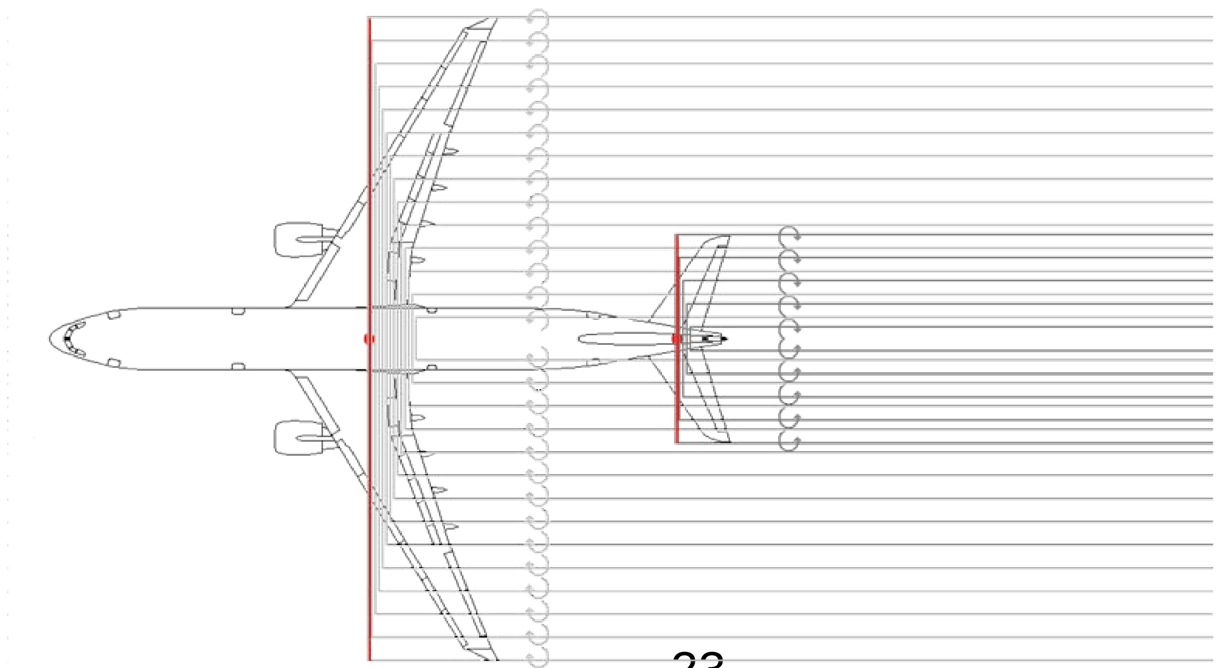
Evaluation of the near velocity field induced by a refueling A330 aircraft: internal project with Airbus (R. Luckner) 2004

- **Aim** was to provide a software module that computes the velocity field experienced by an aircraft flying (in flight simulator) in the near wake of a refueling aircraft.
- Composed of two steps:
  - Vortex rollup pre-simulation using a vortex method based on “horseshoe vortex filaments”
  - Module with efficient evaluation of the velocity components induced by the various “horseshoe vortex filaments”: much faster than real time, and was used successfully in THOR flight simulator by Airbus



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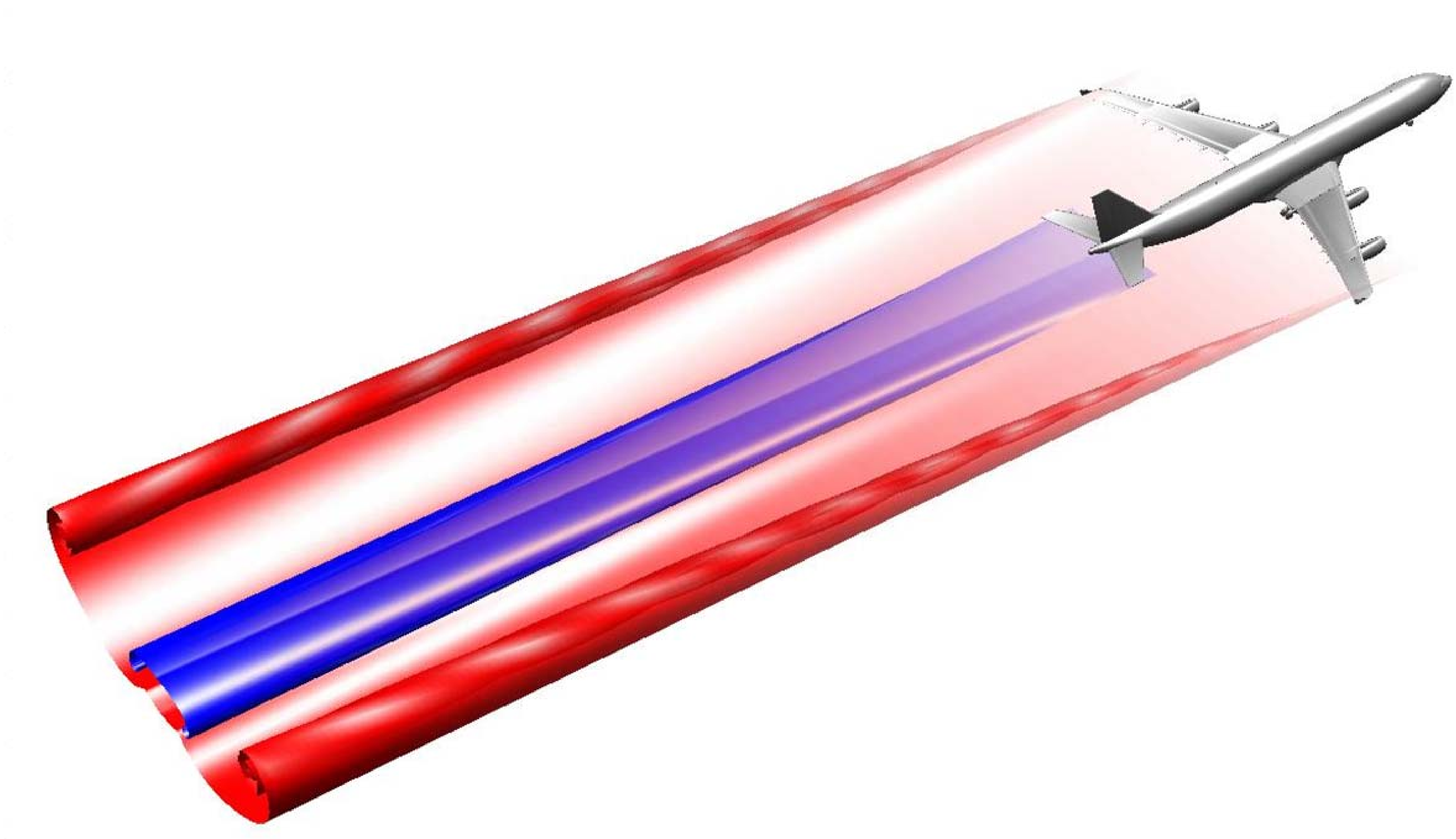
Evaluation of the near velocity field induced by a refueling A330 aircraft

- View of 3D near wake rollup as obtained using the developed routine



Duquesne and Winckelmans, Tech. Report, UCL, 2004

Velocity field induced by wake vortices computed from LES

- In order to represent even more precisely the velocity field induced by vortices evolving in the atmosphere, we can use results of Large Eddy Simulations (LES)

- We can obtain detailed velocity fields of wake vortices in specific realistic conditions

- LES remains expensive in computing time (using parallel computing, etc.) => obviously not real-time

- Nevertheless, the resulting velocity fields can be stored and used operationally as input in a fast “velocity field evaluation” routine

- 3 examples are here shown :
  - Vortices OGE evolving in a weakly turbulent atmosphere leading to the development of the Crow instability, also with reconnection and further decay
  - Vortices OGE evolving in a stratified and weakly turbulent atmosphere
  - Vortices evolving in ground proximity (IGE) and with crosswind

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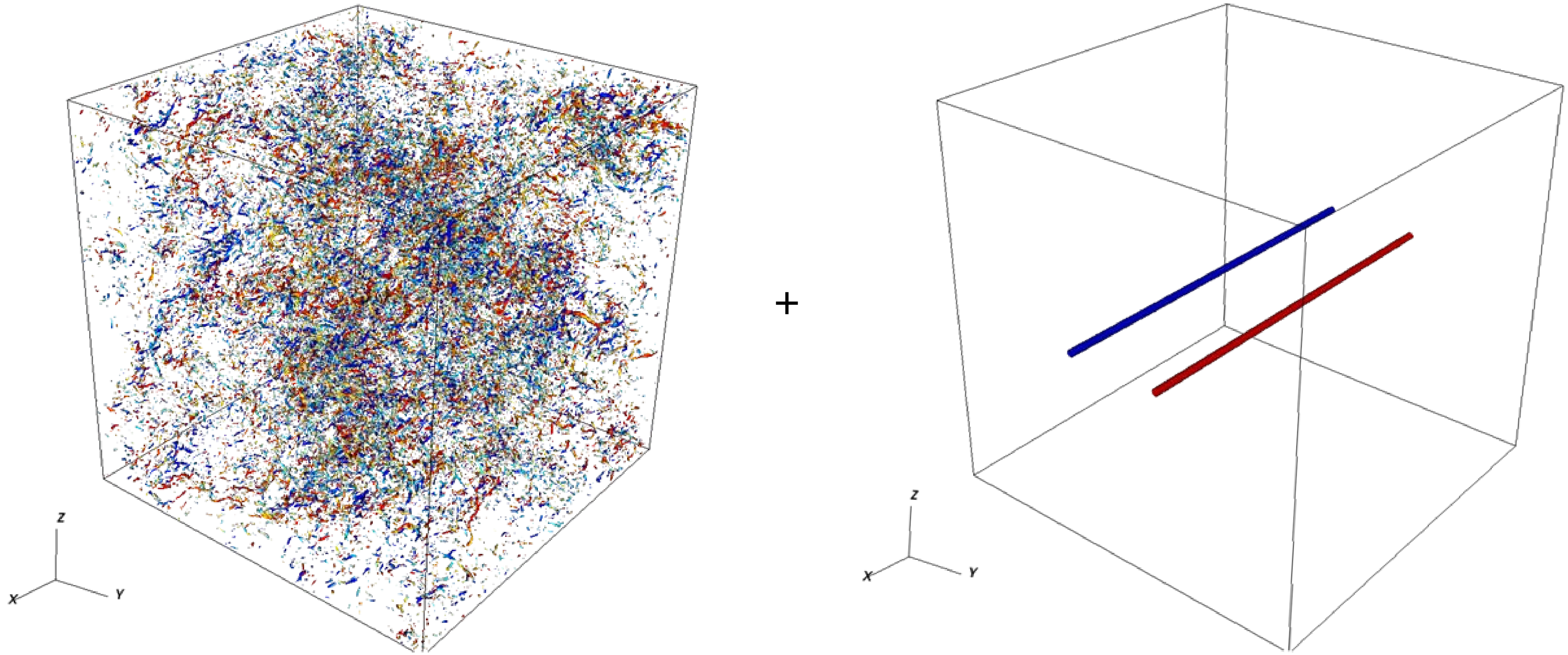
LES of a wake vortex pair evolving in a weakly turbulent atmosphere

Vorticity field (saturated as weak turbulence)



- Pre-simulation of forced turbulence (also using LES)
- LES of a vortex pair evolving in the computed turbulent field

- Pseudo Spectral Code
- very high Re
- ~130 millions grid points
- ~ 1 month on 64 CPU’s

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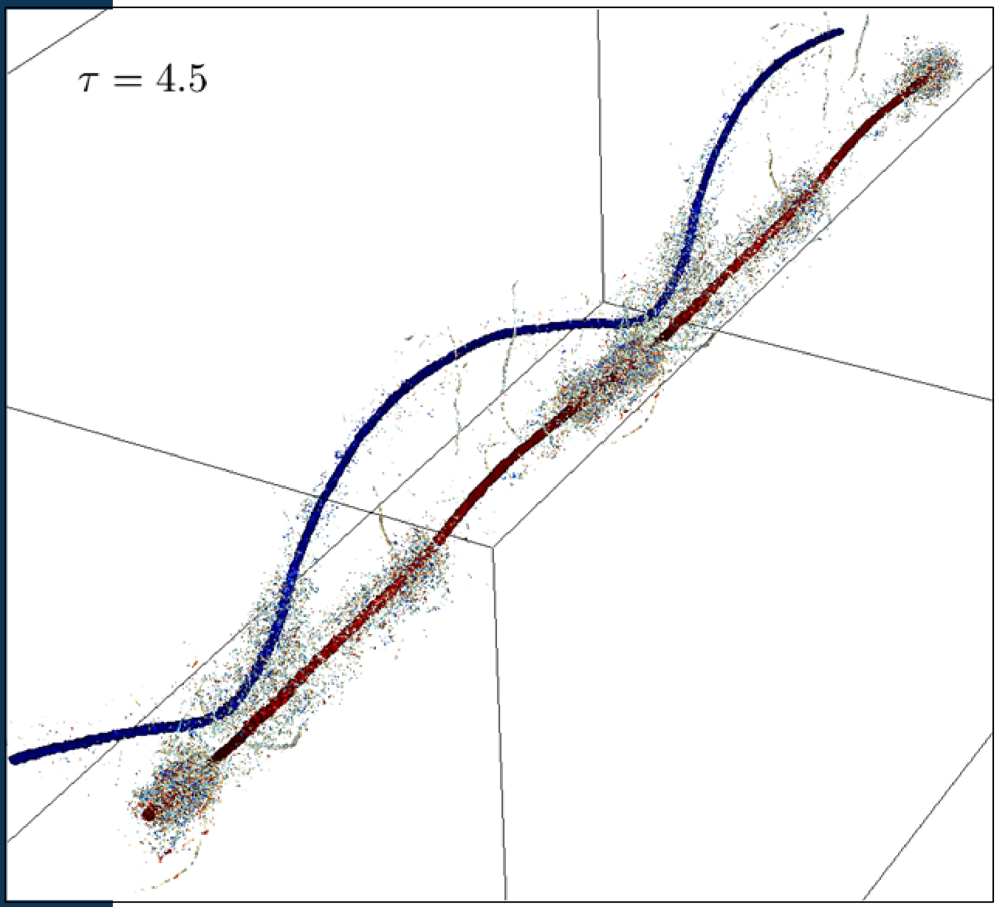
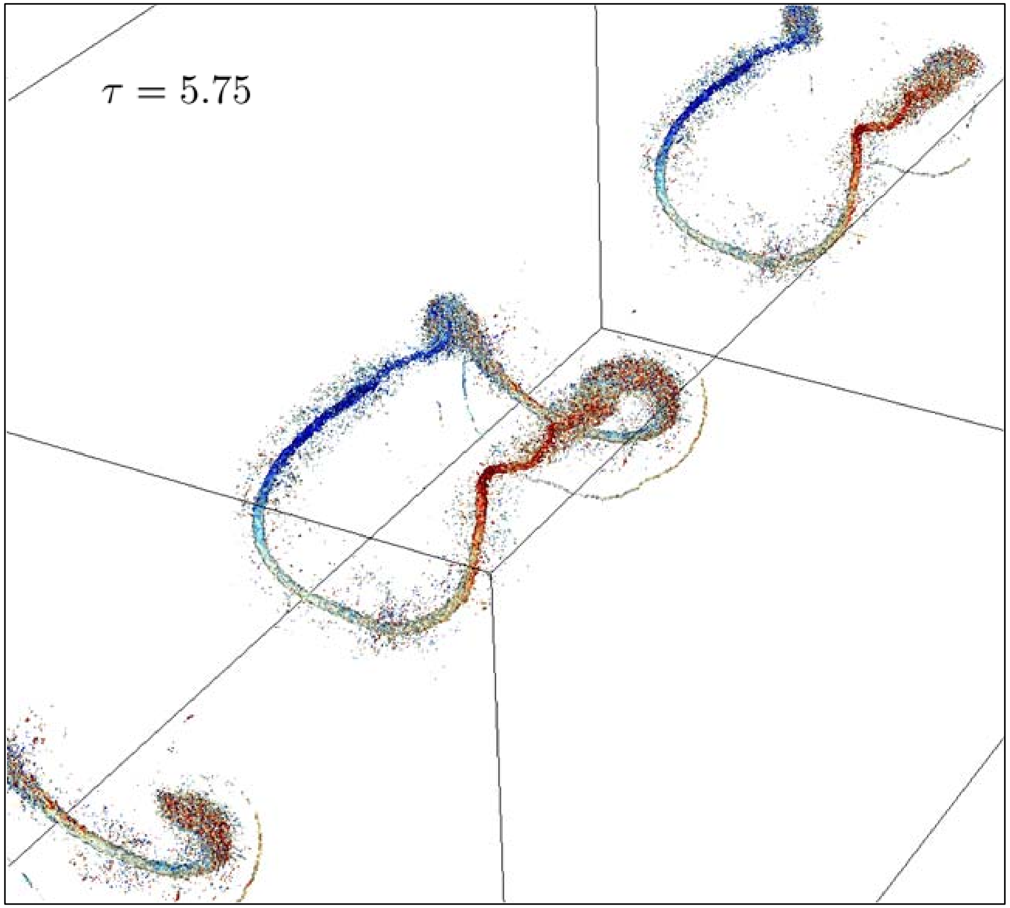
Crow instability





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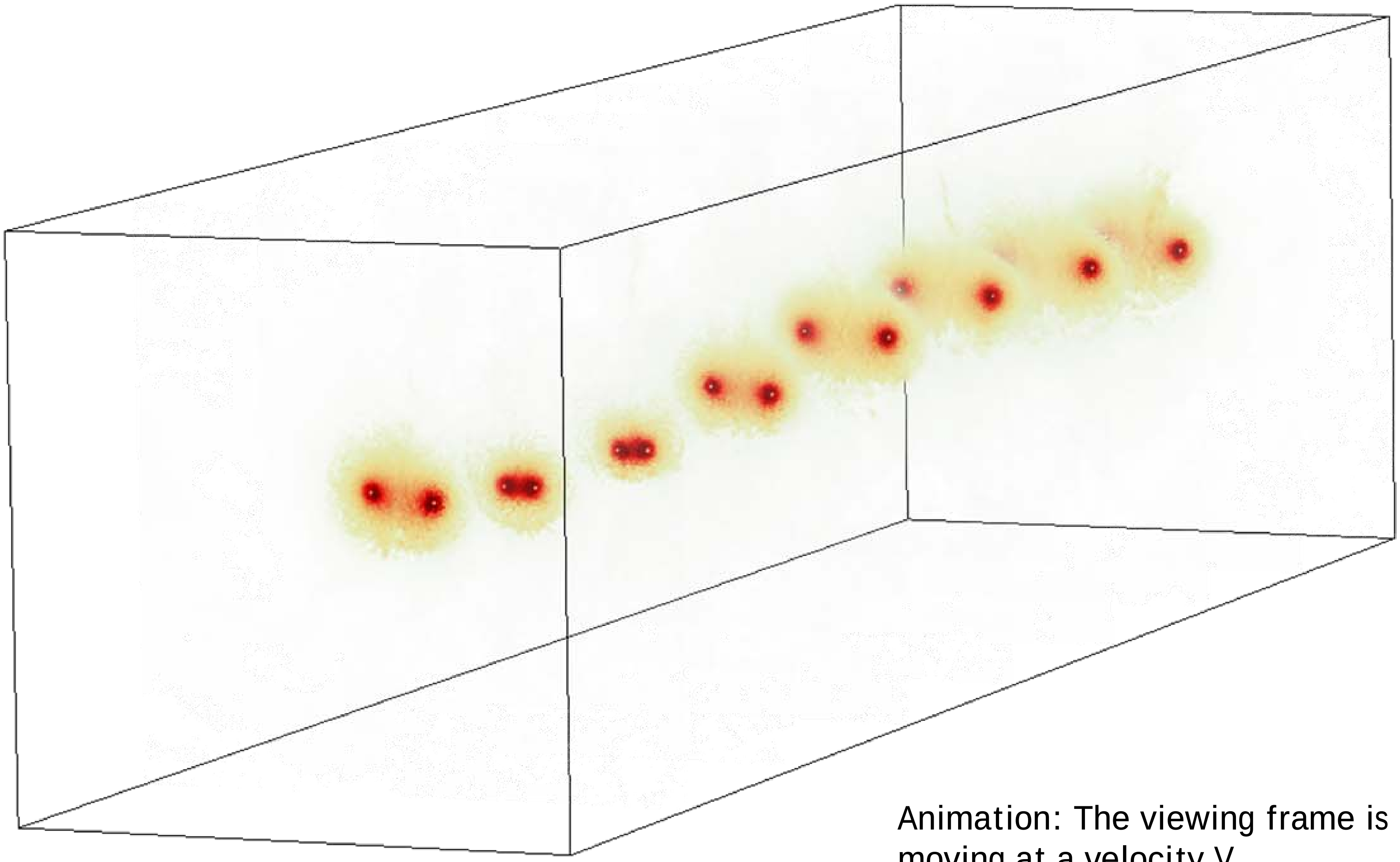
Velocity norm in several planes



Animation: The viewing frame is moving at a velocity V_0

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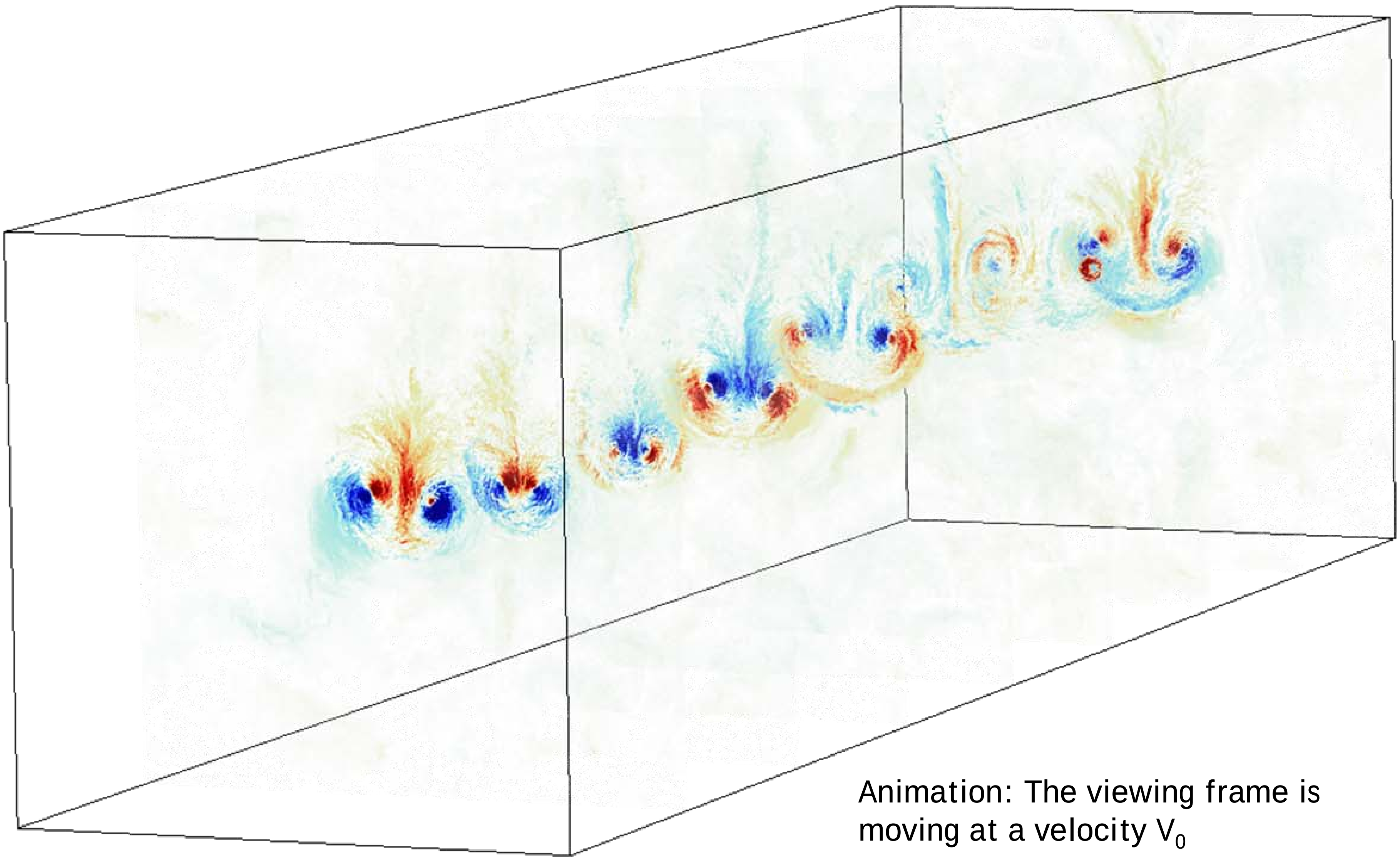
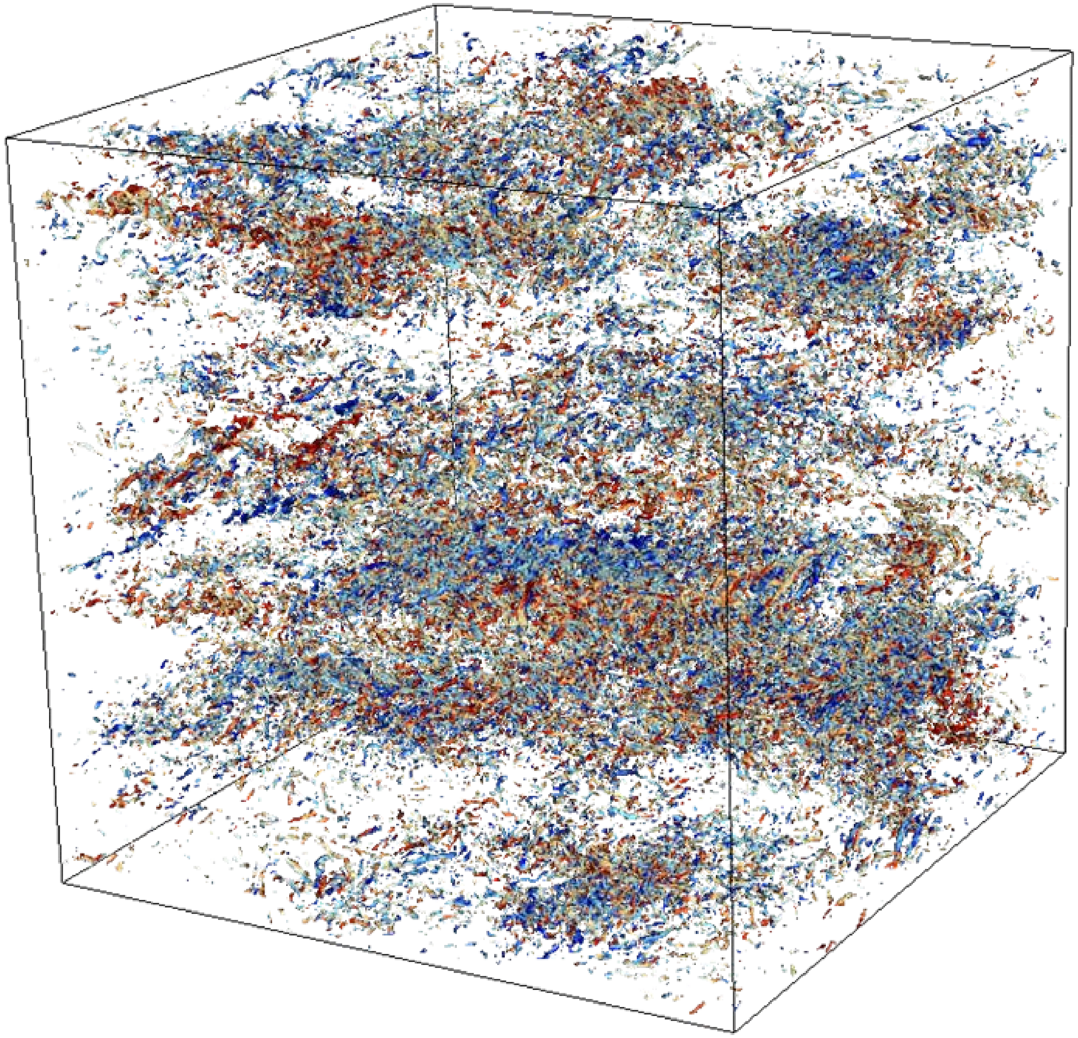
Axial velocity in several planes



Animation: The viewing frame is moving at a velocity V_0

LES of a wake vortex pair evolving in a stratified and weakly turbulent atmosphere

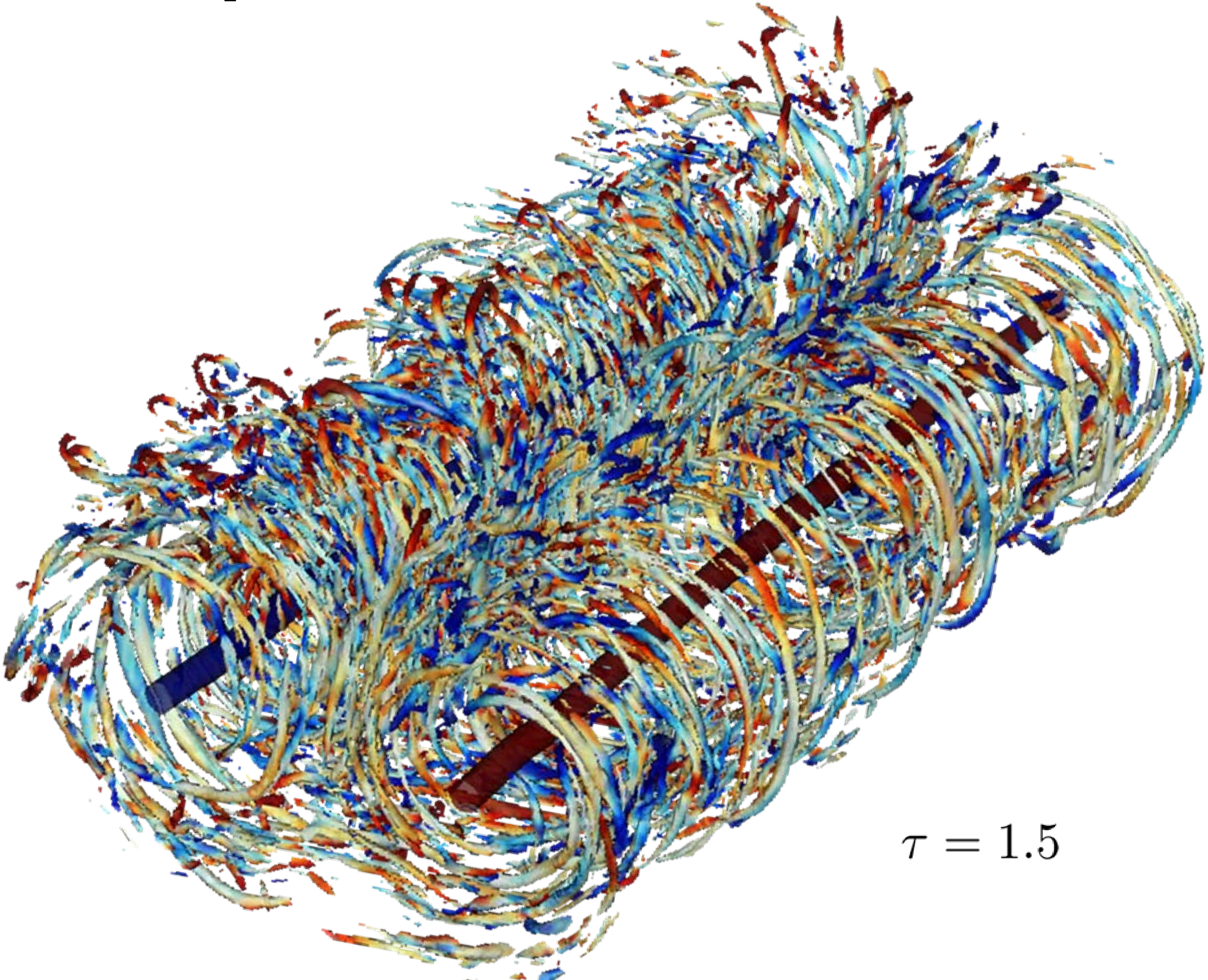


Iso-surfaces of λ_2 colored by the axial vorticity for the case N*=1.0

- Pre-simulation of forced stratified turbulence (also using LES)
- LES of a vortex pair evolving in the computed field
- 4 studied stratification levels from low (N*=0.35) to very high (N*=1.4)

LES of a wake vortex pair evolving in a stratified and weakly turbulent atmosphere

Iso-surfaces of λ_2 colored by the axial vorticity for the case N*=1.0



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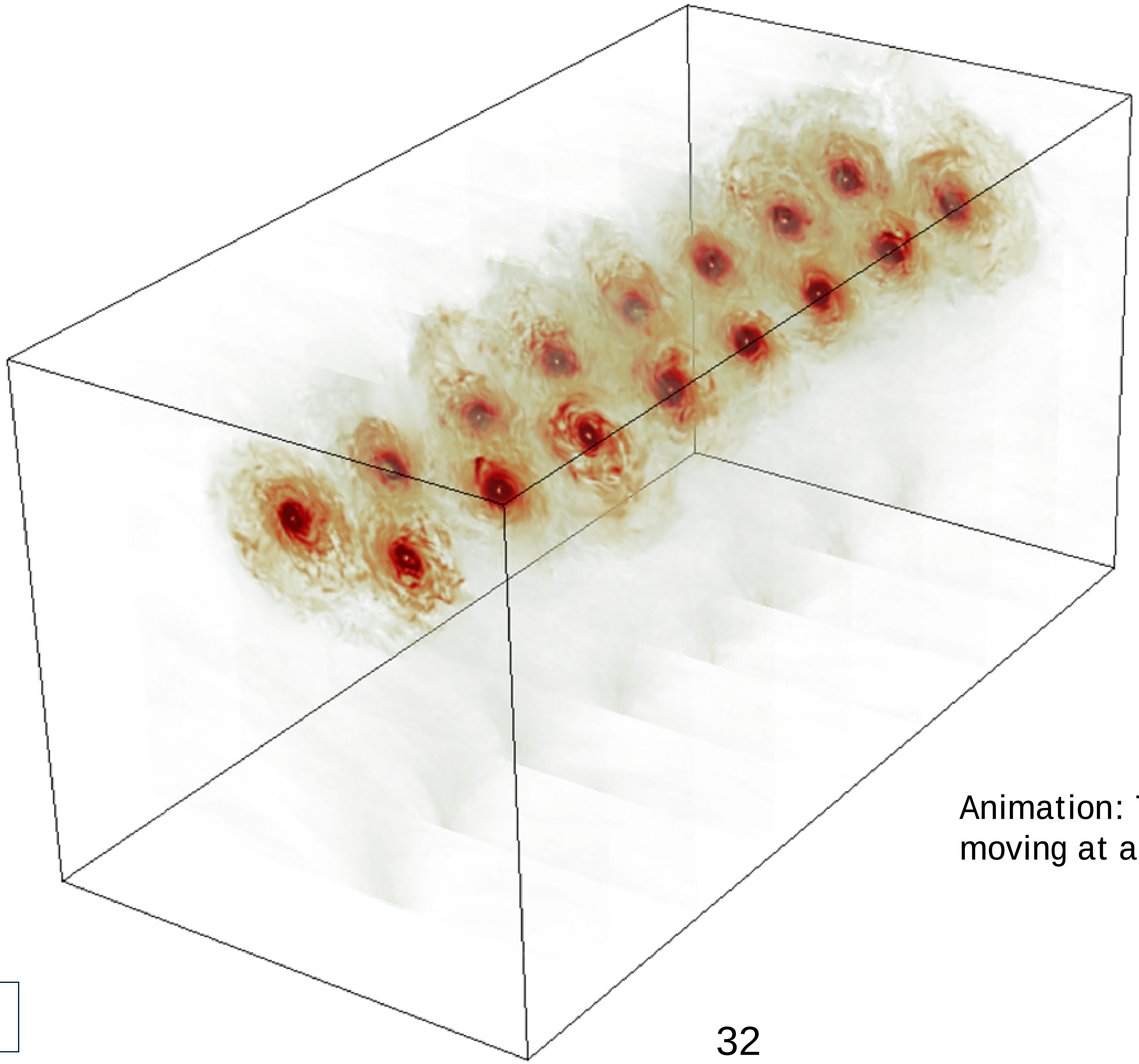
LES of a wake vortex pair evolving in a stratified and weakly turbulent atmosphere (case N*=1.0)

Velocity norm in several cross-planes



Animation: The viewing frame is moving at a velocity V_0

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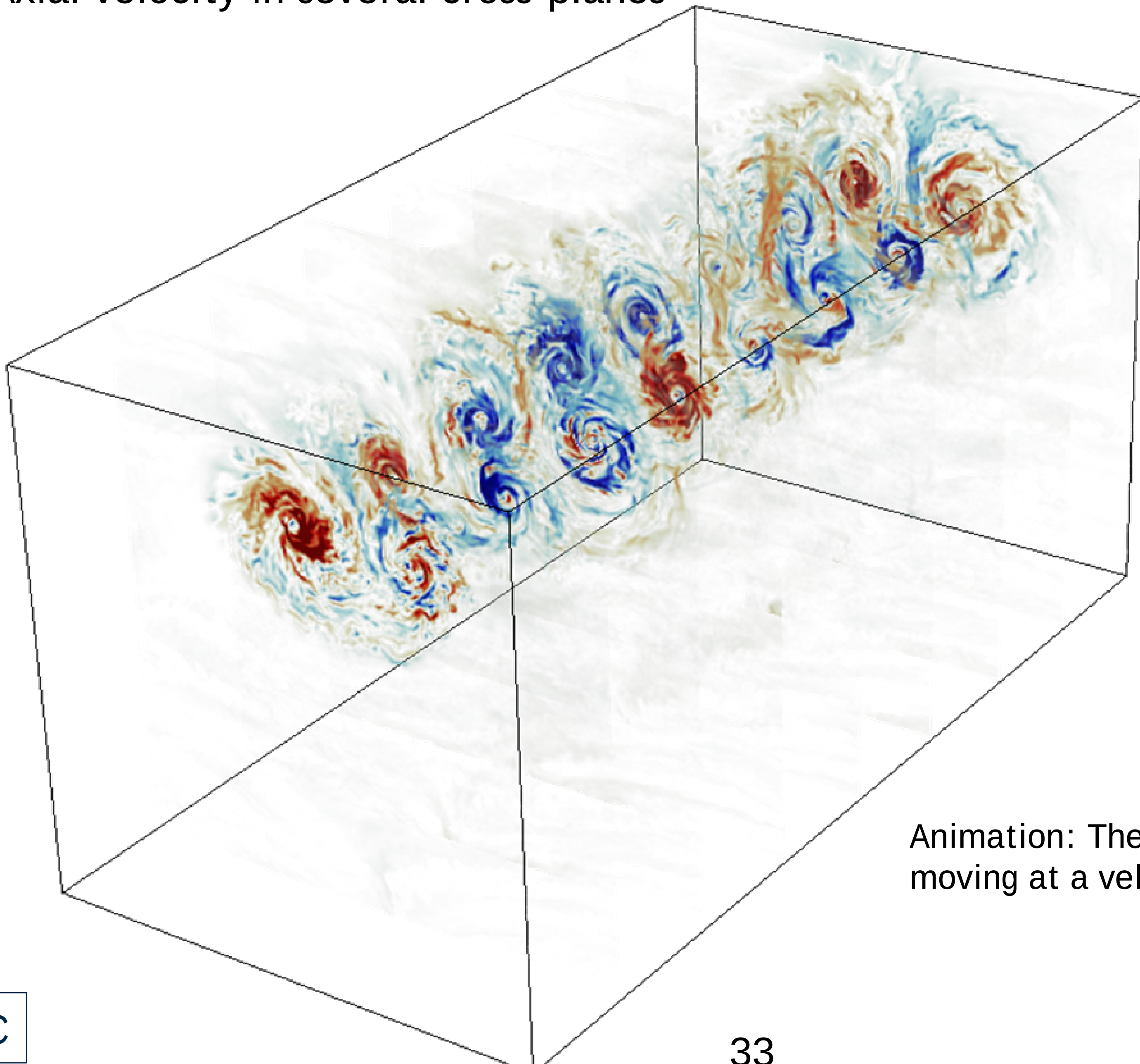
LES of a wake vortex pair evolving in a stratified and weakly turbulent atmosphere (case N*=1.0)

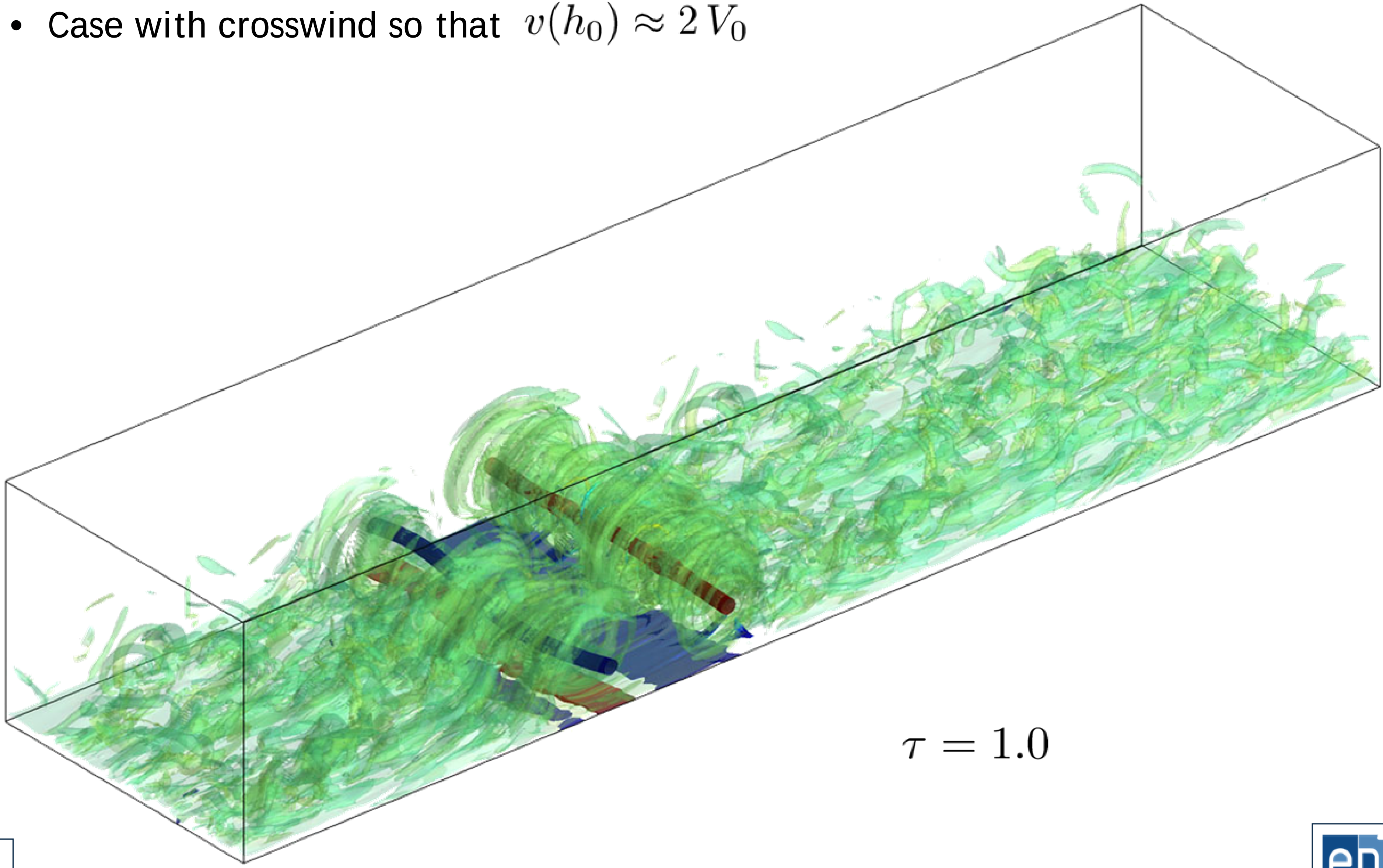
Axial velocity in several cross-planes



Animation: The viewing frame is moving at a velocity V_0

LES of a vortex pair IGE and with crosswind

- The background turbulent boundary layer is obtained by a pre-simulation
- A LES of the vortex system is then performed in the pre-computed field
- Case with crosswind so that $v(h_0) \approx 2\,V_0$



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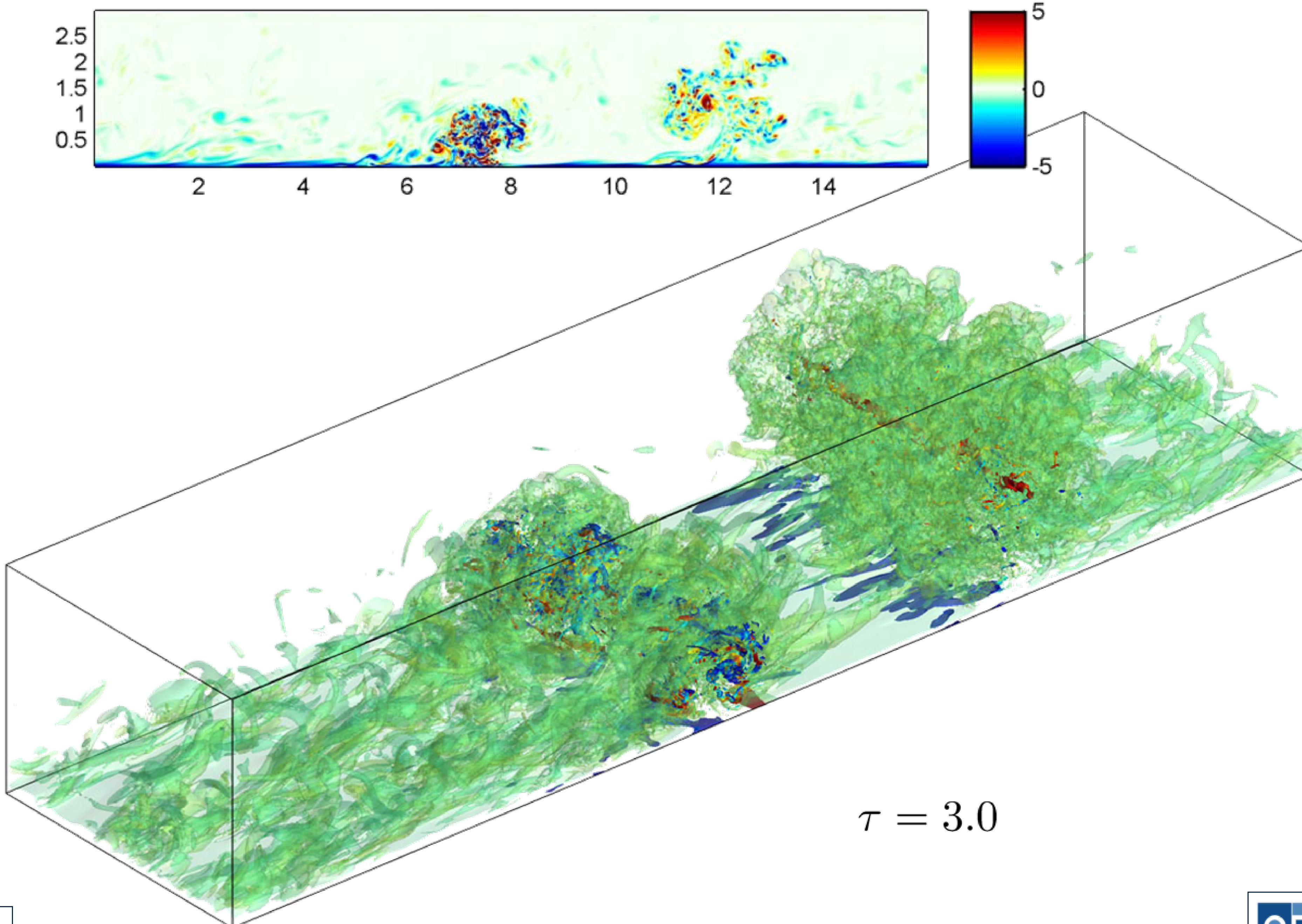
LES of a vortex pair IGE with crosswind



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