The WAKE4D Platform with the Deterministic wake Vortex Model (DVM) and the Probabilistic wake Vortex Model (PVM): Description and Applications

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Outline

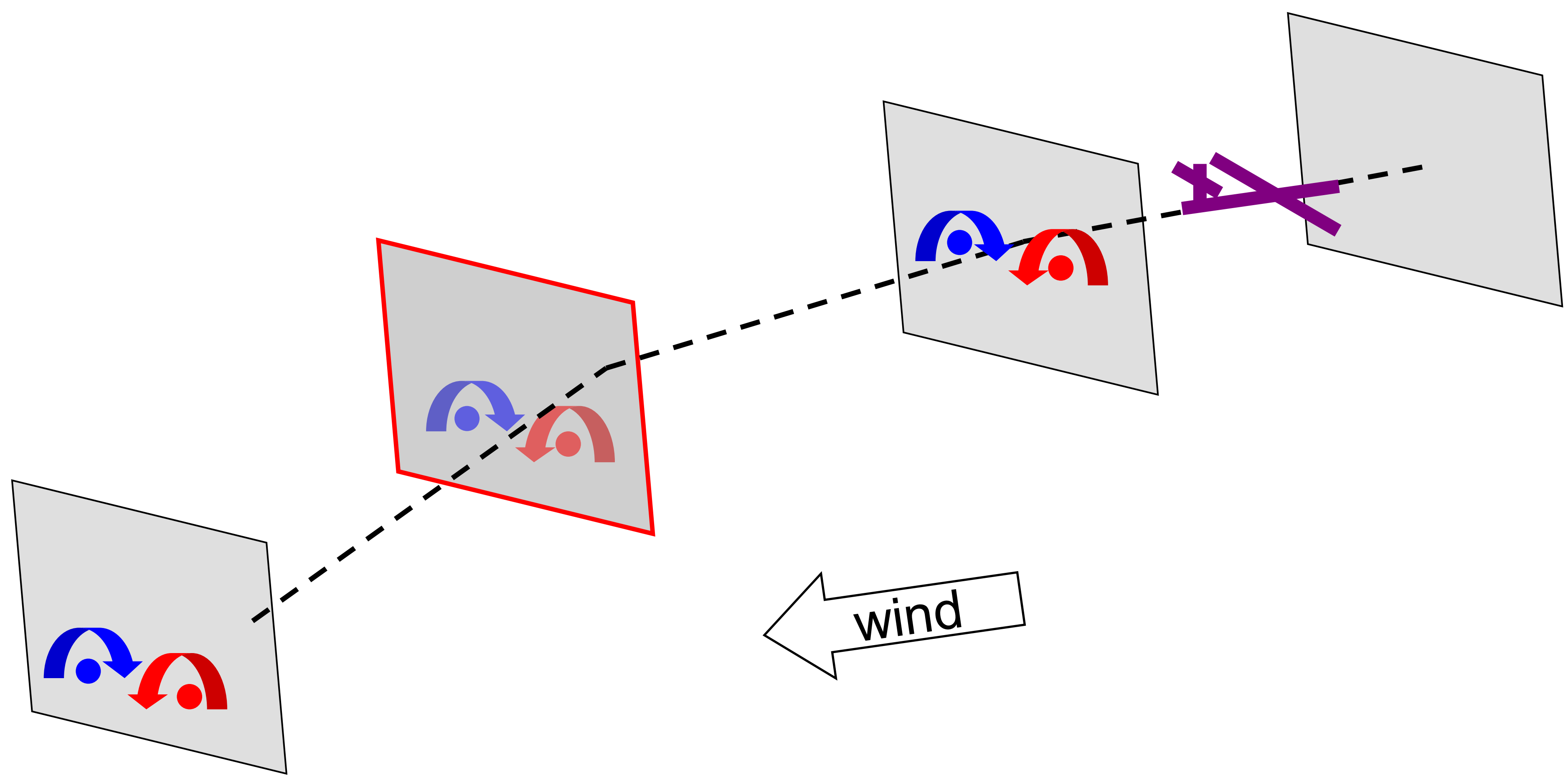
- Presentation of the WAKE4D platform and its subcomponents DVM/PVM
  - Description of the DVM
  - Description of the PVM
  - Description of the WAKE4D
  - Description of the “trajectory generator tool” (Pre-Processor)

- Examples of application of the WAKE4D-DVM + Pre-Processor
  - 3-D wake of a typical approach to the Marseille-Provence airport with two wind profiles
  - Induced velocity field evaluation for a typical take-off
  - Induced velocity field evaluation taking into account the Crow instability

- Examples of application of the WAKE4D-PVM
  - Investigation of a Time-Based Separation (TBS) concept
  - Investigation of potential wake vortex encounter (WVE) for parallel runways

WAKE4D: “3-D space + time” wake vortex prediction platform

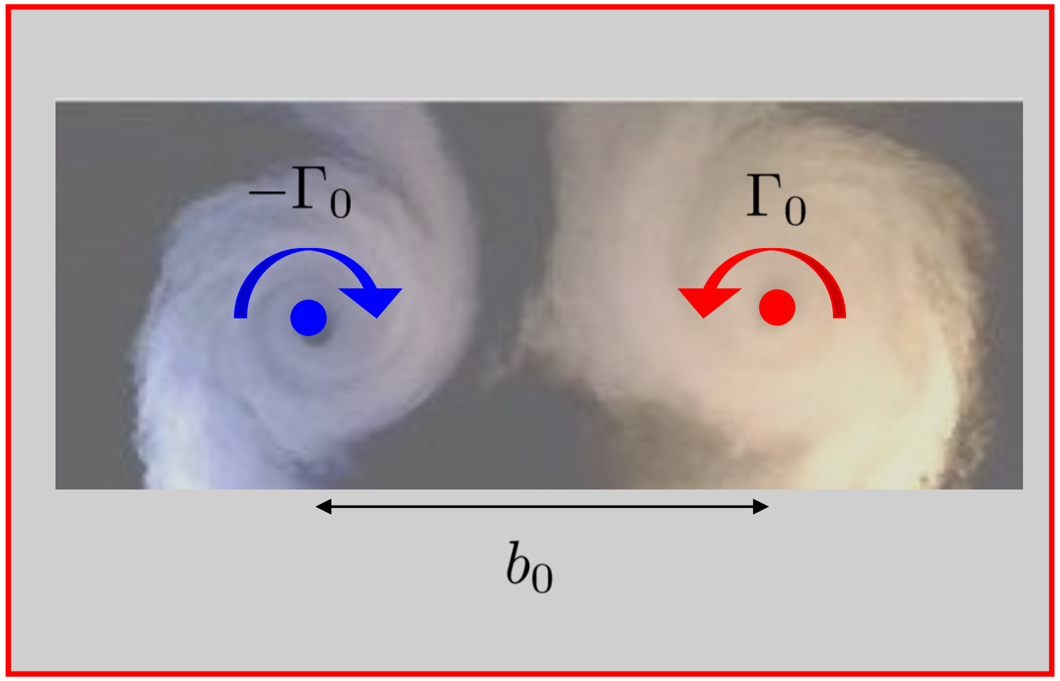
- It uses as input:
  - the a/c trajectory
  - the met conditions.
- The computational domain is divided in various “computational gates” crossing the flight path.
- The aircraft crossing one of the gates generates a pair of wake vortices (WV) that are transported (also by the headwind) and also decay.



The Deterministic wake Vortex Model (DVM)

- The DVM forecasts, in real-time, the WV behavior (transport and decay) in one computational gate, using simplified physical models.

- The initial wake is computed using the a/c characteristics (position, mass, TAS, wingspan, lift distribution, and flight angles) when the aircraft crosses the gate.

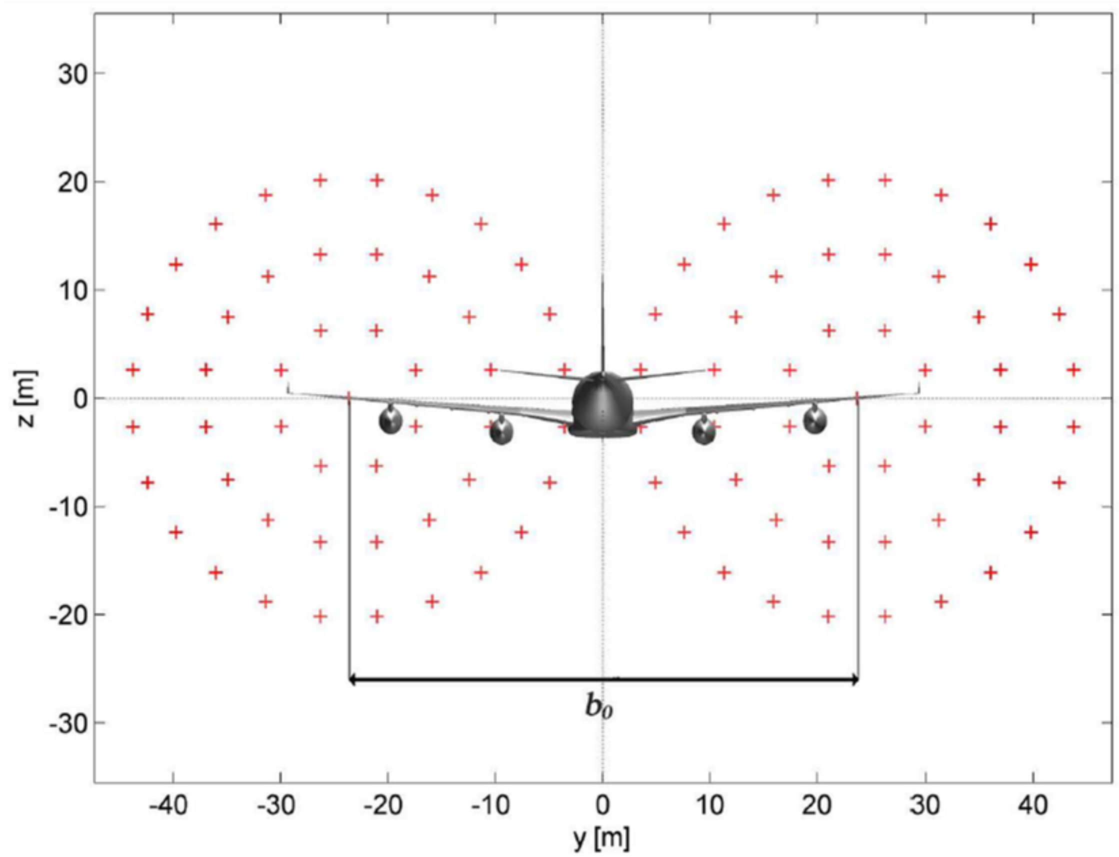


$$
\begin{aligned}
b_0 &= s\,b \\
\Gamma_0 &= \frac{M g}{\rho\, U_\infty\, b_0} \\
V_0 &= \frac{\Gamma_0}{2\pi b_0} \\
t_0 &= \frac{b_0}{V_0}
\end{aligned}
$$

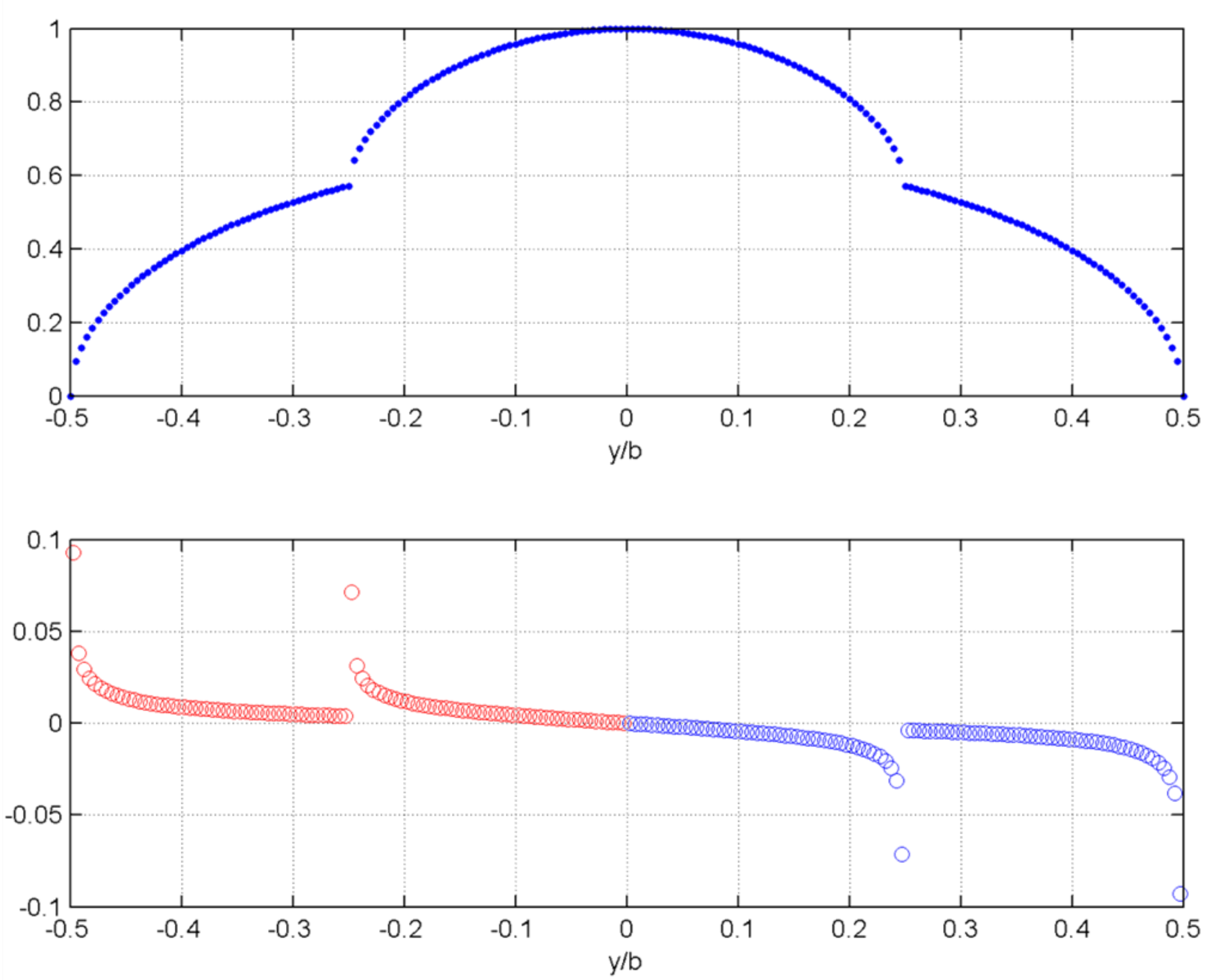
- Each wake vortex is represented by a vortex particle with a chosen circulation distribution profile:
  - the Burnham-Hallock model (= low-order algebraic model),
  - the high-order algebraic model, or
  - the two-scales Proctor-Winckelmans model

Other available wake initialization options

- Near wake model
  - 2 rolled-up vortices with the Proctor-Winckelmans distribution discretized using n layers of particles (example n=3)

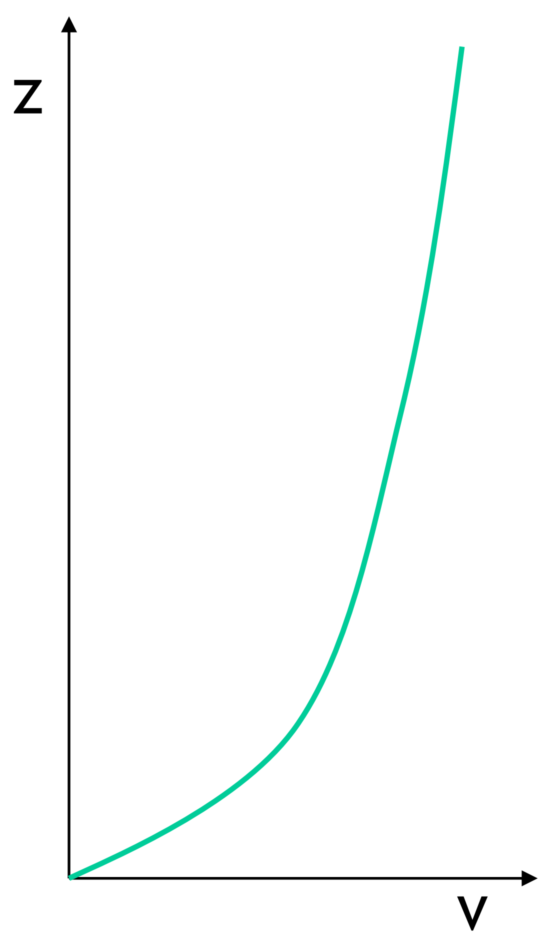


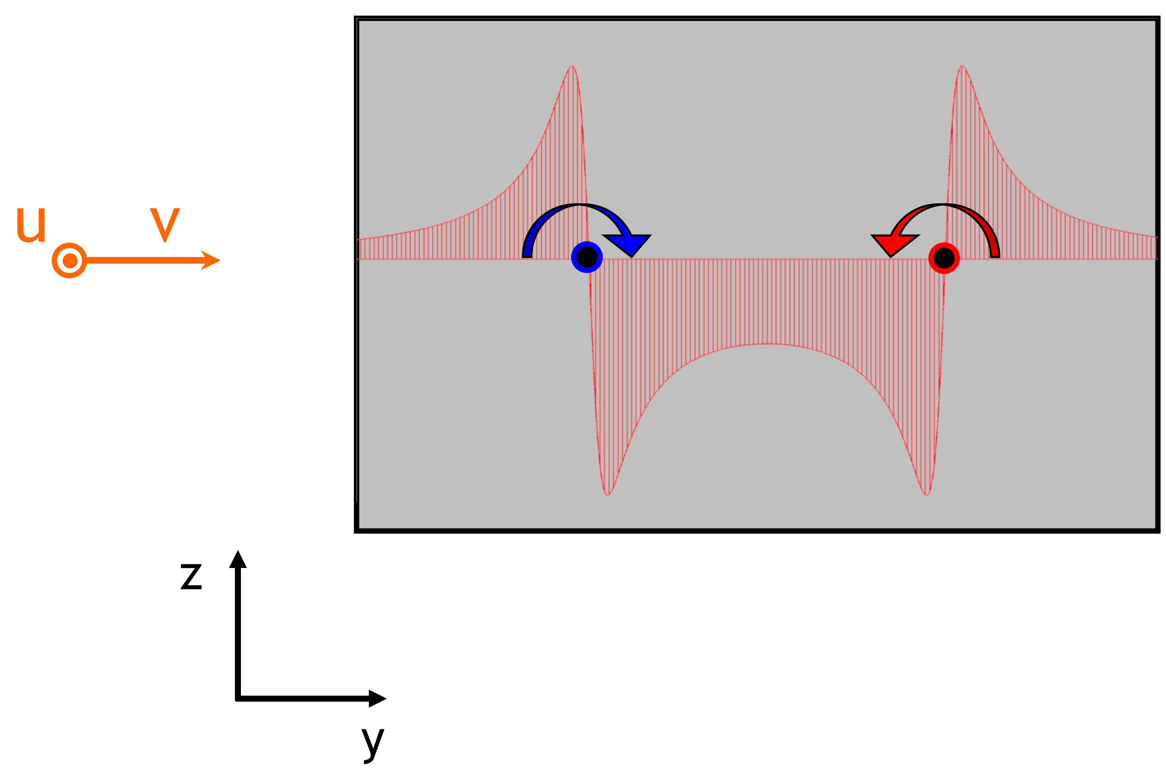
- Vortex sheet with various circulation distributions
  - Example: double elliptical distribution

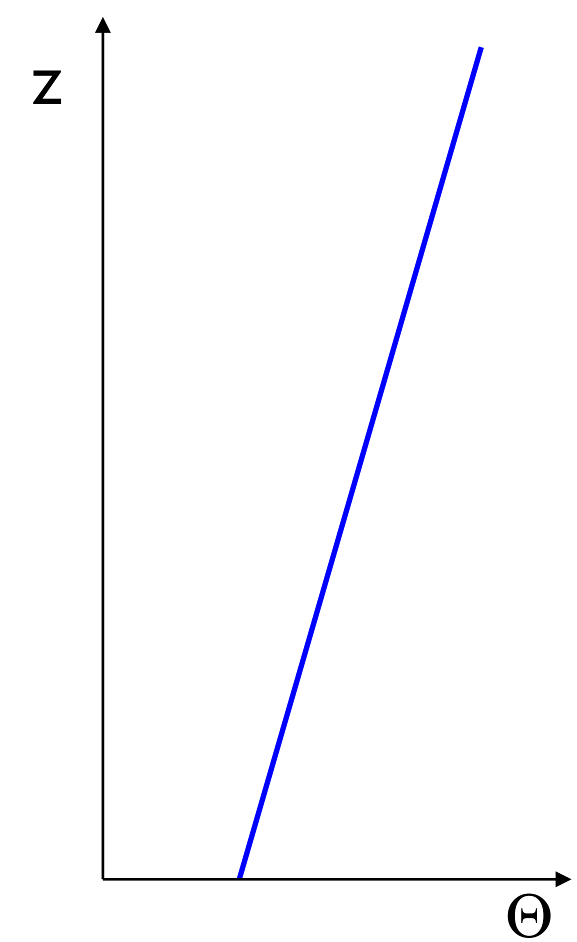


The physical transport models used in the DVM

- Self-induced velocity: Biot-Savart law (also using image particles for NGE modeling)
- Wind convection: by both the axial and lateral components evaluated at the altitude of WV evolution
- Wind shear: the shear of the wind profile is computed and the tilting effect is modeled
- Stratification effects: the stratification level, N*, is computed from the potential temperature profile and the thermally induced rebound is modeled

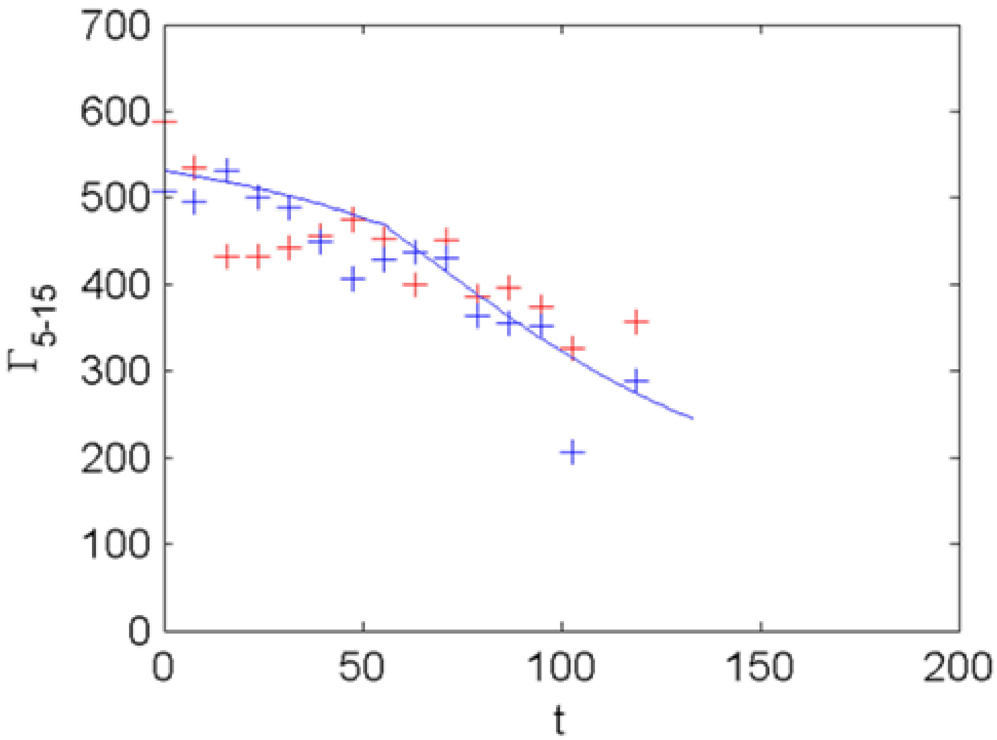


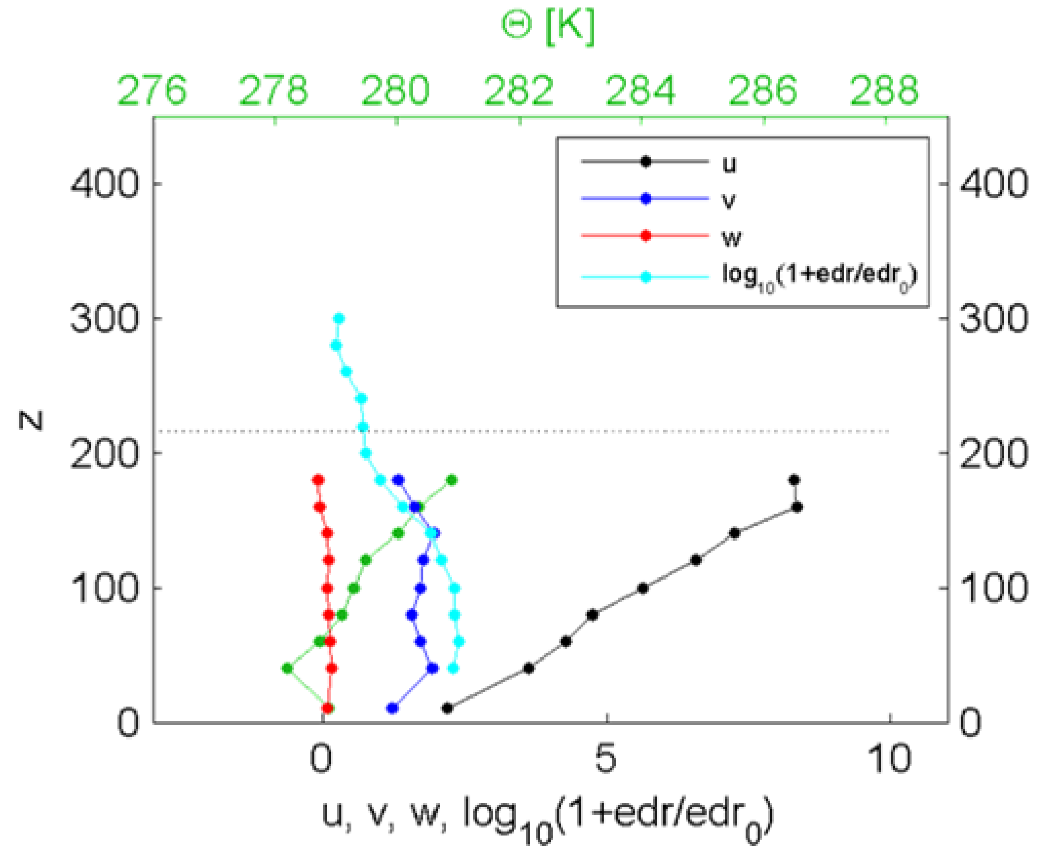




The physical models used in the DVM

- Circulation decay
  - Two phase decay: slow decay phase followed by a rapid decay phase
  - Accumulated "time-to-demise" approach: starting time of the fast decay phase t_d(EDR, N*)
  - The decay rate of both phases also depends on EDR and N*
  - Possibility to also use a TKE-based decay model or the APA decay model using EDR

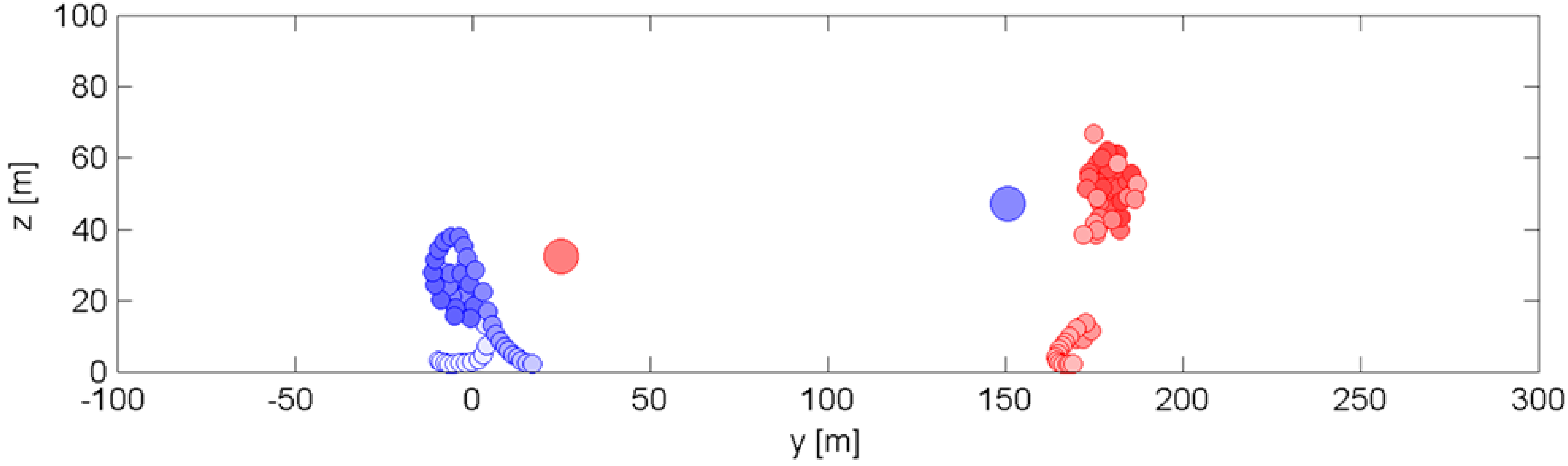




- Crow instability model
  - Model of the space developing Crow instability amplitude for predicting the WV deformation
  - Based on the time-to-demise and thus the atmosphere turbulence level

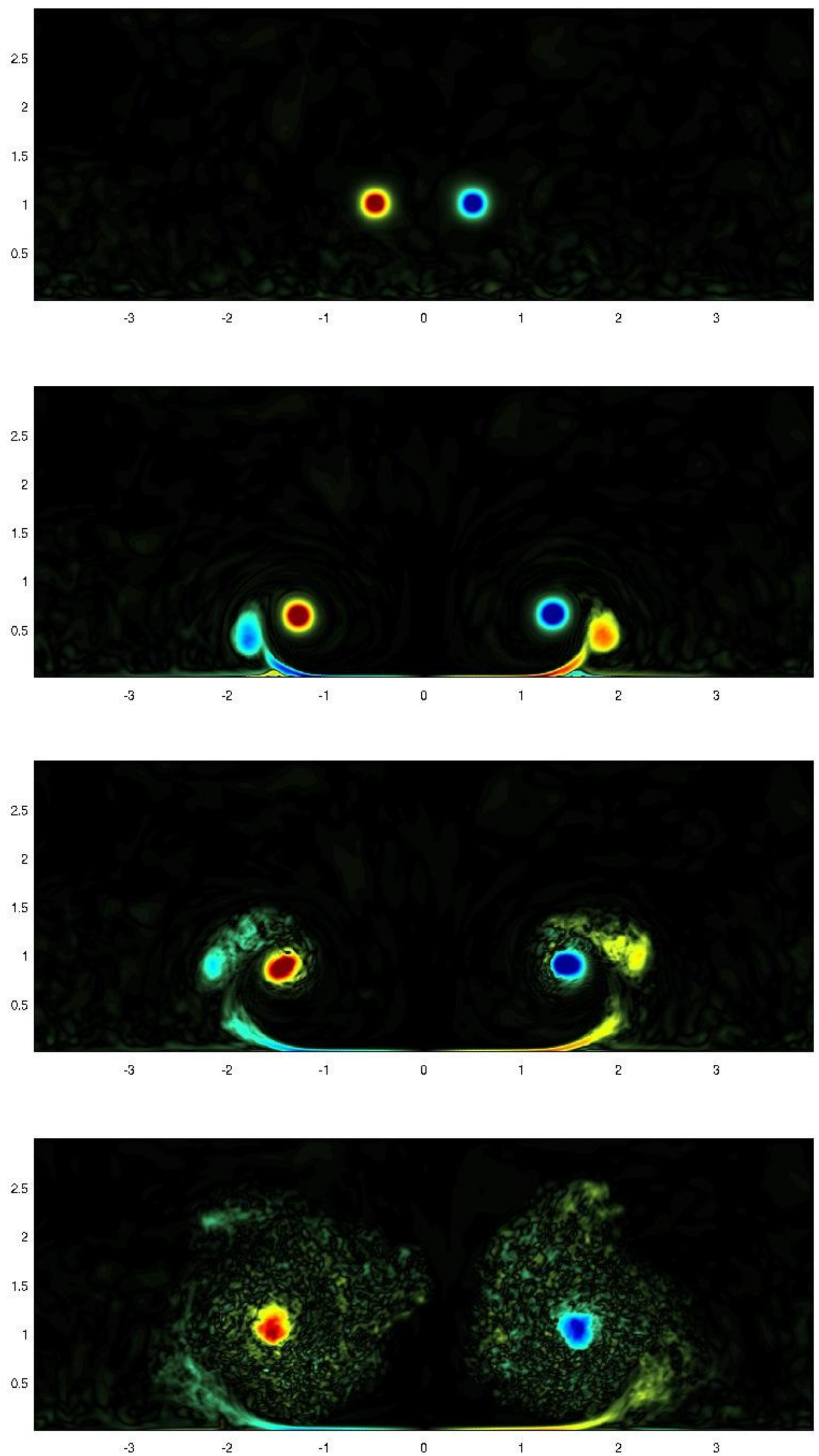
DVM In Ground Effect (IGE) modeling

- Generate new « secondary » vortex particles close to the ground, to model the ground-generated boundary layer due to no-slip
- Those particles also dynamically separate from the ground
- They interact with the primary vortices and induce the rebound
- There is a redistribution of the secondary particles when the primary vortex has bounced
- An additional IGE decay model, based on a “Particle strength exchange”, enhances the decay of the vortices IGE after rebound.

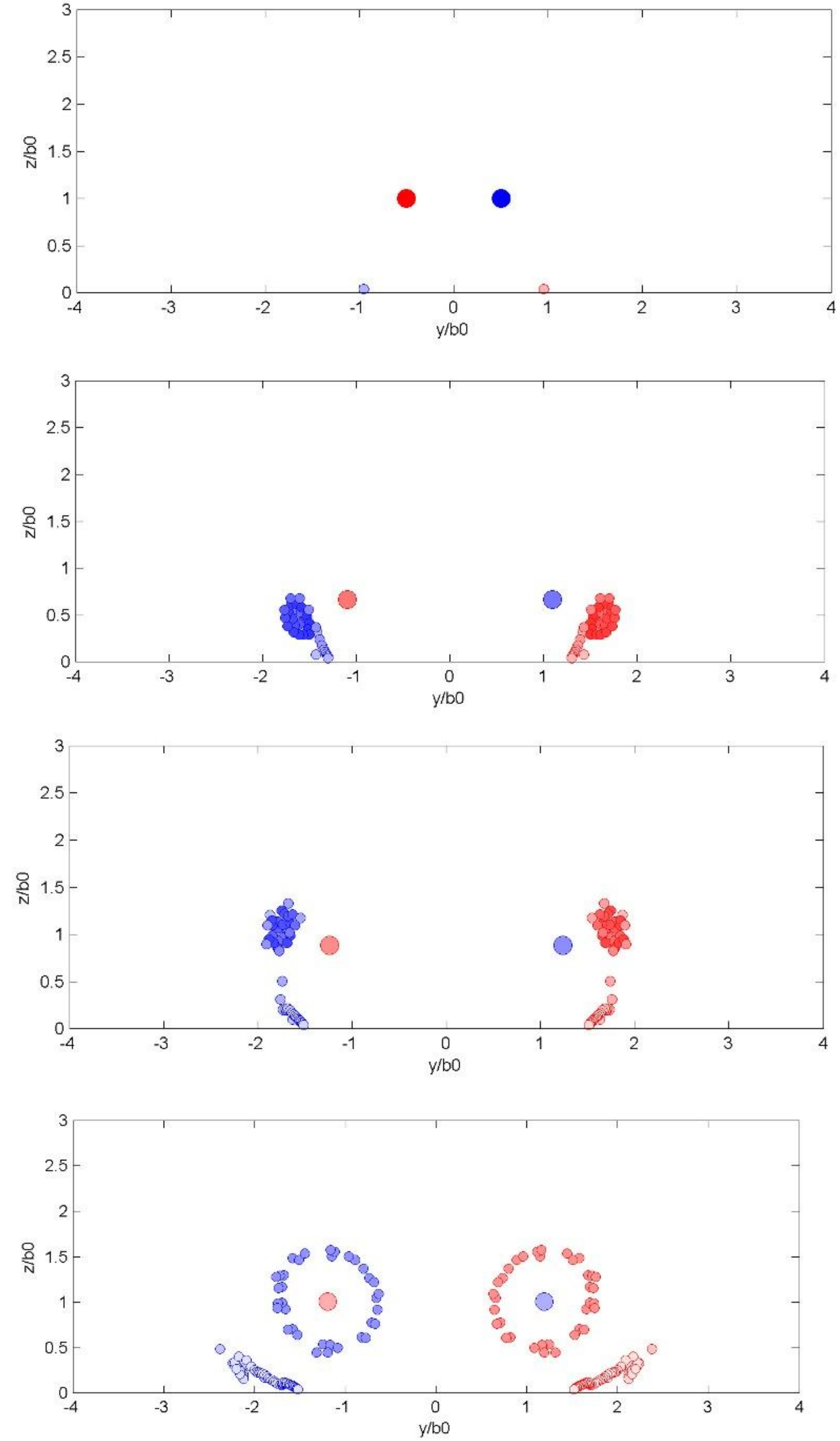


Comparison between LES and DVM results: case IGE with headwind

Mean axial vorticity field as computed by a LES



Particles used in the DVM to model WV IGE



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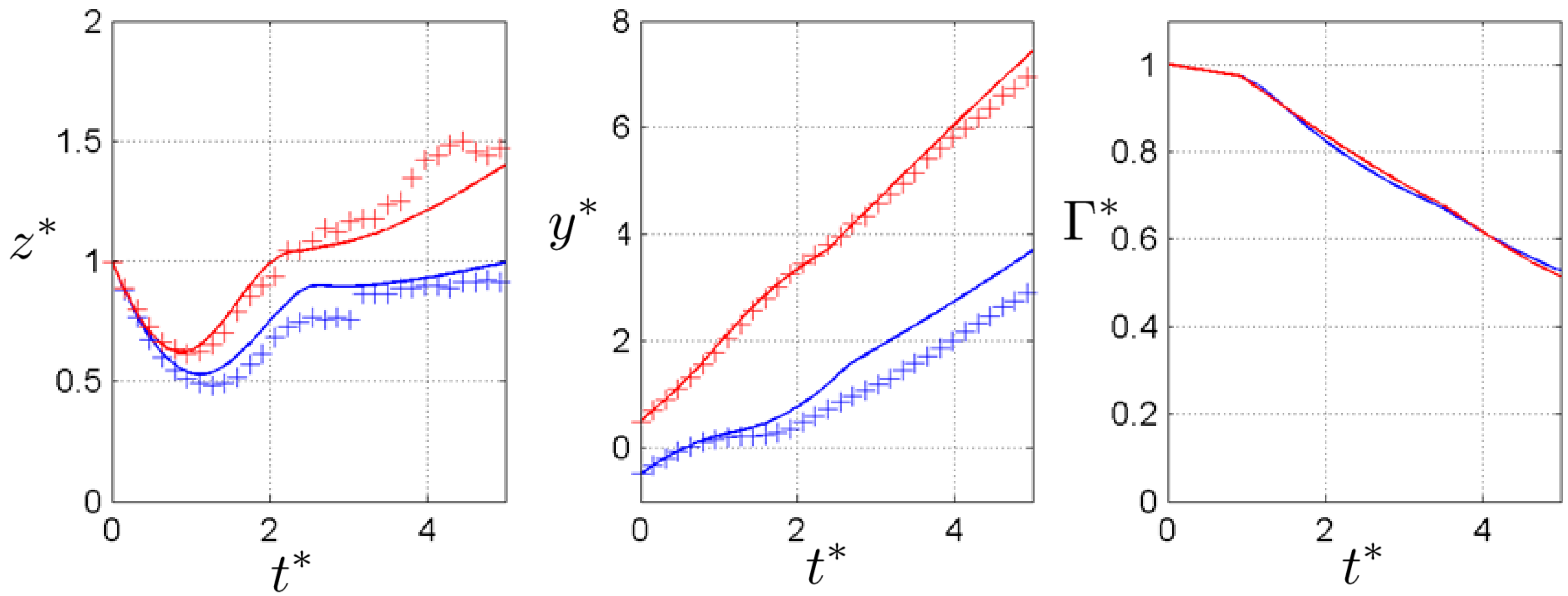
Example of comparison between LES and DVM results: case IGE with crosswind

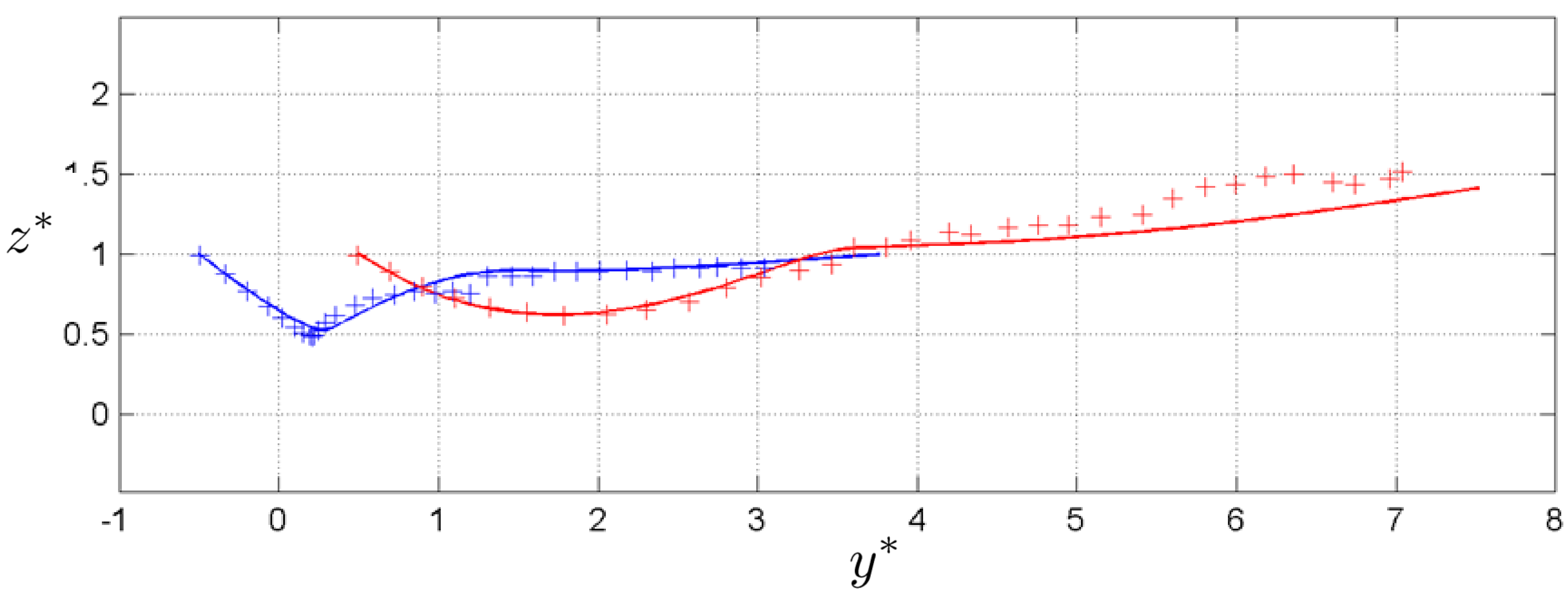


$$z^* = z/b_0$$

$$y^* = y/b_0$$

$$\Gamma^* = \Gamma/\Gamma_0$$

$$t^* = t/t_0$$



Crosses: LES

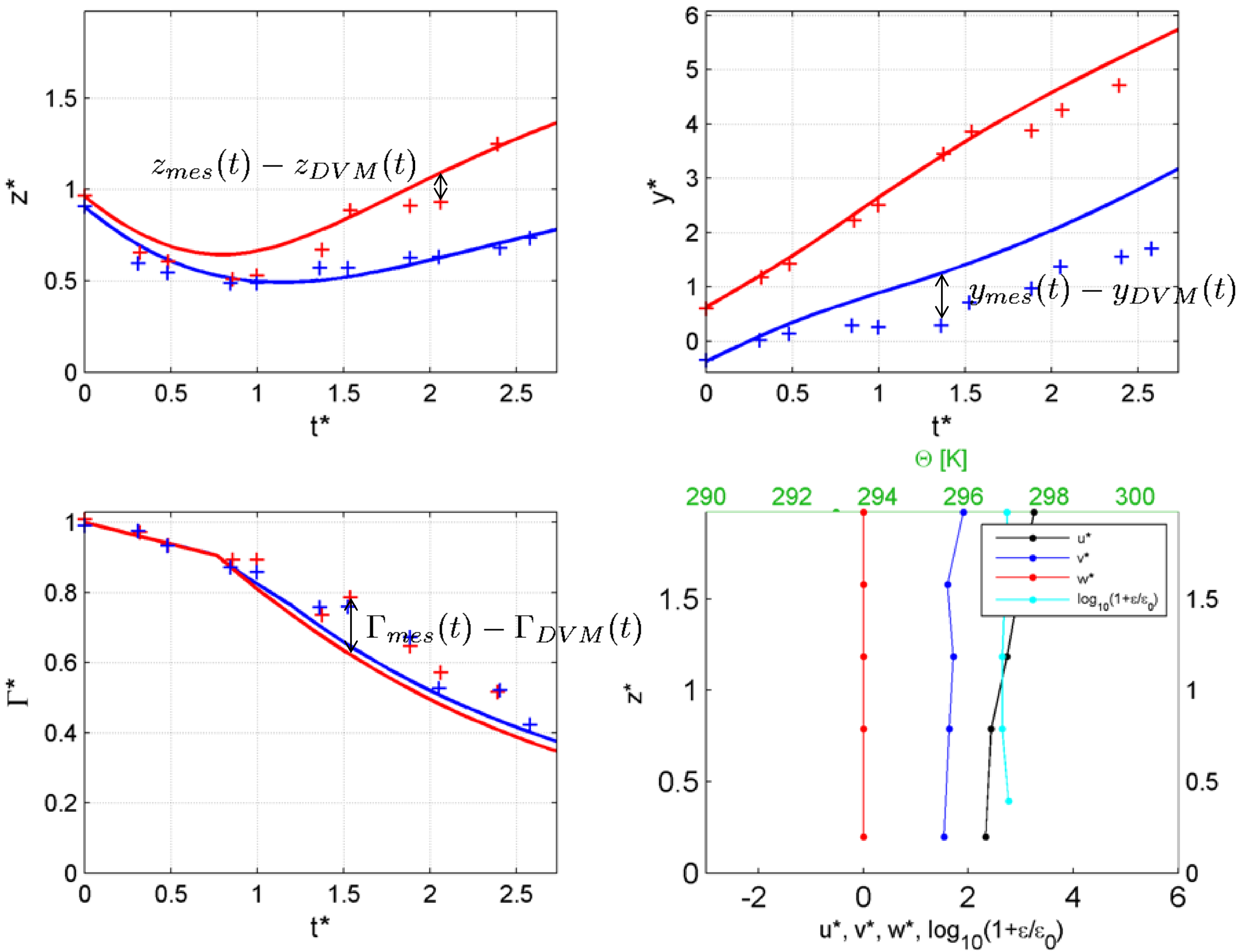
Solid curves: DVM

Blue: port vortex

Red: starboard vortex

Example of comparison between DVM results and measurements

LIDAR measurement campaign of WV generated by heavy aircraft in ground proximity (WakeFRA 2004)



$$z^* = z/b_0$$

$$y^* = y/b_0$$

$$\Gamma^* = \Gamma/\Gamma_0$$

$$t^* = t/t_0$$

Crosses: measurements

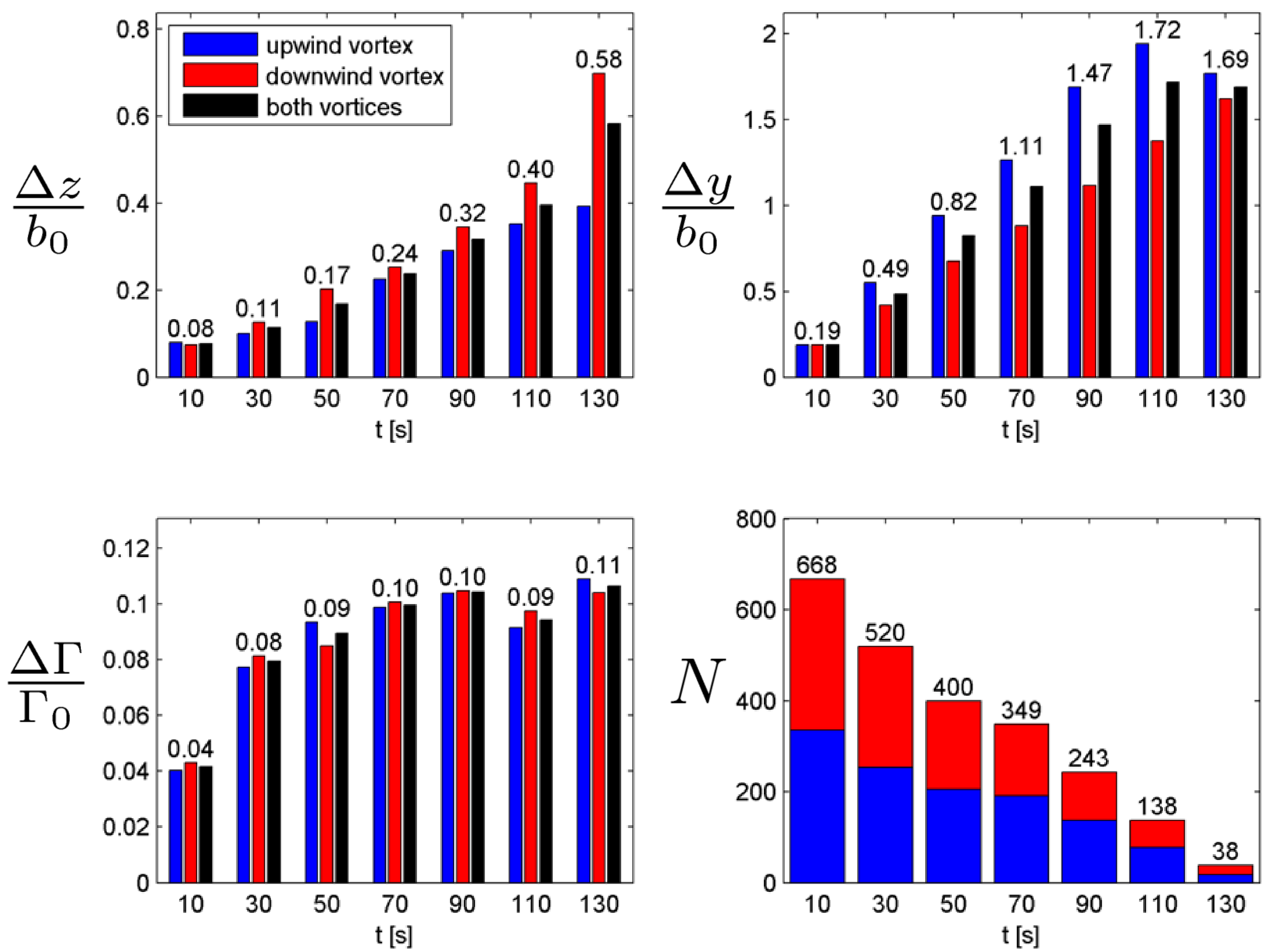
Solid curves: DVM

Blue: port vortex

Red: starboard vortex

Example of assessment of the DVM against measurements (using WakeFRA 2004)

Histograms of the deviations between measurements and predictions as a function of time (t) for the vertical (Δz) and lateral (Δy) positions and for the circulation ($\Delta\Gamma$). The number of cases in each time frame (N) is also provided.



$$\Delta z(t) = \sqrt{\frac{1}{N(t)} \sum (z_{mes}(t) - z_{DVM}(t))^2}$$

$$\Delta y(t) = \sqrt{\frac{1}{N(t)} \sum (y_{mes}(t) - y_{DVM}(t))^2}$$

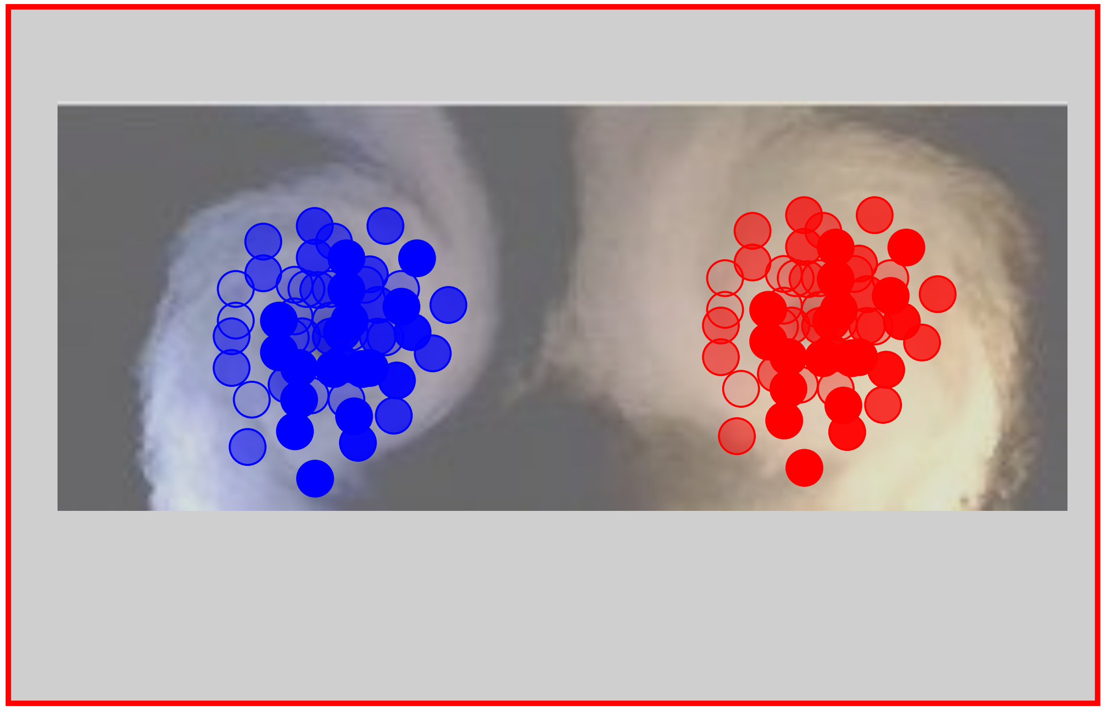
$$\Delta\Gamma(t) = \sqrt{\frac{1}{N(t)} \sum (\Gamma_{mes}(t) - \Gamma_{DVM}(t))^2}$$

The Probabilistic wake Vortex Model (PVM)

- Probabilistic modeling and assessment of wake vortices is often what is operationally required.

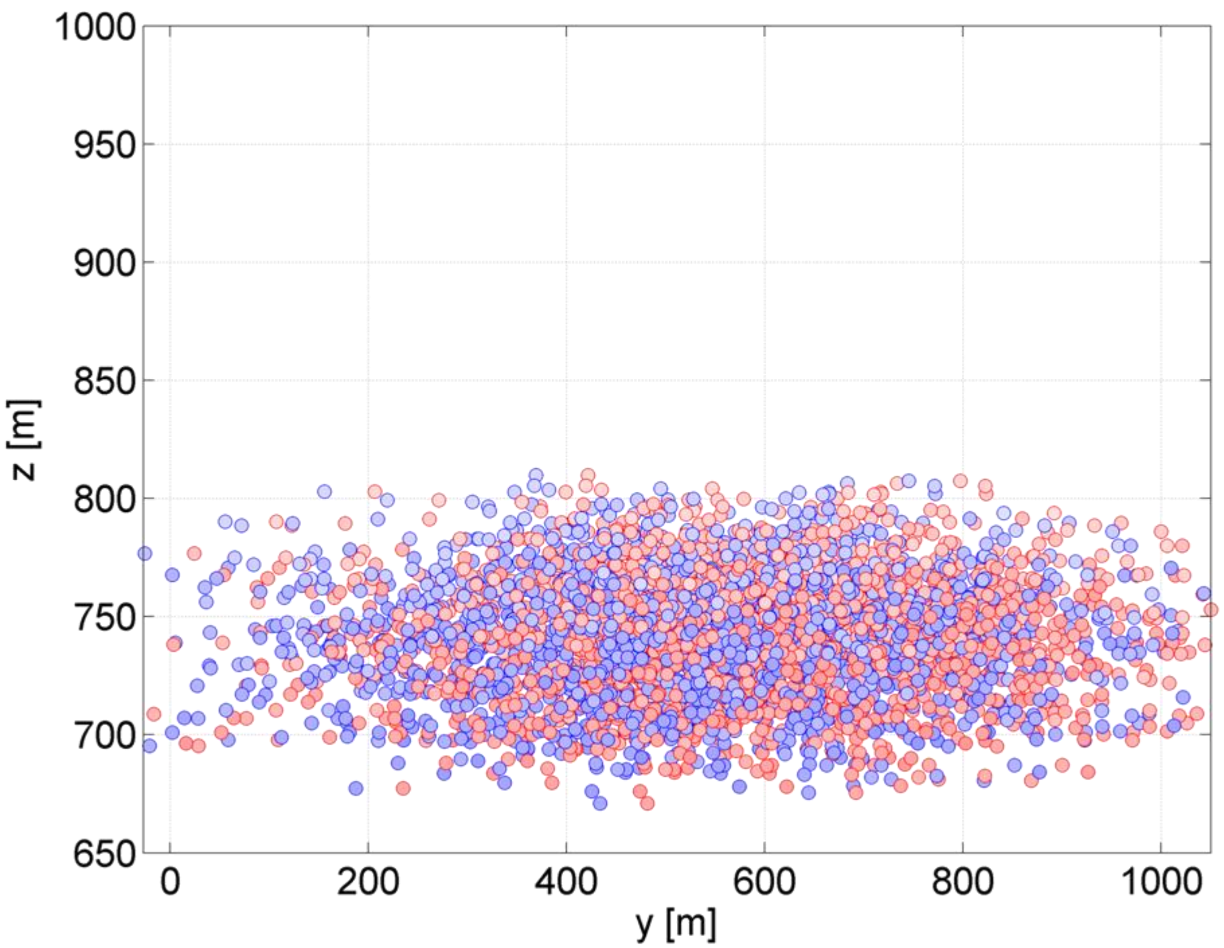
- The PVM is an upper software layer, based on a Monte-Carlo approach, using the DVM as a sub-tool.

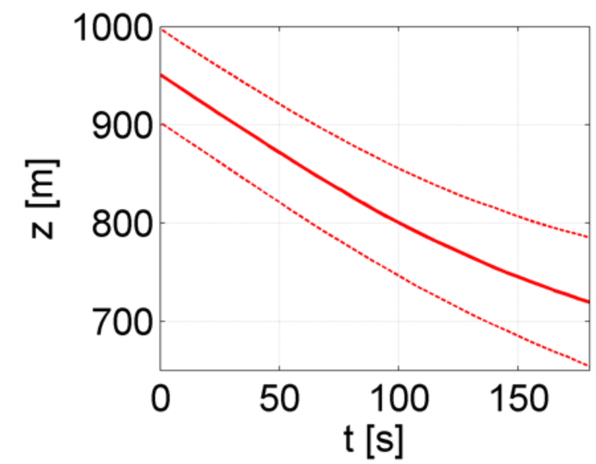
- For each PVM run, many DVM runs are performed, with random variations on the impact parameters (each one following its own distribution):
  - met conditions (natural variations and uncertainties)
  - a/c characteristics (uncertainties)
  - some coefficients of the physical models (calibration uncertainties)

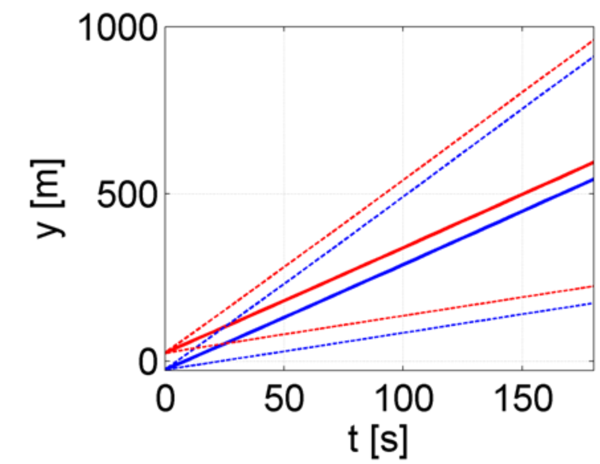


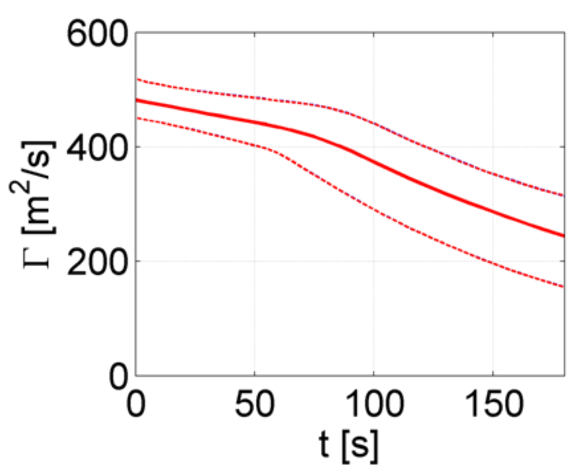
PVM outputs

- One then obtains, in a computational gate at each time:
  - a set of vortex positions,
  - their associated circulations.
- The output distribution is not just a "simple image" of the input distribution
- A statistical analysis on the result sample can be performed to obtain:
  - PDF, mean, median, variance, percentiles, …





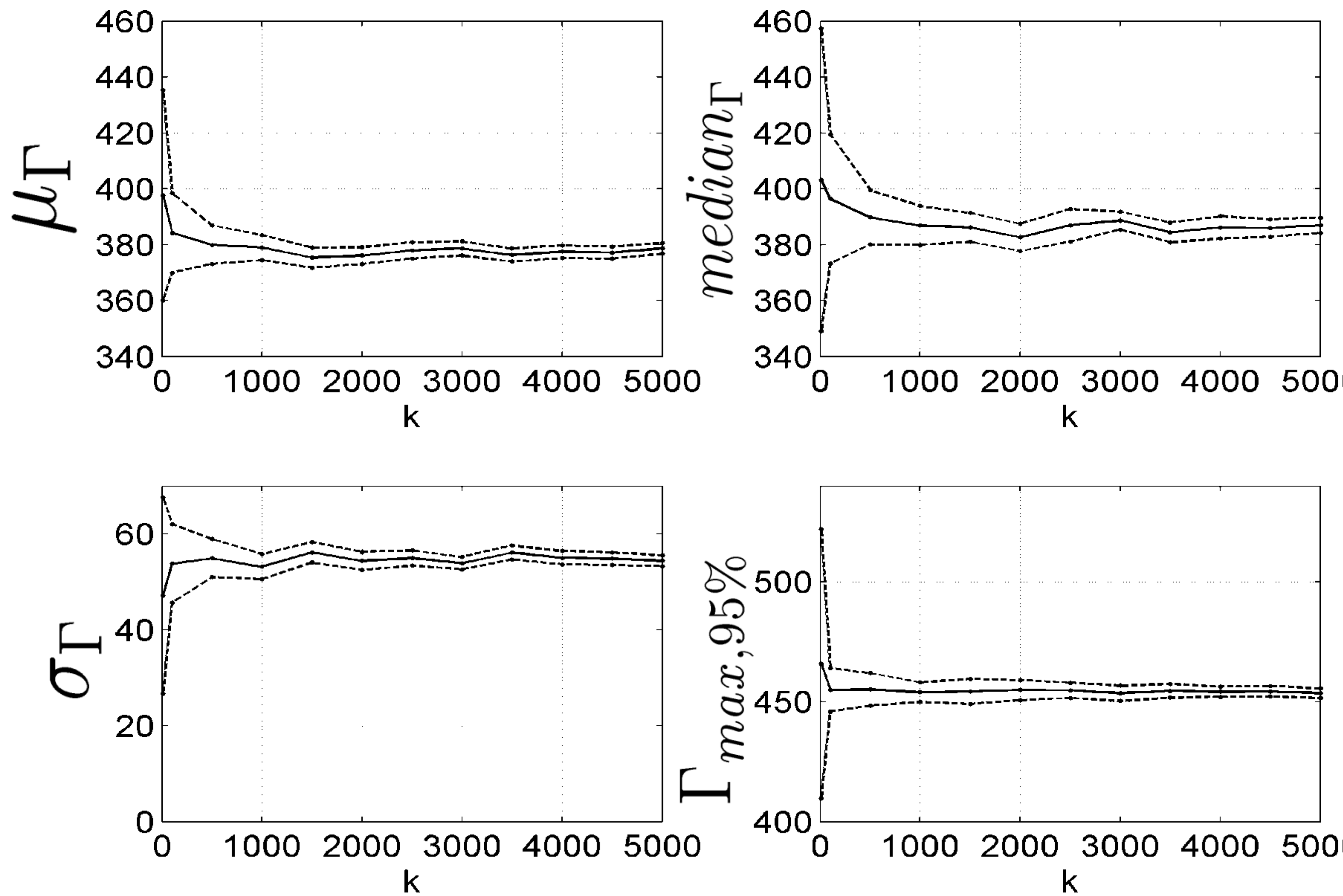




Solid : median
Dash : 95 % envelopes

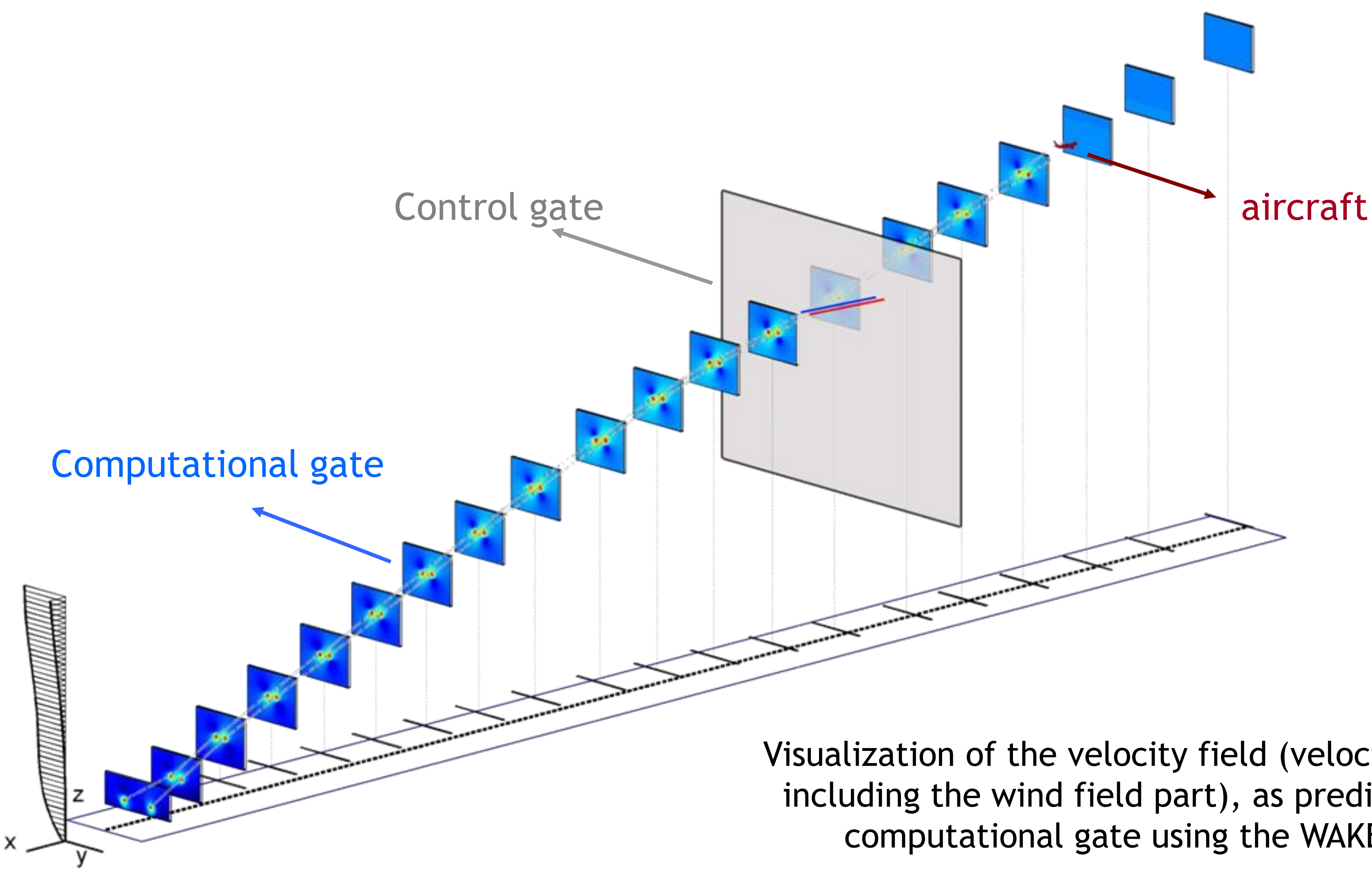
Bootstrap resampling technique

- Aim : obtain conservative statistical results while limiting the number of DVM runs
- The resampling technique provides an estimate of the variance of the statistics of the Monte-Carlo results: the “statistics on the statistics”
- Obtain PVM confidence envelopes that are sufficiently accurate and usable, using a moderate number of DVM runs.
- Obtain a PVM approach that is computationally efficient; hence also usable for real-time systems.



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).
- From the 3-D "gate by gate" DVM (resp. PVM) computations, one can rebuild the 3-D wake (resp. envelope of the wake).
- "Control gate": interpolation in a fixed plane (similar to a LIDAR scanning plane).
- "Control box": recording of the vortices present in a box as a function of time.



Visualization of the velocity field (velocity norm, also including the wind field part), as predicted in each computational gate using the WAKE4D-DVM

The Pre-Processor tool

- Helps the user in the generation of the a/c trajectory

- Takes several waypoints as inputs and the trajectory type (straight line, left/right turn) between each of them

- The pre-processor computes all inputs needed by the WAKE4ED as a function of wind, TAS and aircraft mass:
  - Position evolution: $x(t)$, $y(t)$, $z(t)$
  - Bank angle evolution: $\phi(t)$
  - Relative azimuthal and elevation angles evolutions: $\psi_r(t)$, $\gamma_r(t)$

- Left/right turn: constant rate of turn ω. Typically, we use $\omega = 3[deg/s]$

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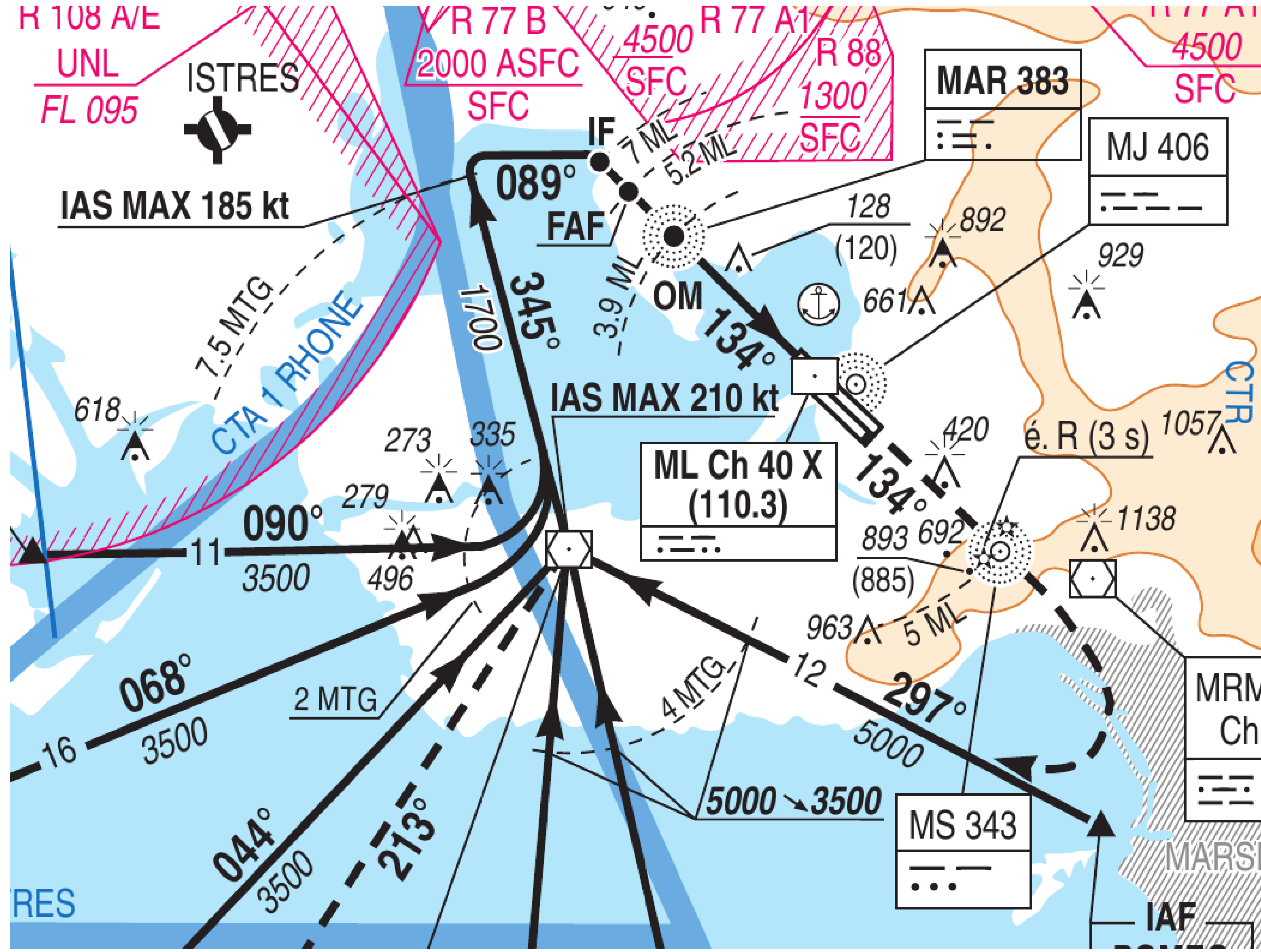
The Pre-Processor tool: application for the approach to the Marseille-Provence airport

- Aircraft : B747-400
  - MLW : 295,000 kg
  - b=64.4 m
  - s= 0.75 [-]

- Met conditions :
  - **Wind:** 15kts at z=10m;
    log profile in the TBL;
    Ekman spiral
  - **Turbulence:** EDR is fixed by wind within TBL and is equal to 1e-3 [m^2/s^3] above
  - **Stratification:** N = 0.01 [1/s]
    (N* = 0.29)



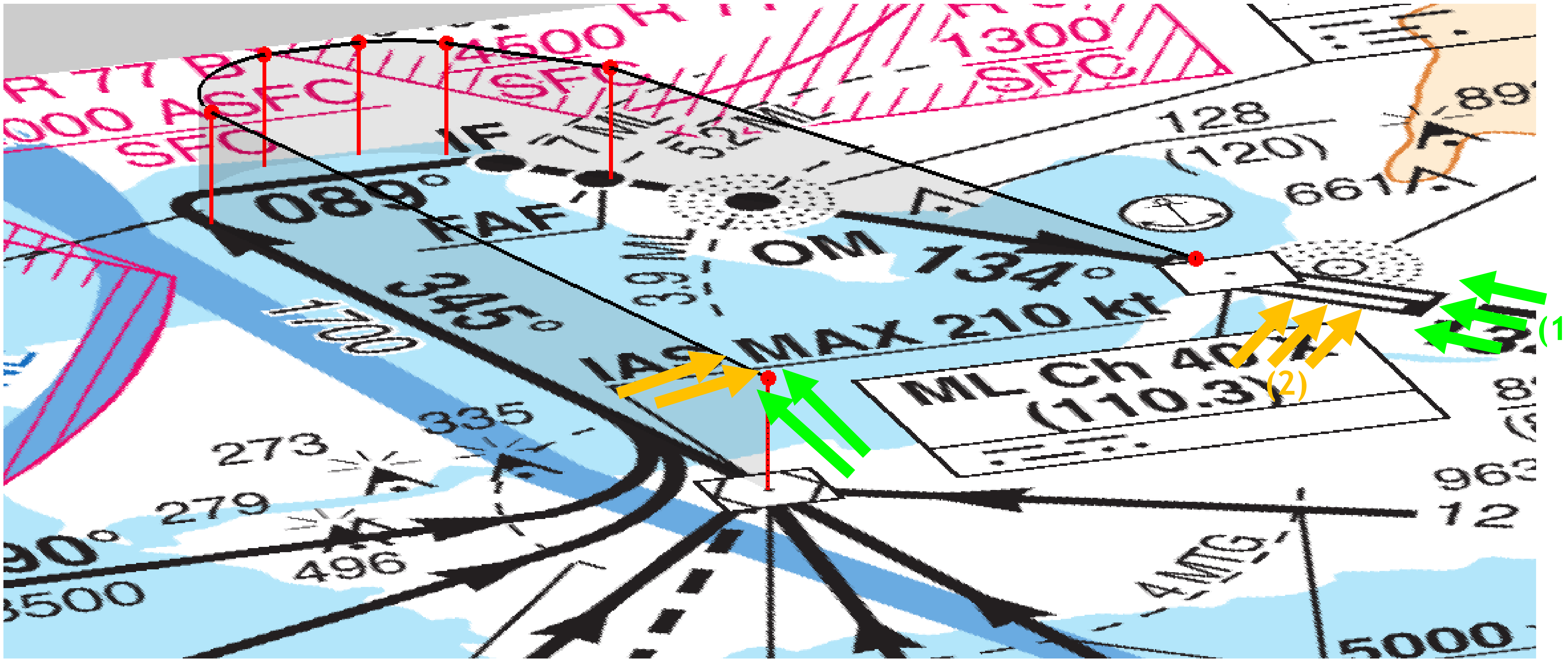
The Pre-Processor tool: application for the approach to the Marseille-Provence airport

- Two wind directions are investigated:

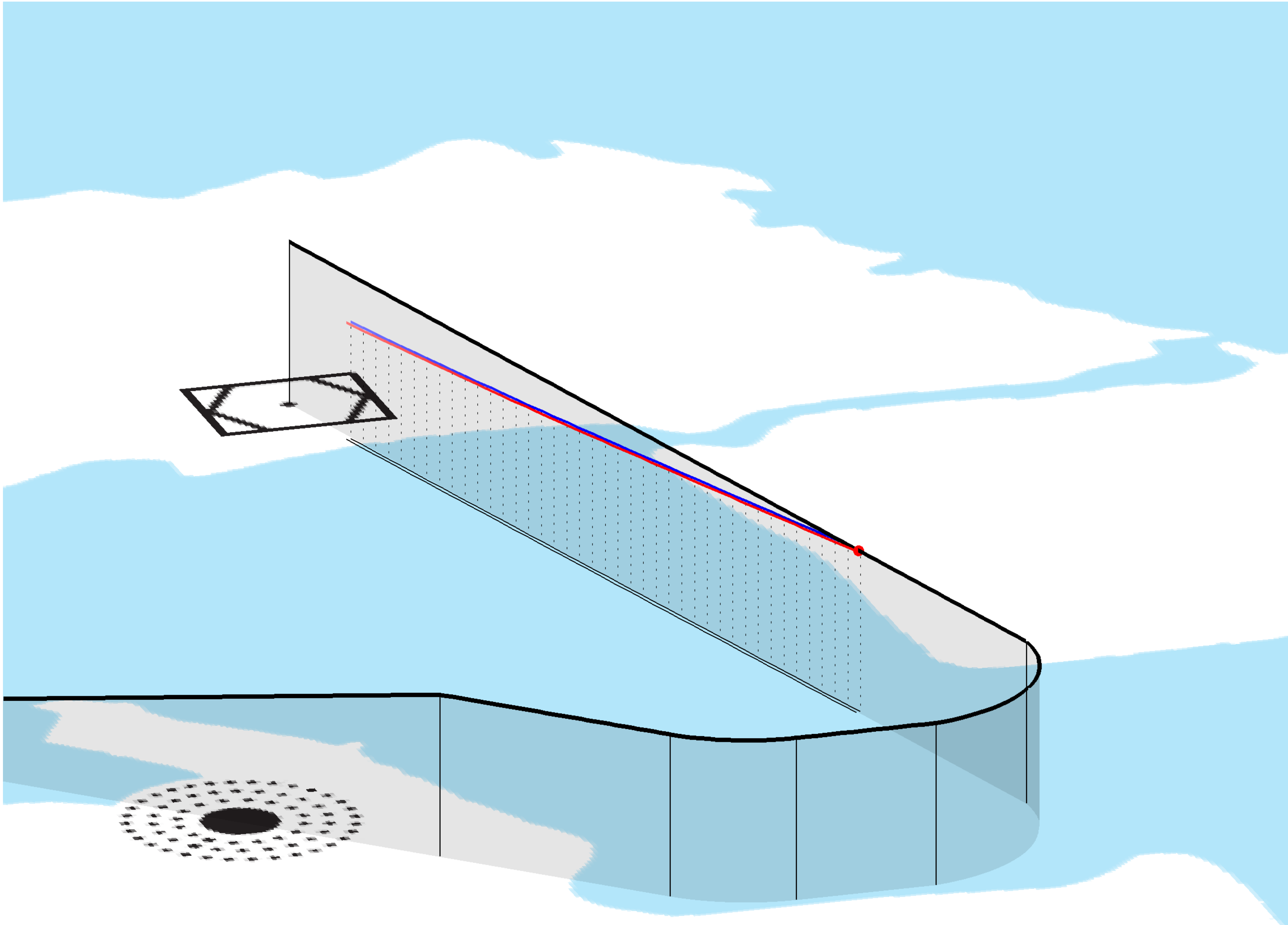
(1) Pure headwind on the runway (S-E wind)

(2) Pure crosswind on the runway (S-W wind)

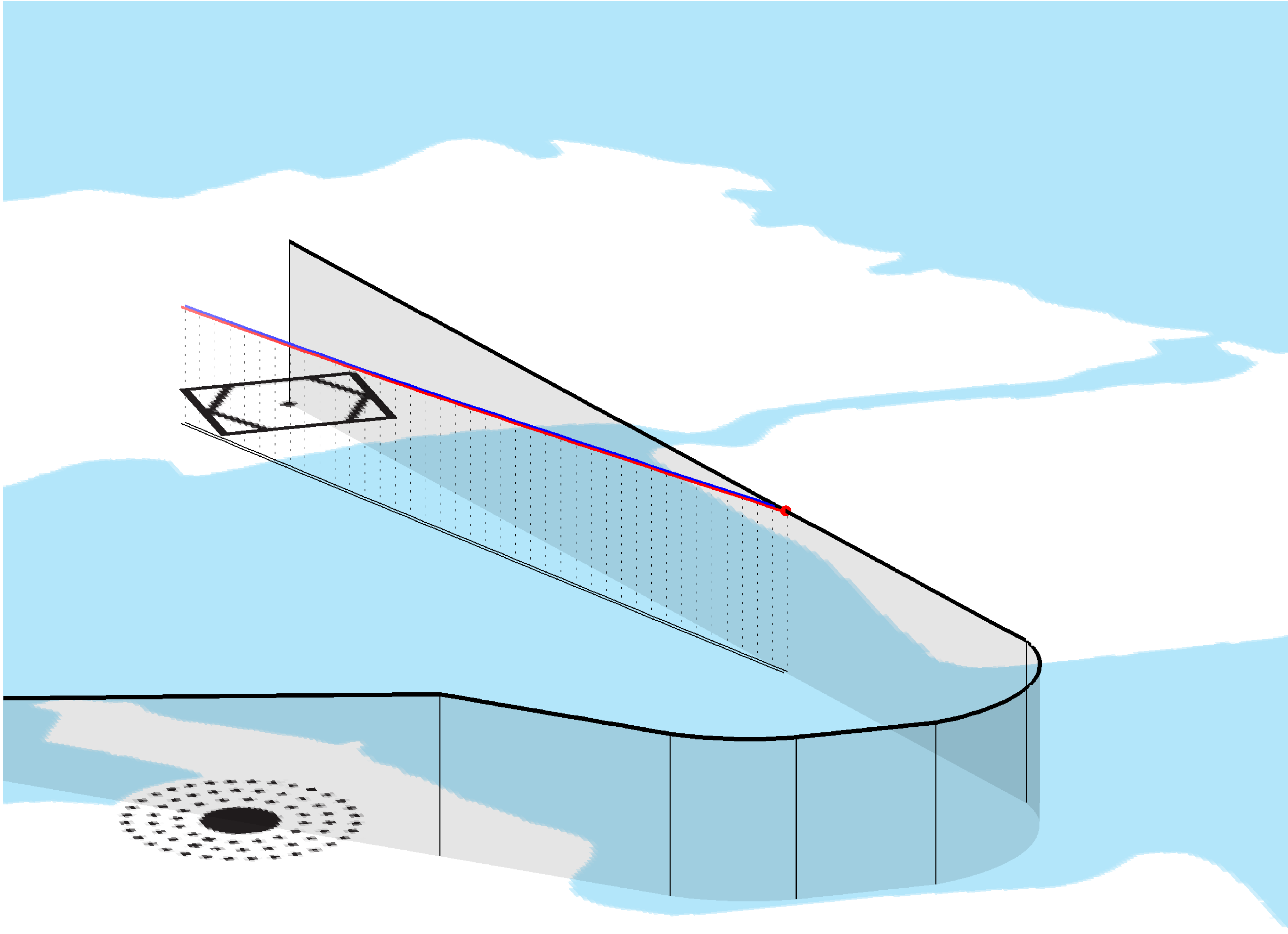
- 7 waypoints are needed (4 straight lines + 2 right turns)



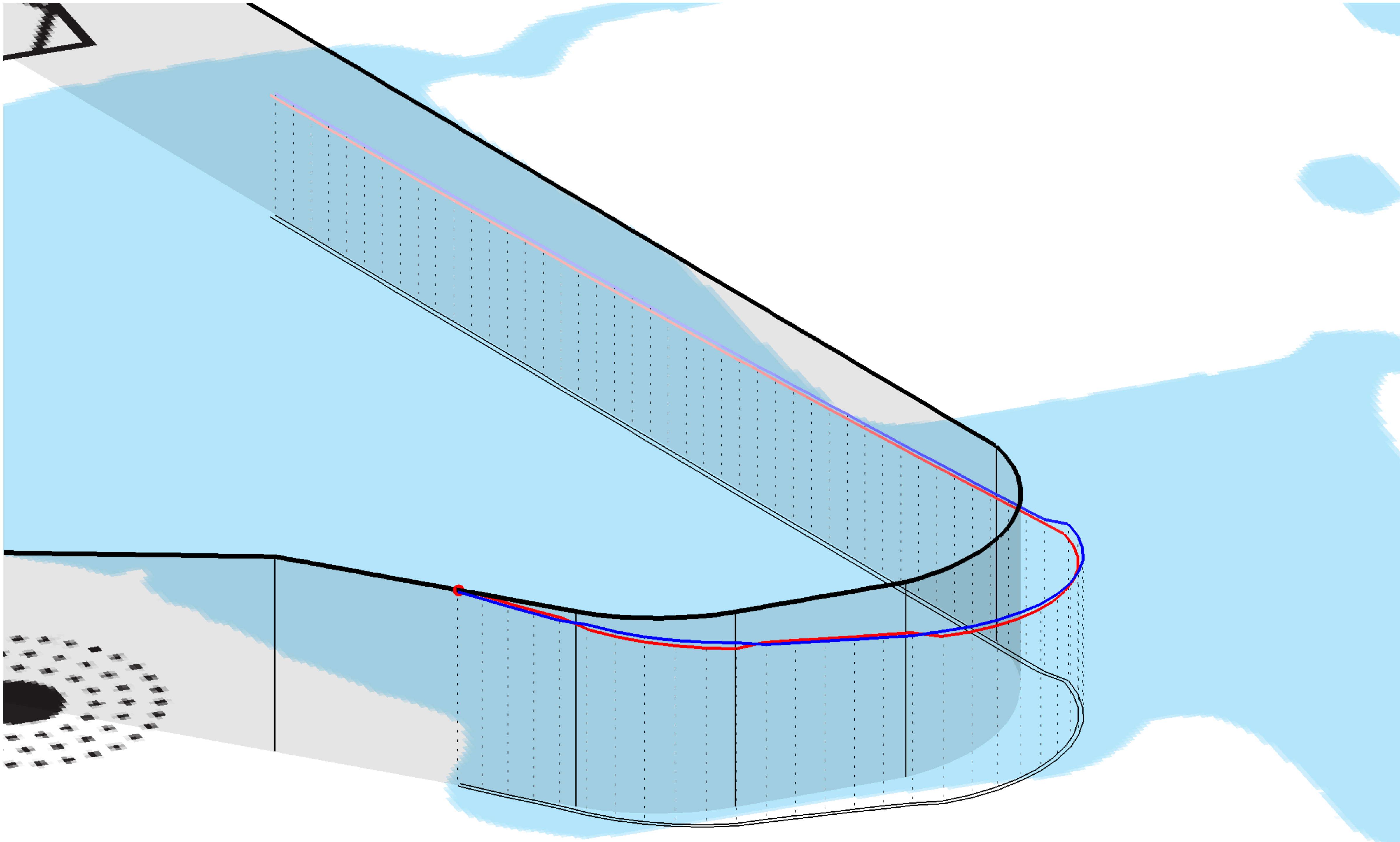
Wake at time t=100 s for S-E wind



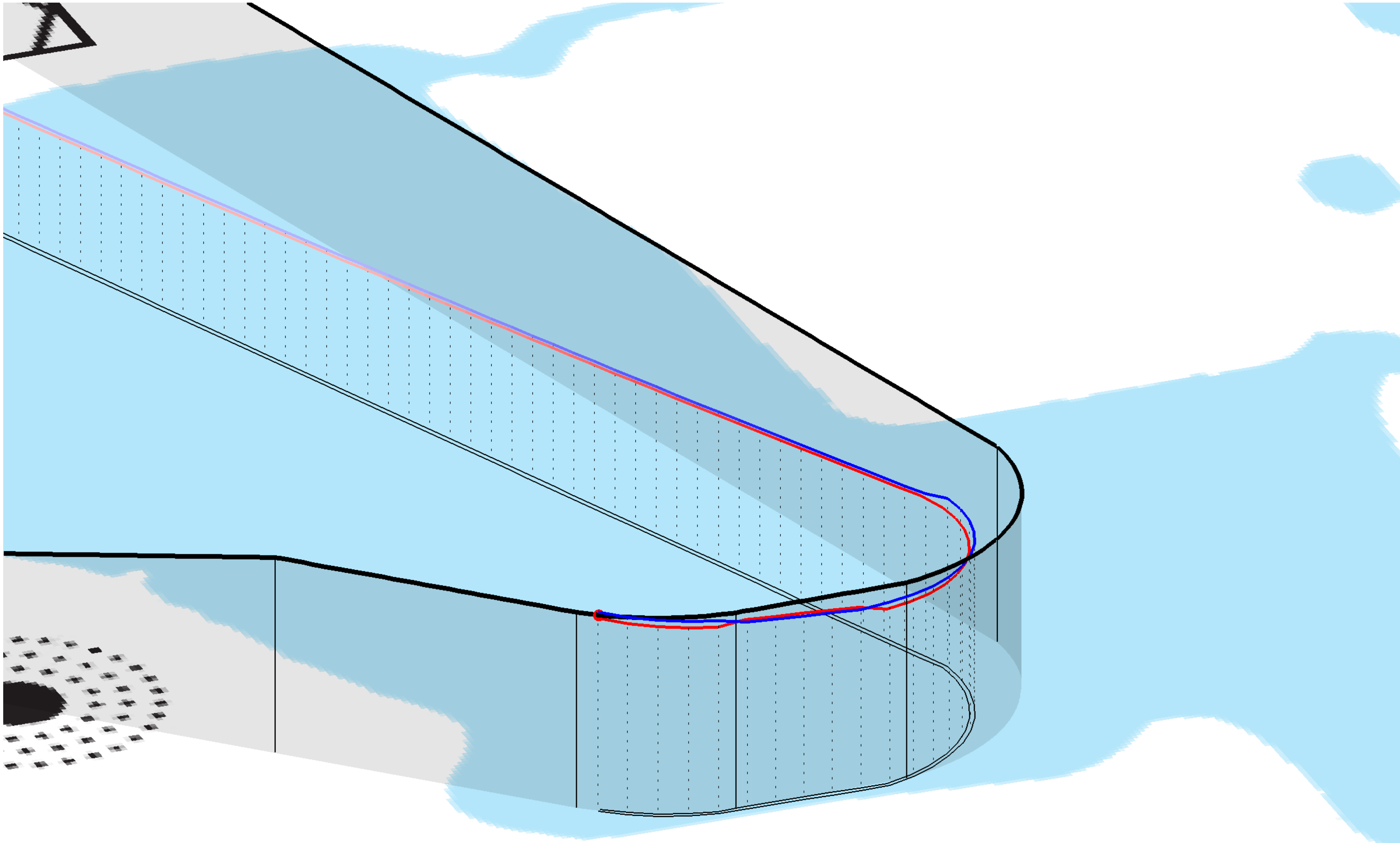
Wake at time t=100 s for S-W wind



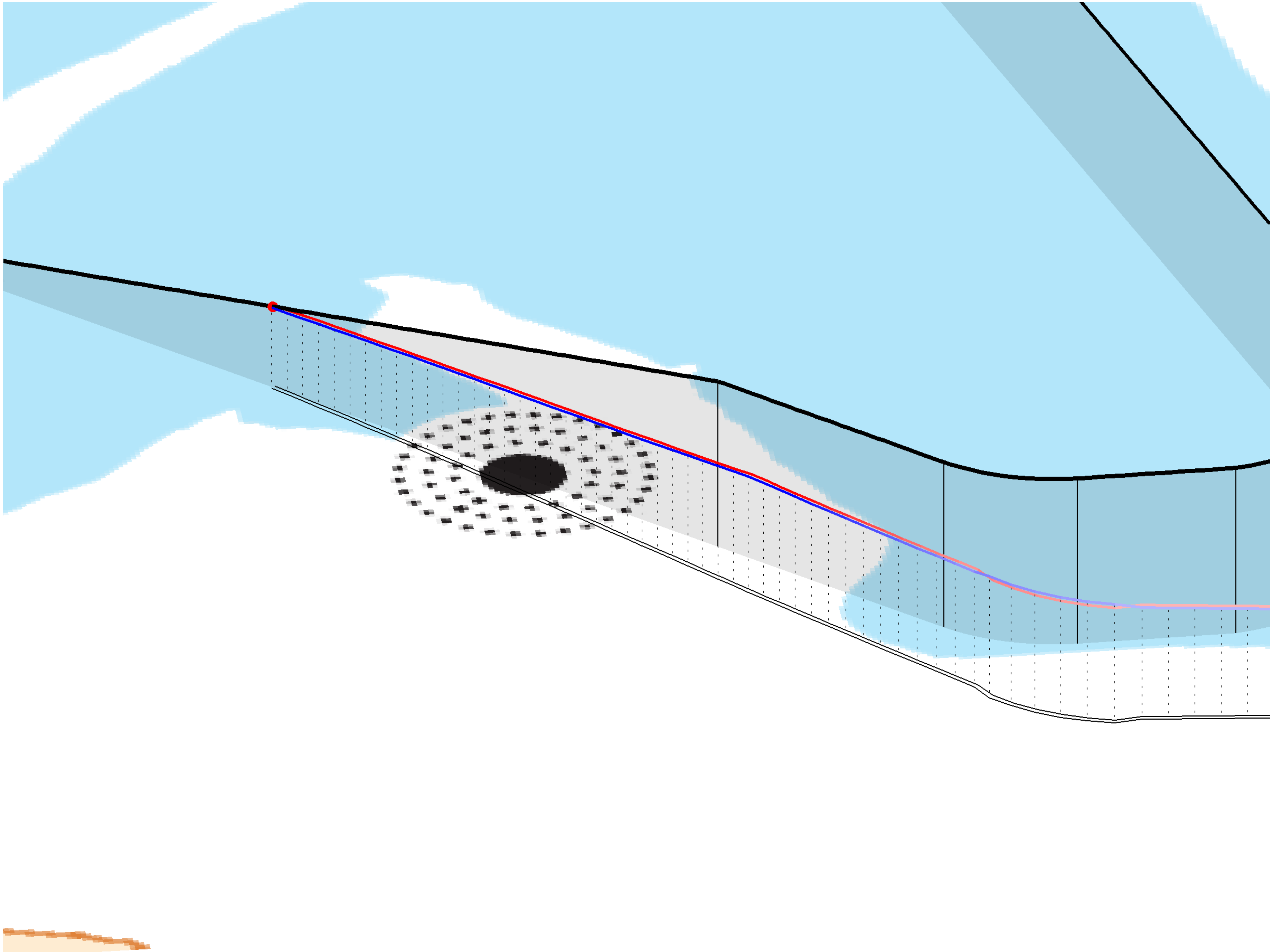
Wake at time t= 200 s for S-E wind



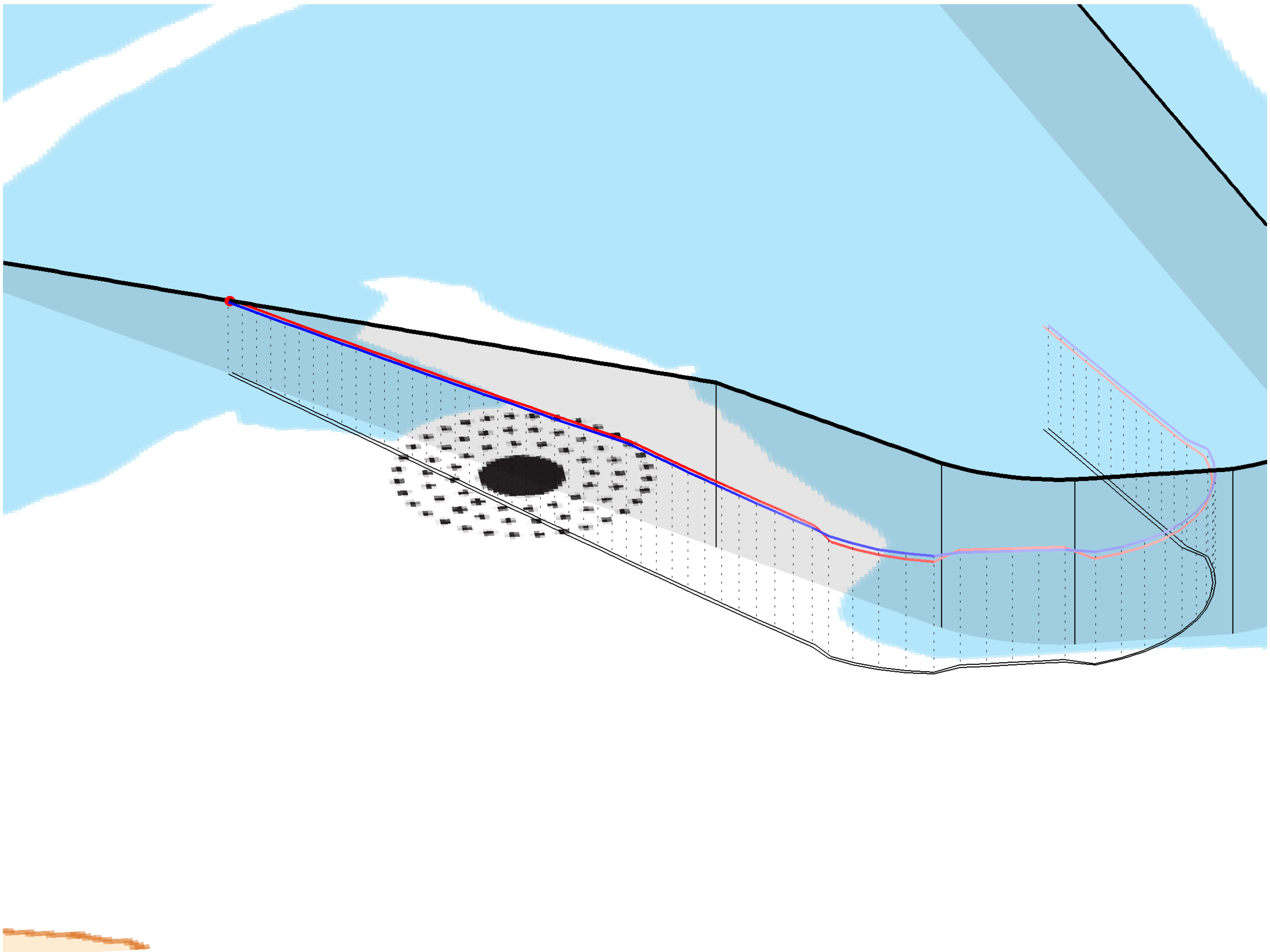
Wake at time t= 200 s for S-W wind



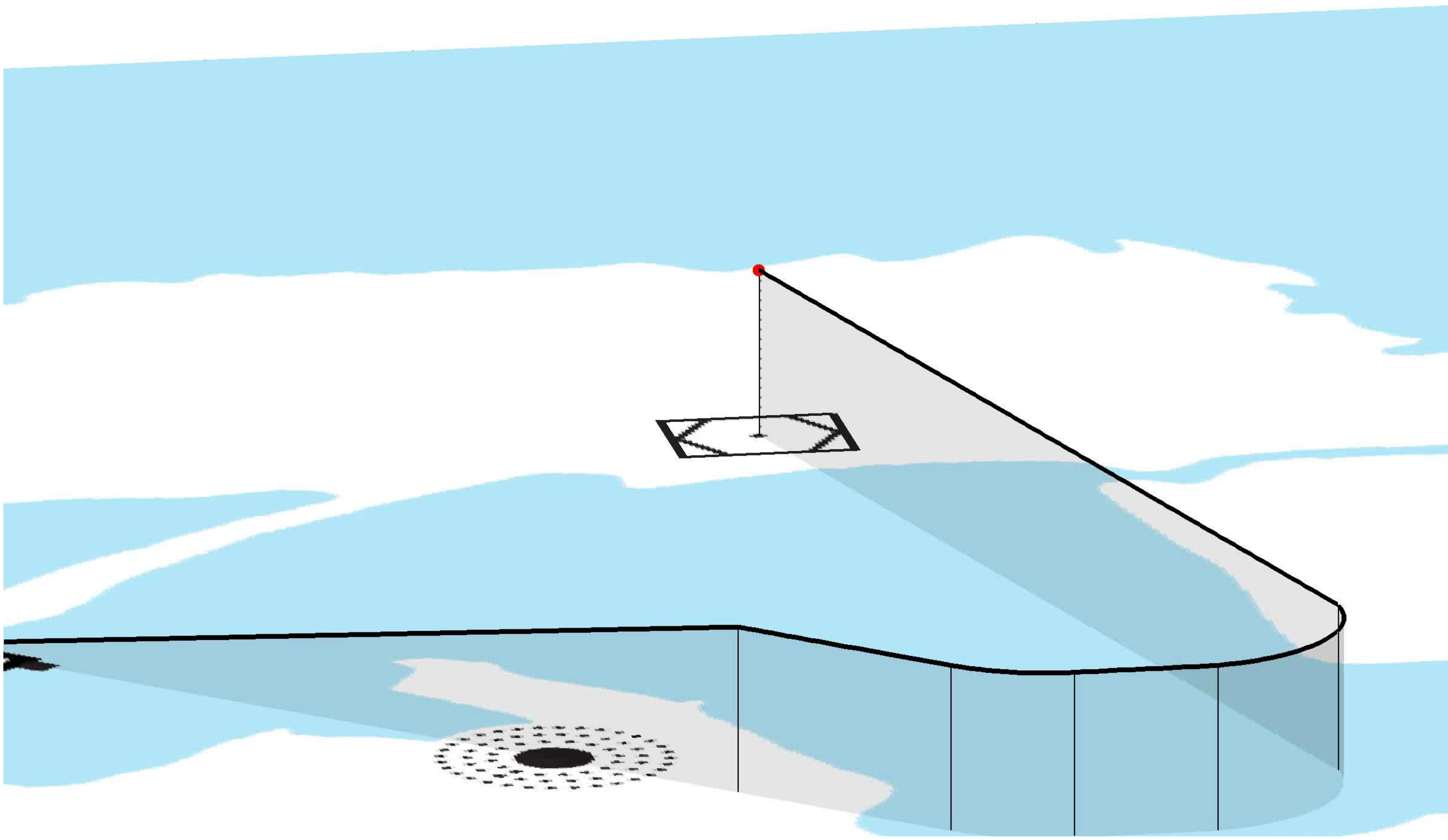
Wake at time t= 300 s for S-E wind



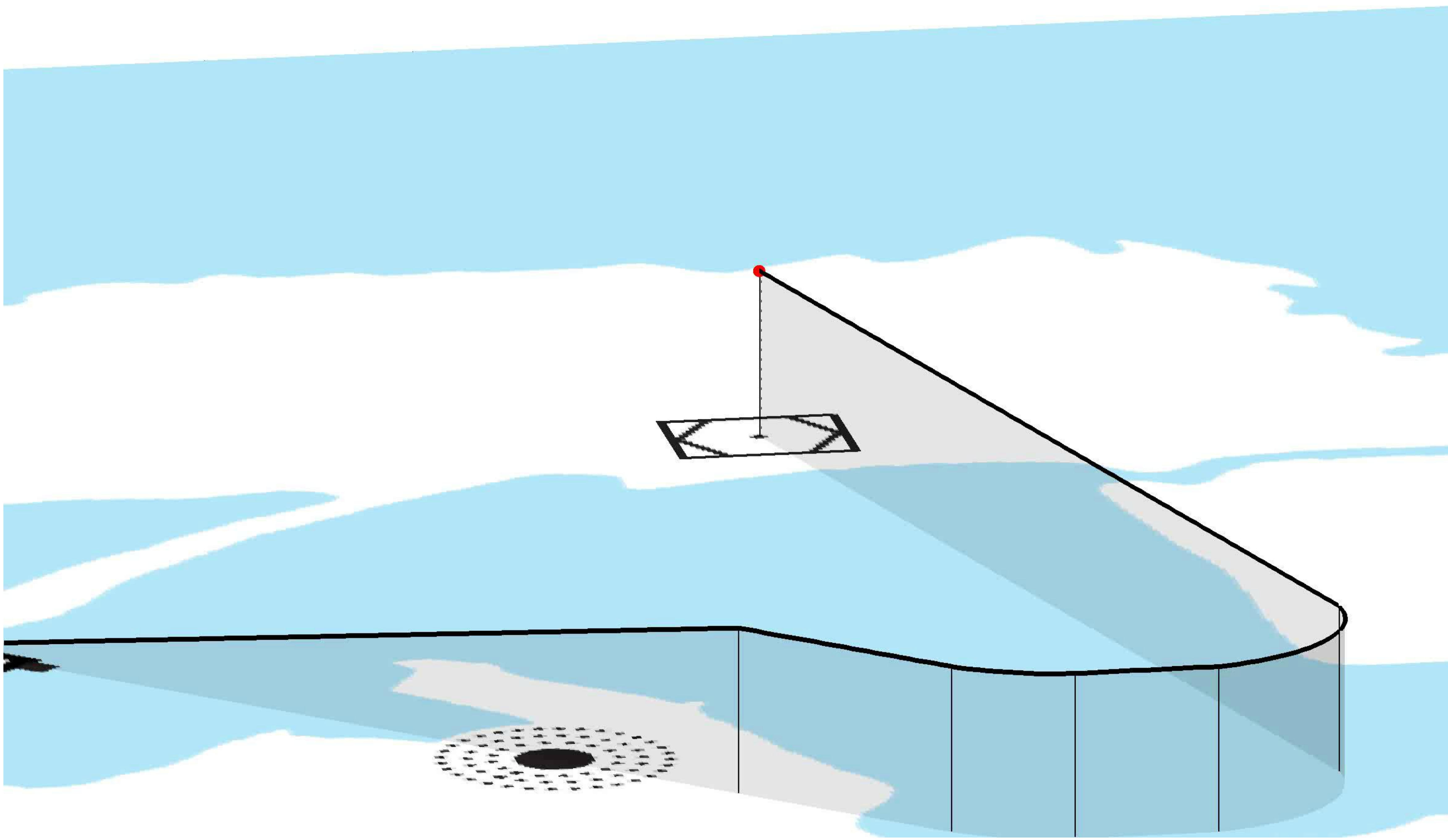
Wake at time t= 300 s for S-W wind



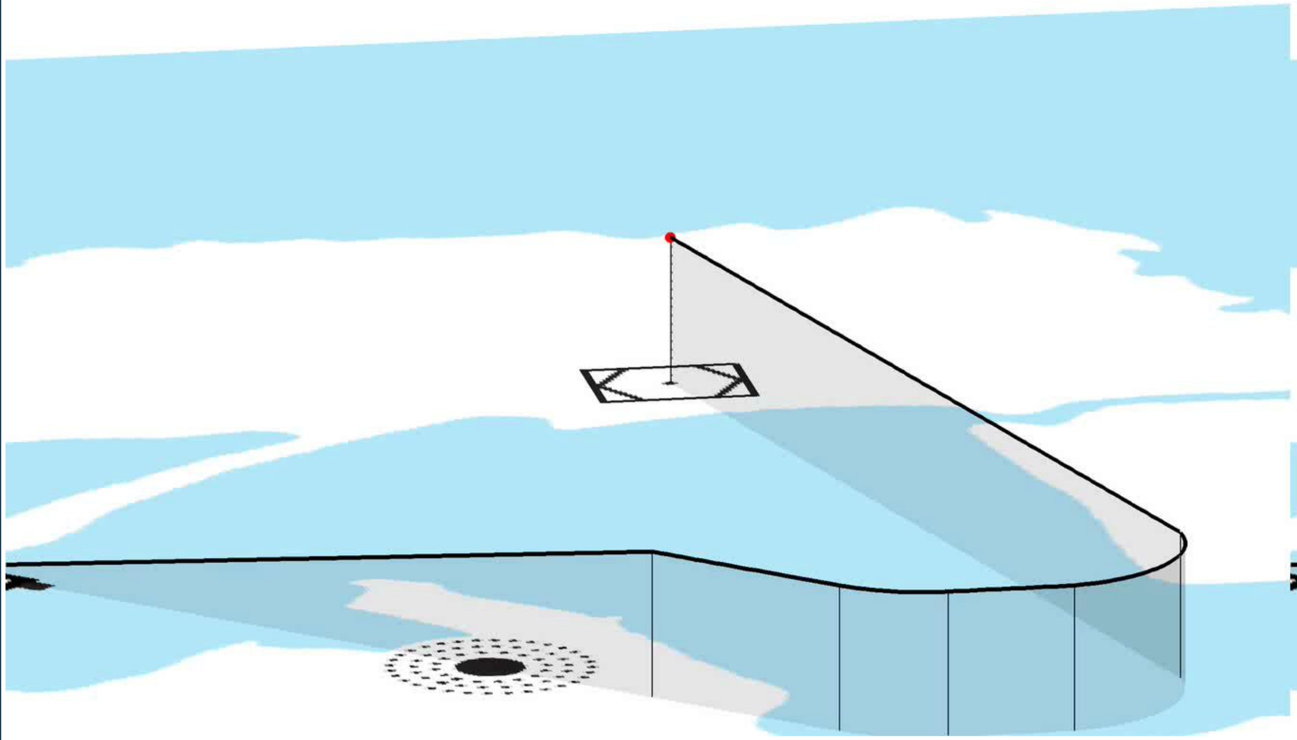
Animation for the S-E wind

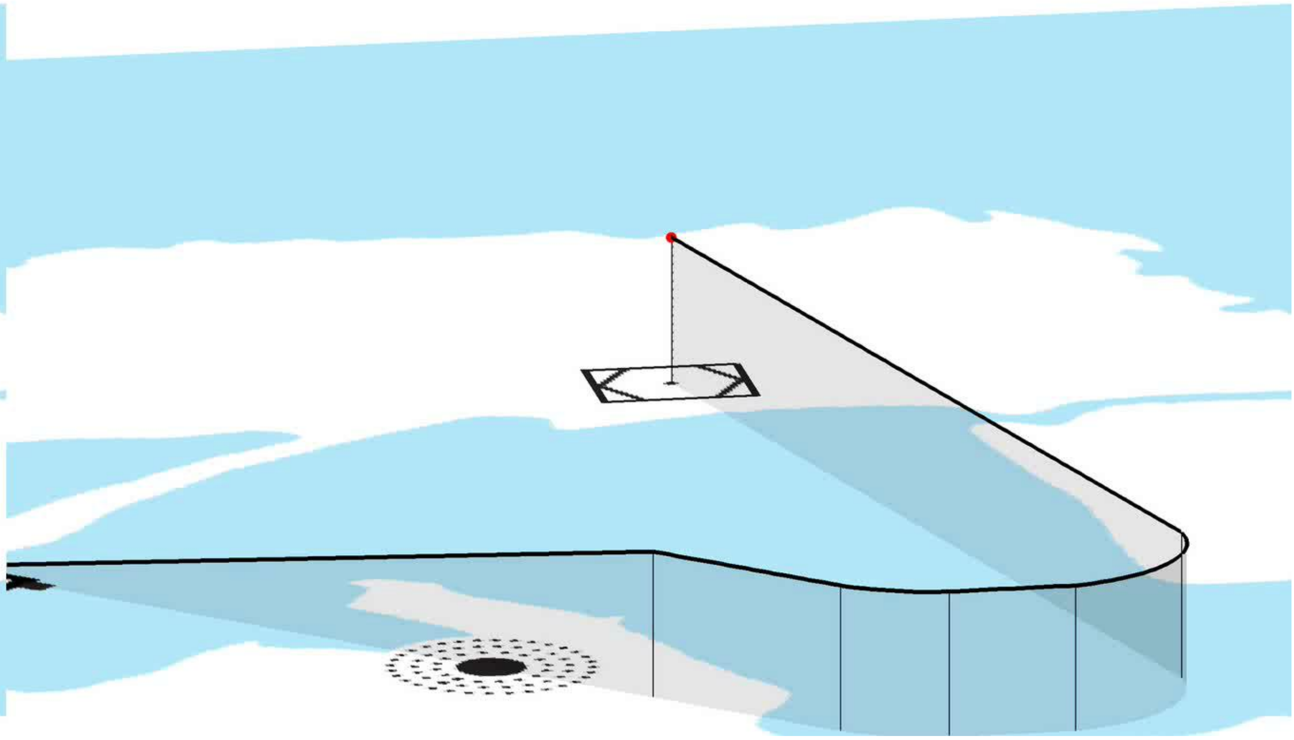


Animation for the S-W wind



Animations for both cases

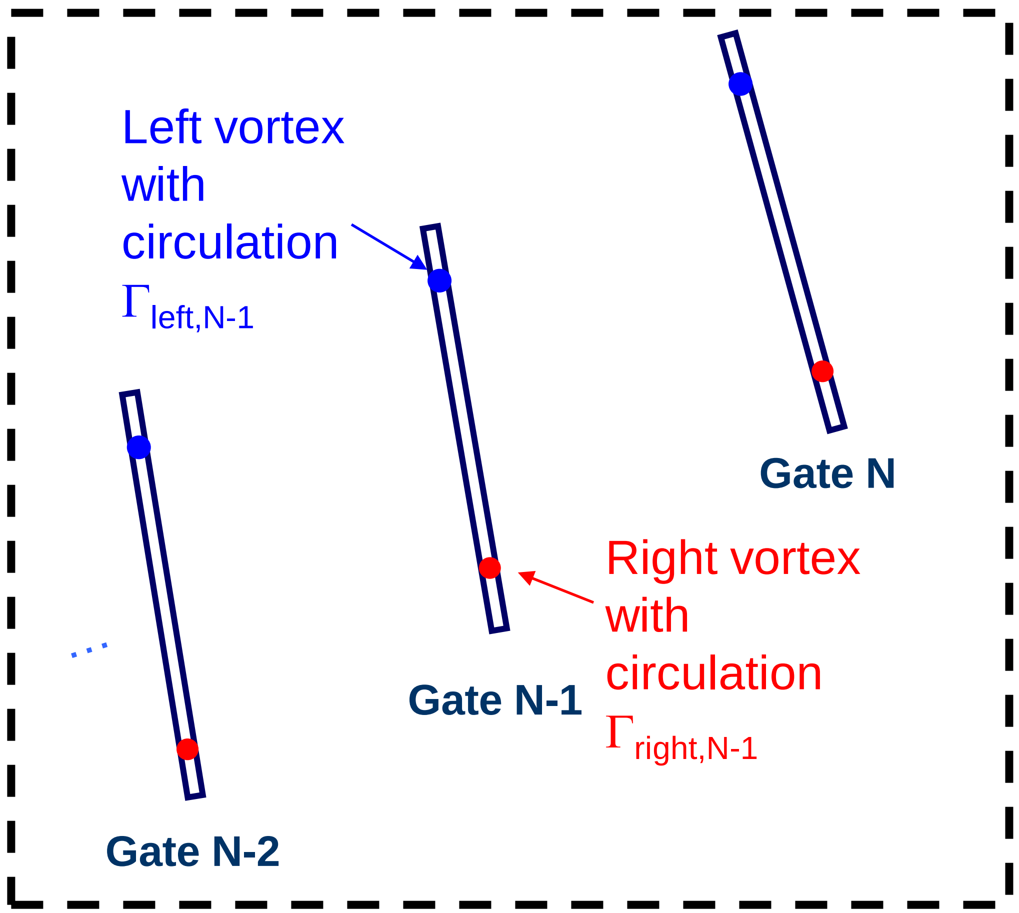




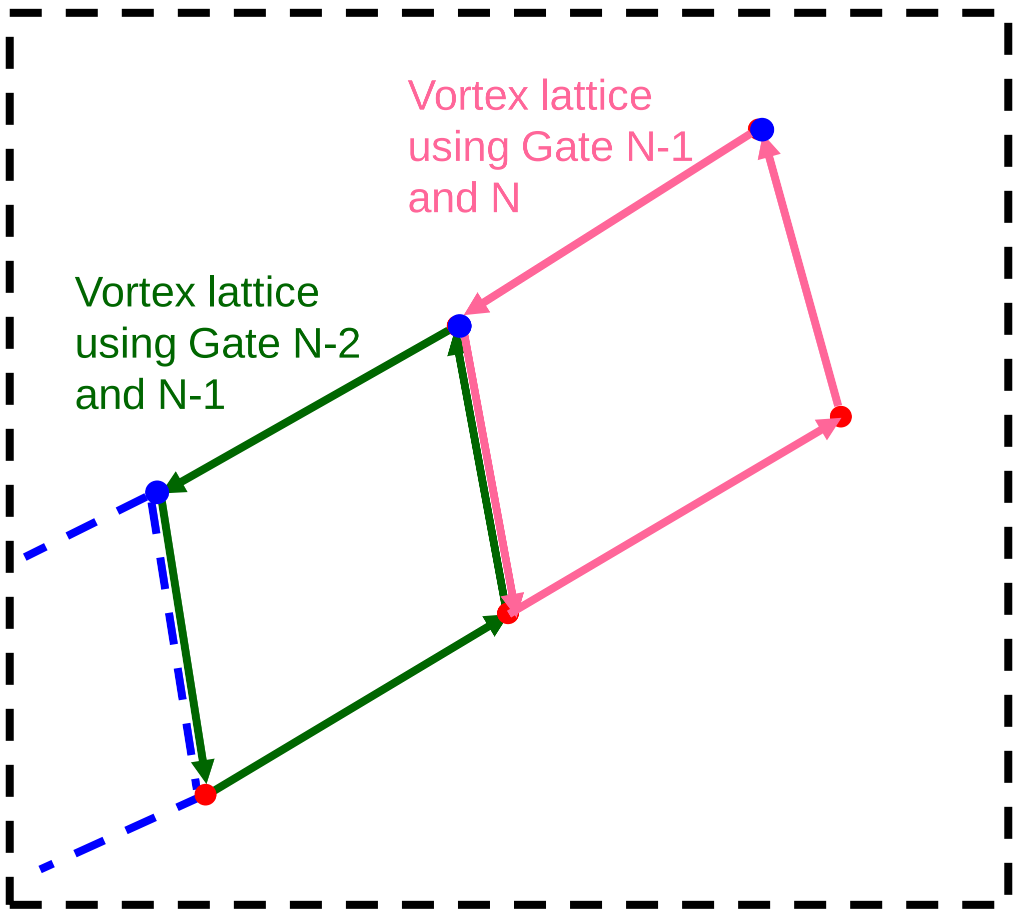
Induced velocity field evaluation using the WAKE4D-DVM results

- 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 equal to
  - the sum of the induced velocity of all "active" vortex lattices
  - plus the interpolated velocity induced by the secondary vorticity (if IGE).



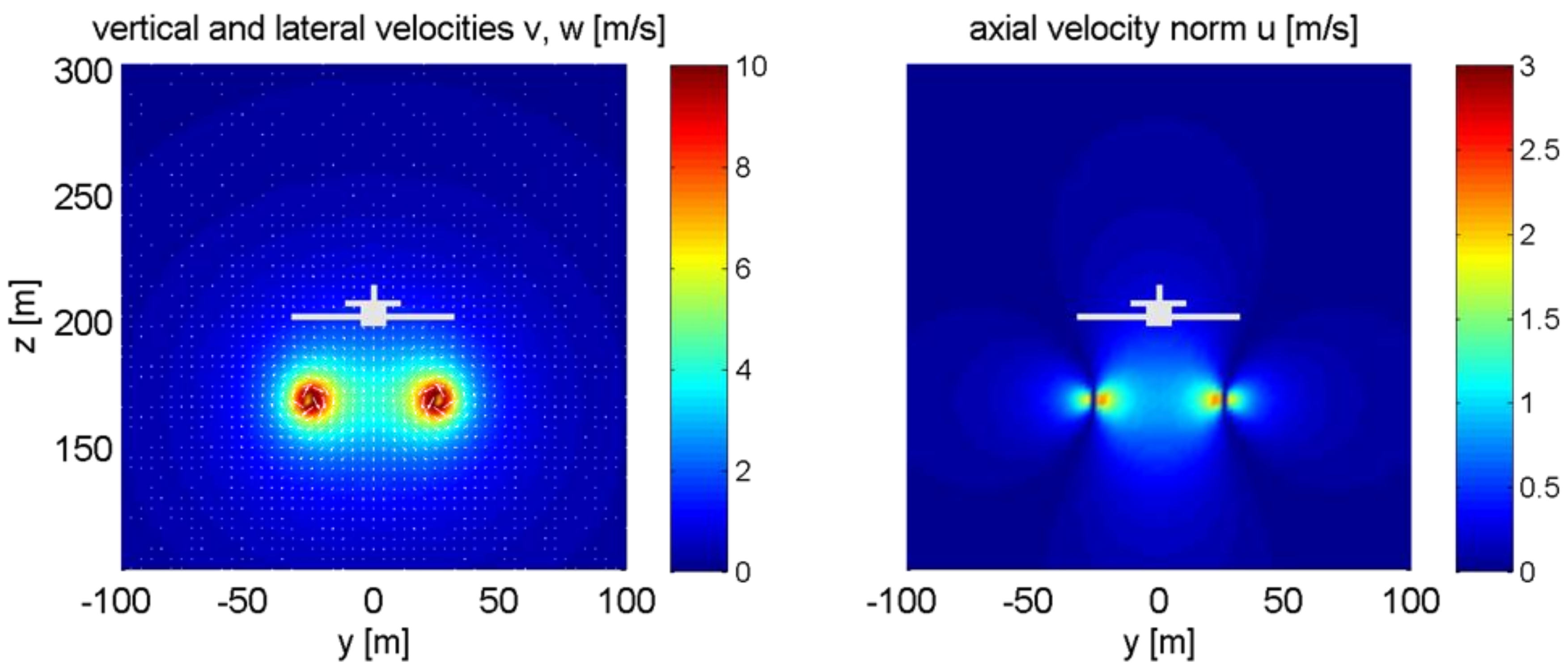
WAKE4D outputs at time t

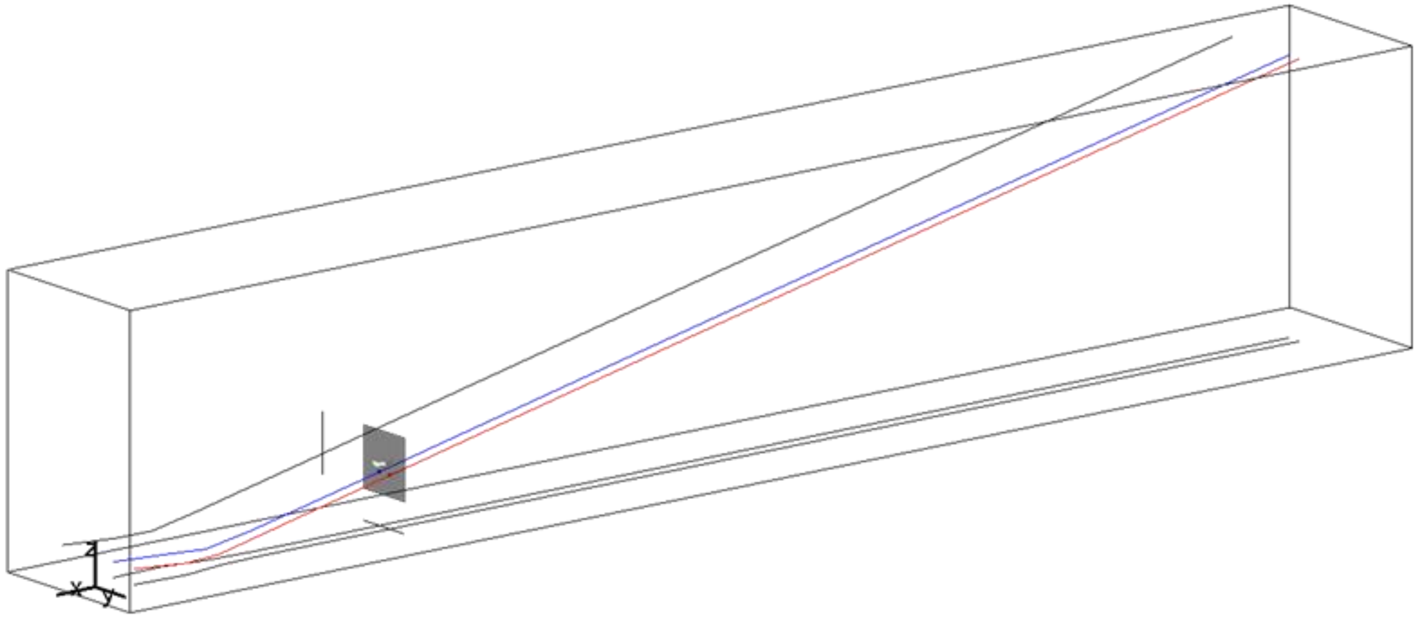


Vortex lattice representation for velocity field evaluation at time t

Induced velocity field evaluation using the WAKE4D results

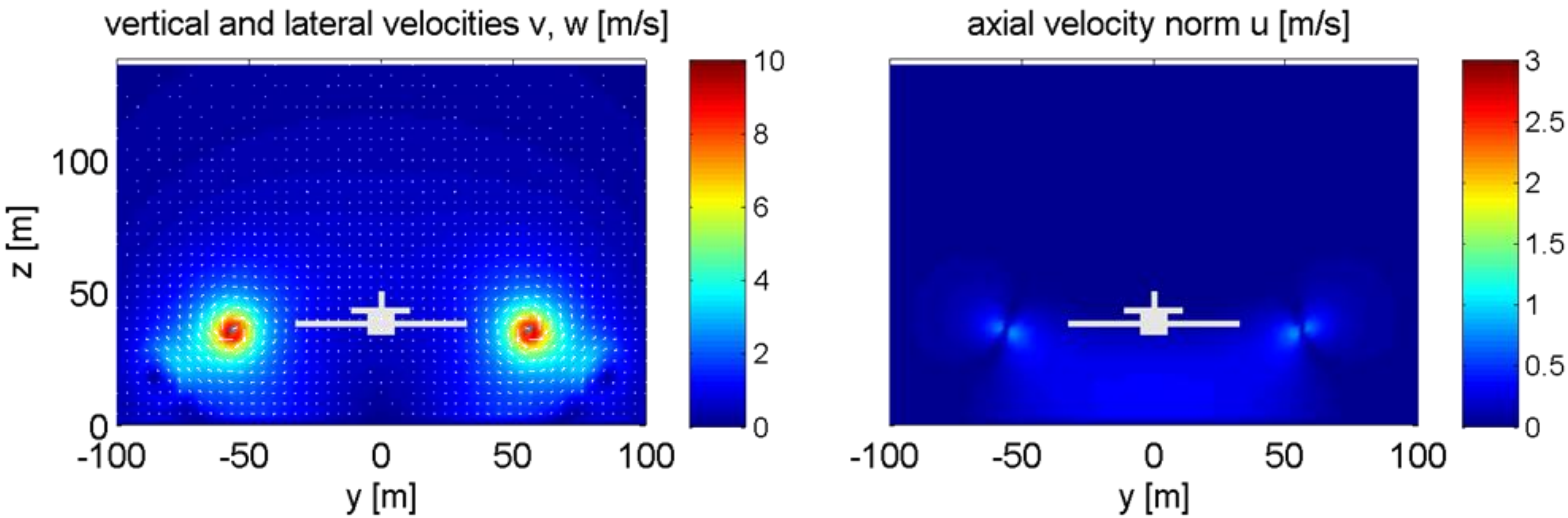
- Evaluation of the velocity for complex aircraft trajectory scenarios (e.g., take-off, landing, turns, …)
- Real-time evaluation of the induced velocity at a hundred of points.

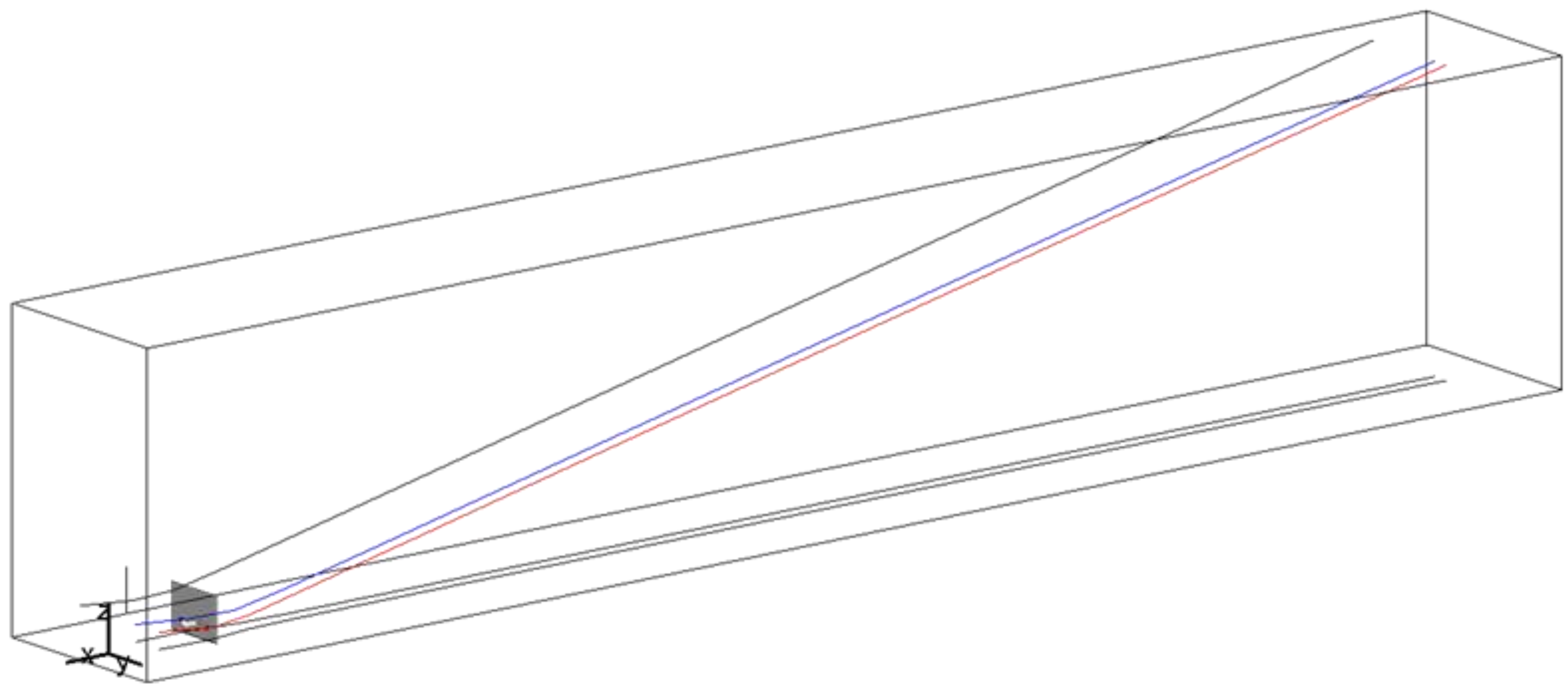




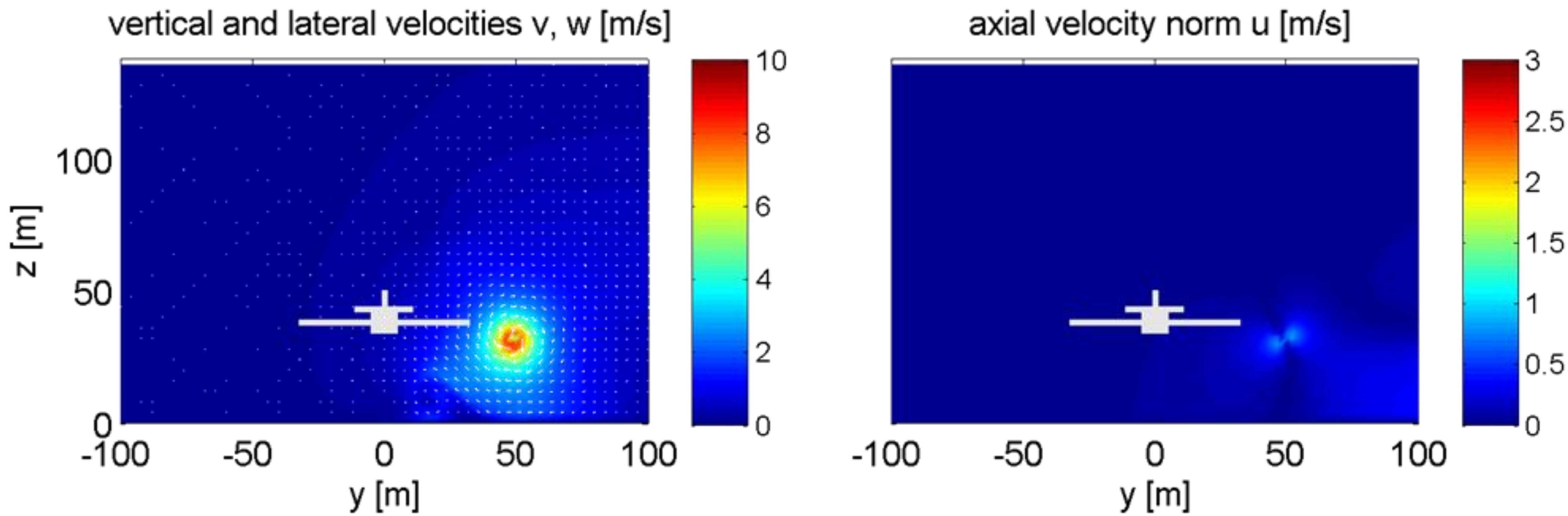
Example: Typical take-off of a large aircraft with headwind but no crosswind with a 90 s separation

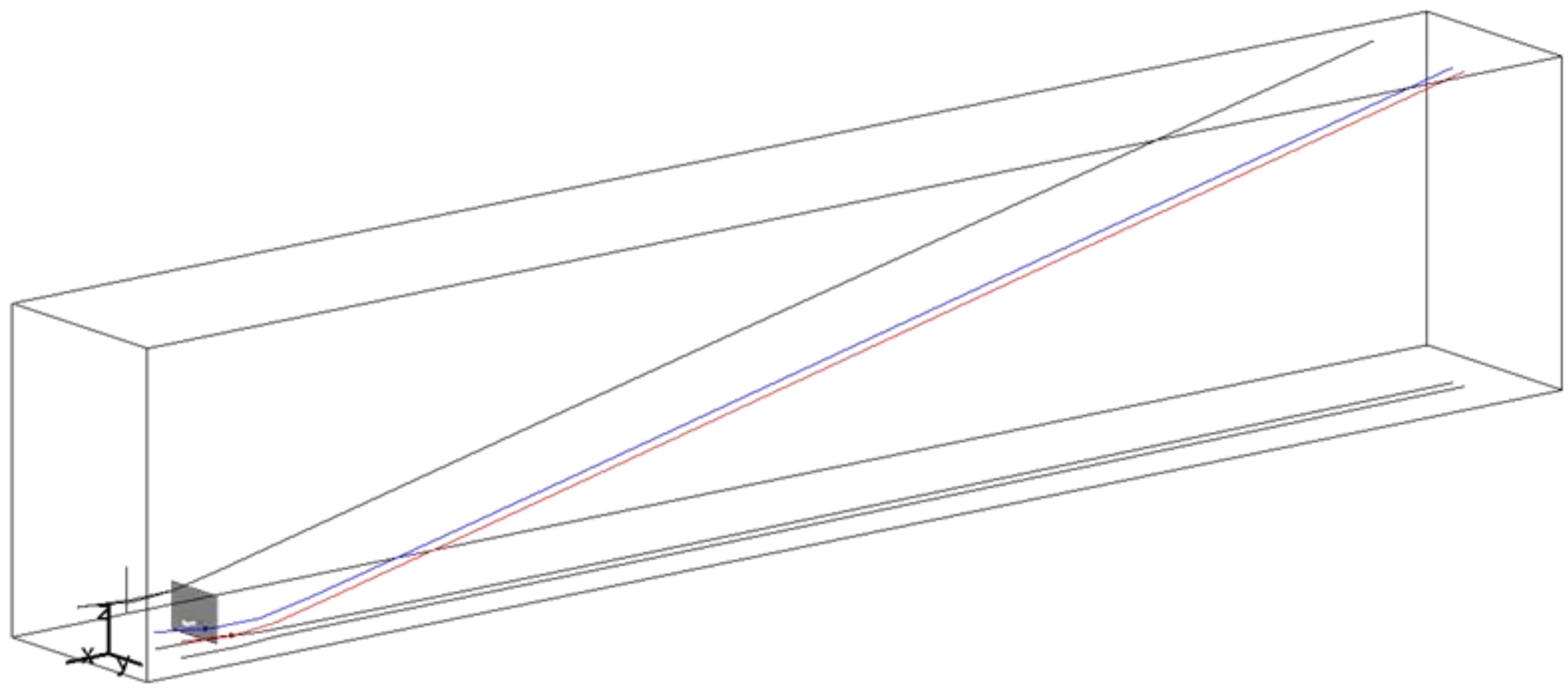
Typical take-off without crosswind with a 90 s separation





Typical take-off with low crosswind and with a 90 s separation





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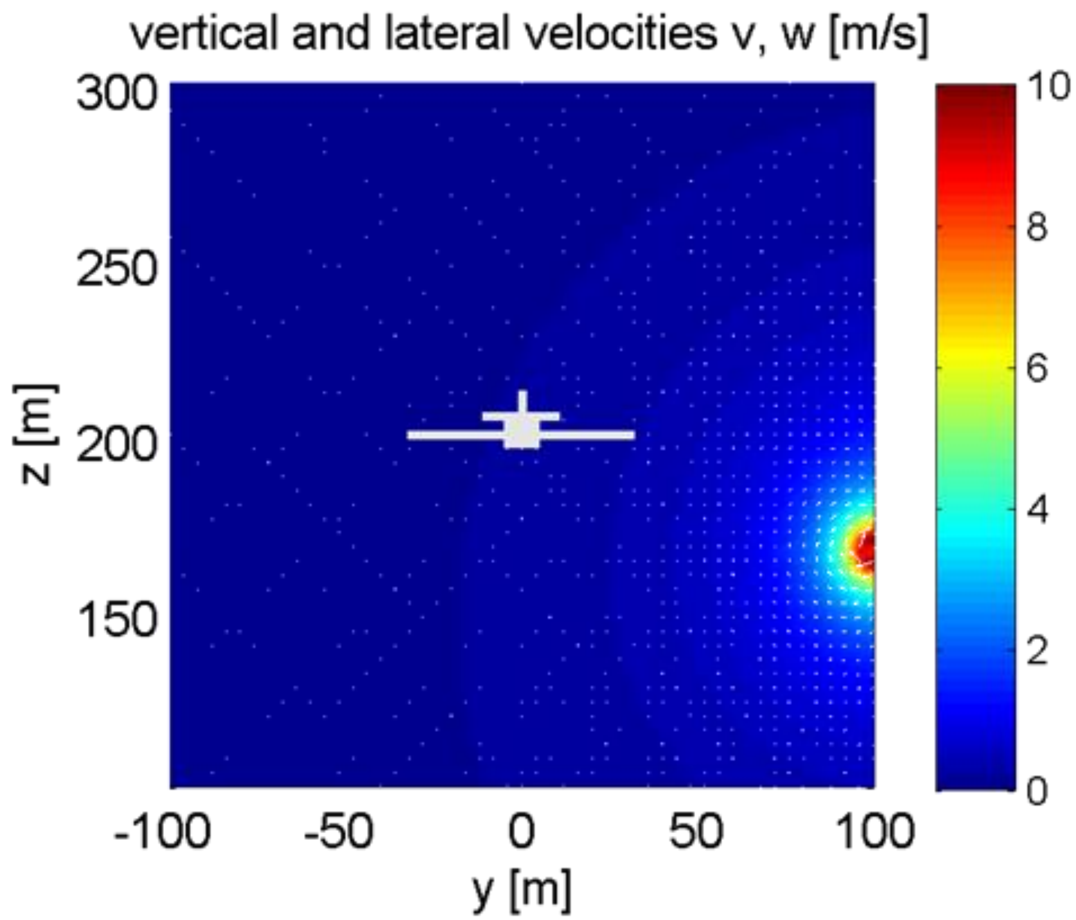
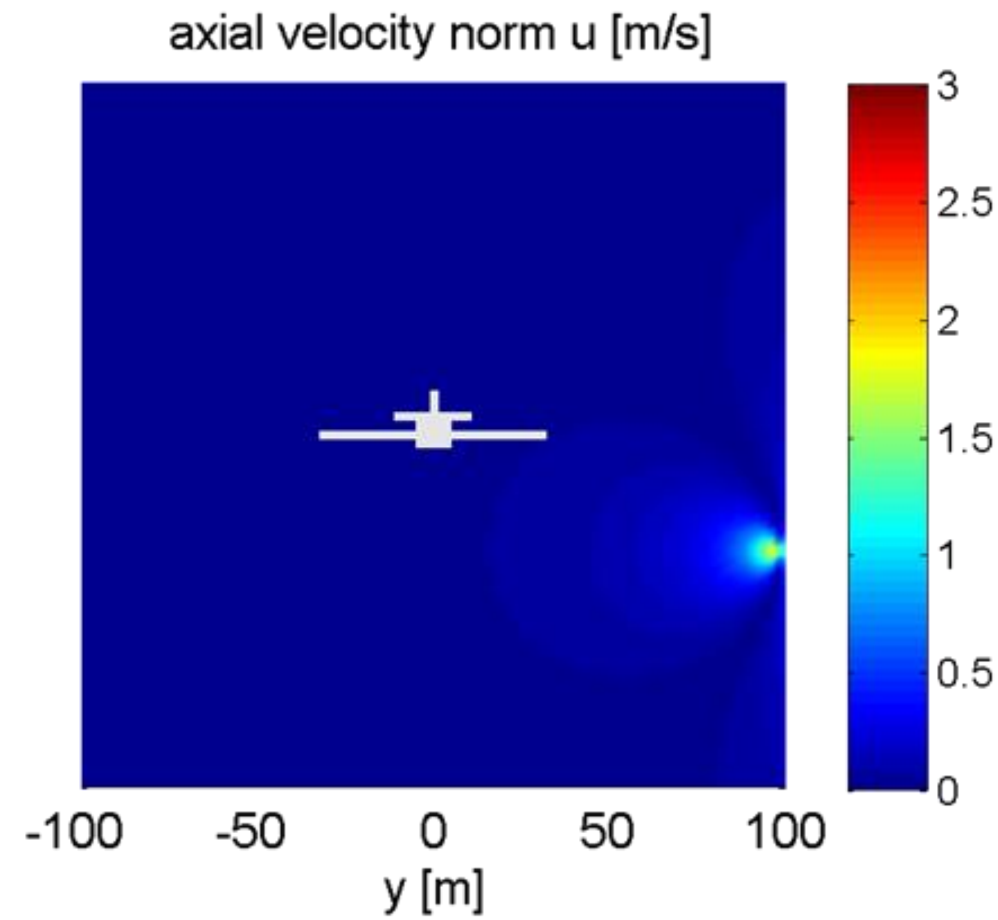
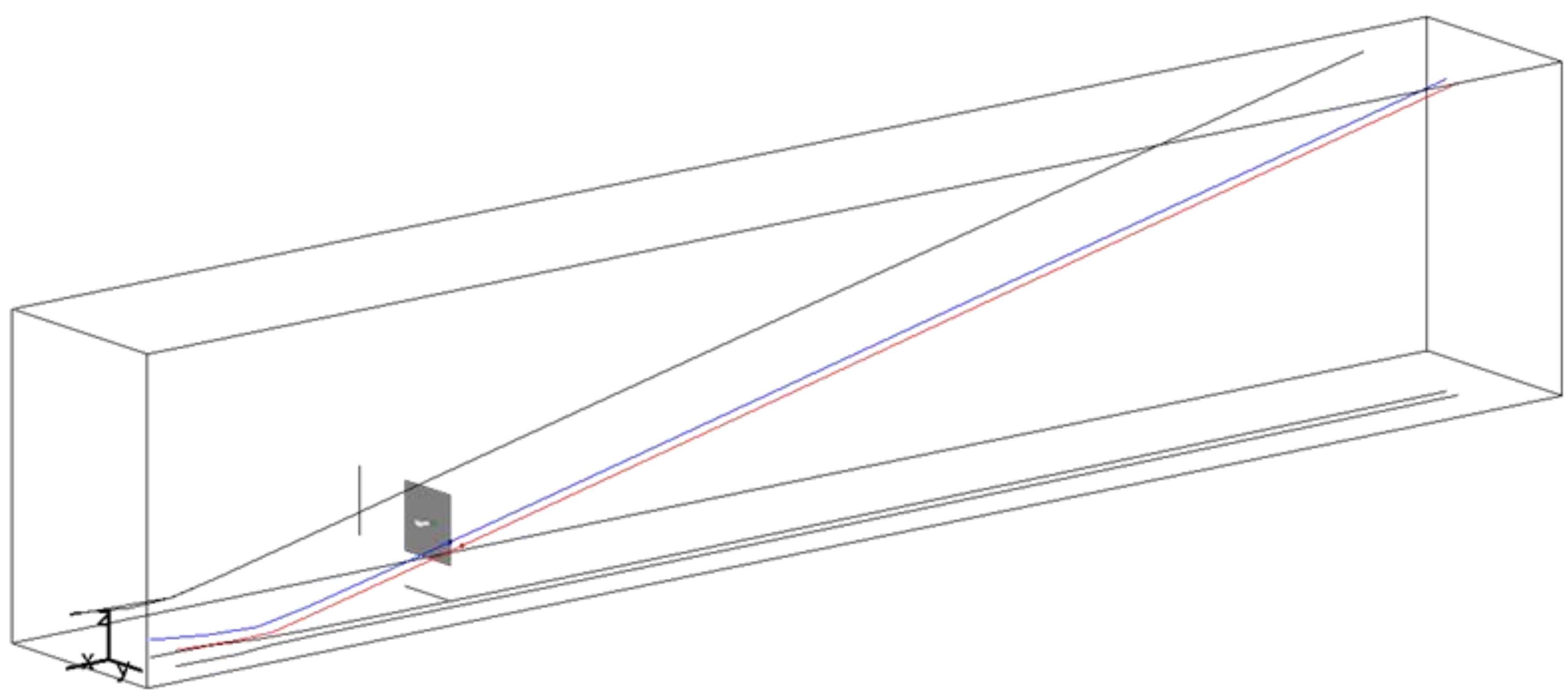
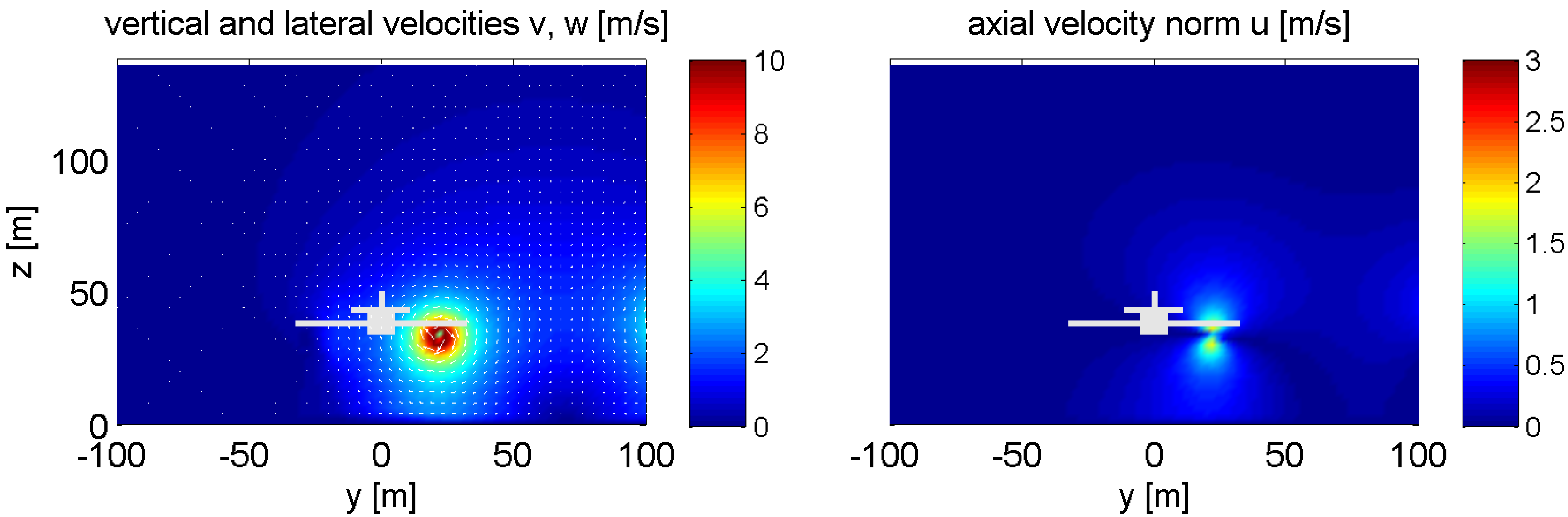
Typical take-off with low crosswind and with a 90 s separation

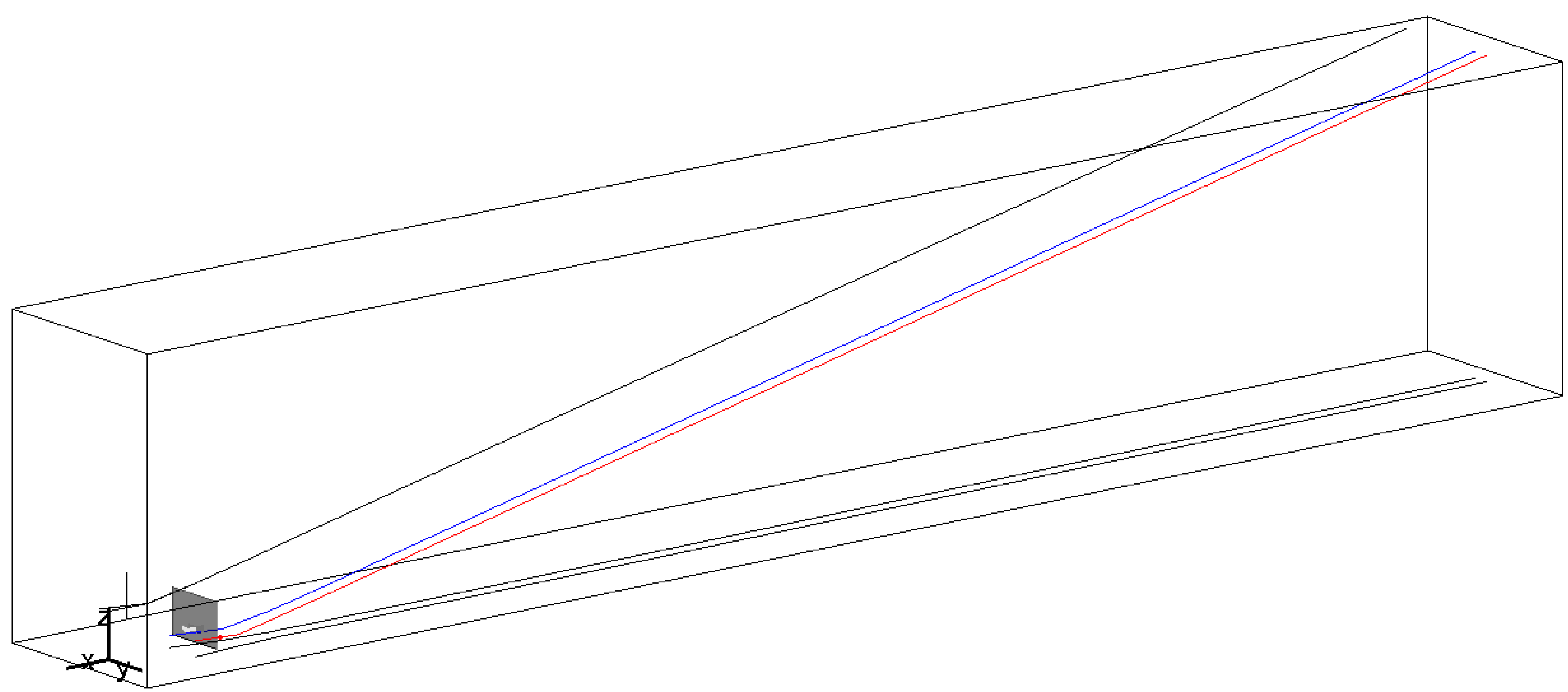






Typical take-off with low crosswind and with a 60 s separation



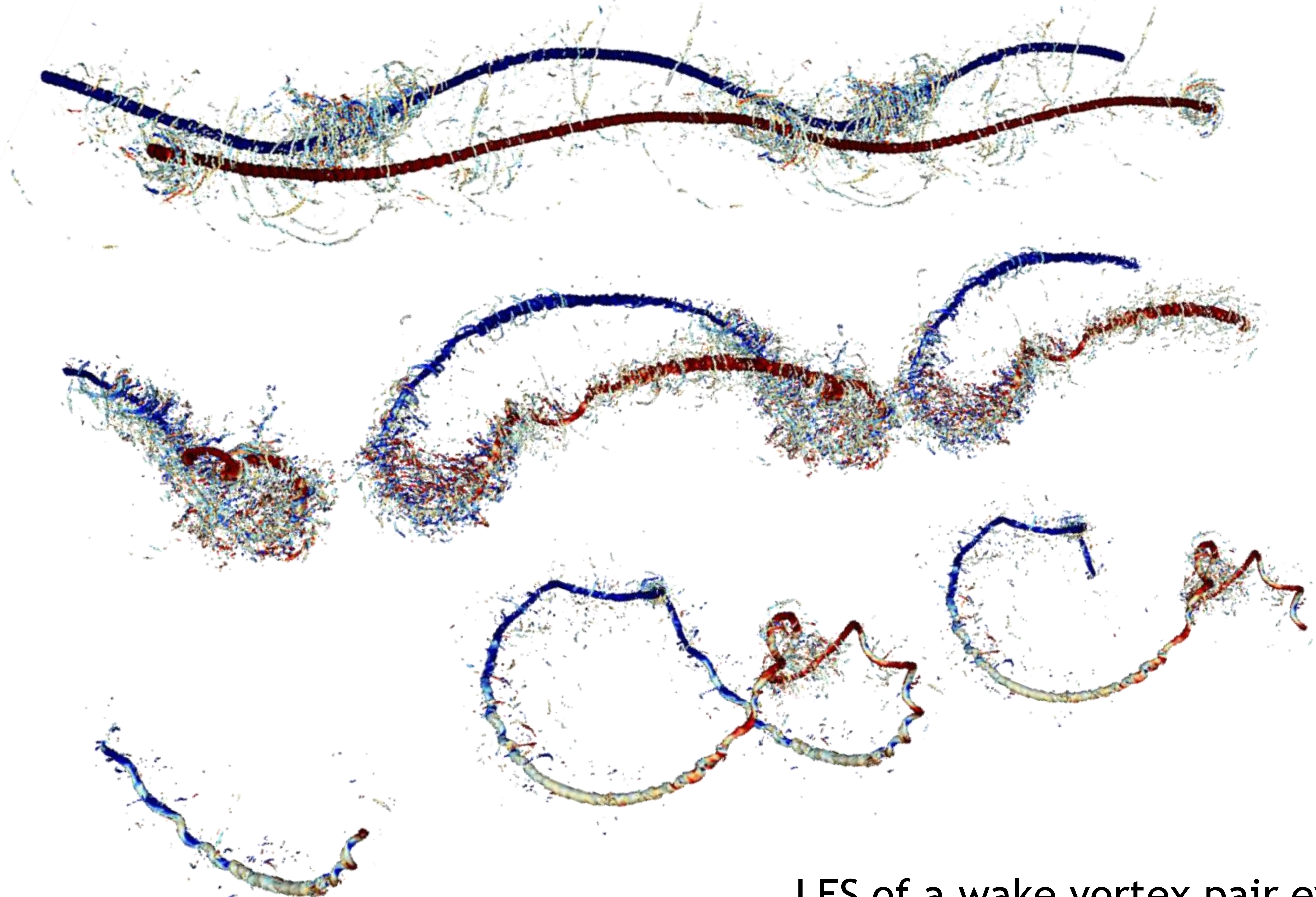


Crow instability

$\tau = 4.0$

$\tau = 5.0$

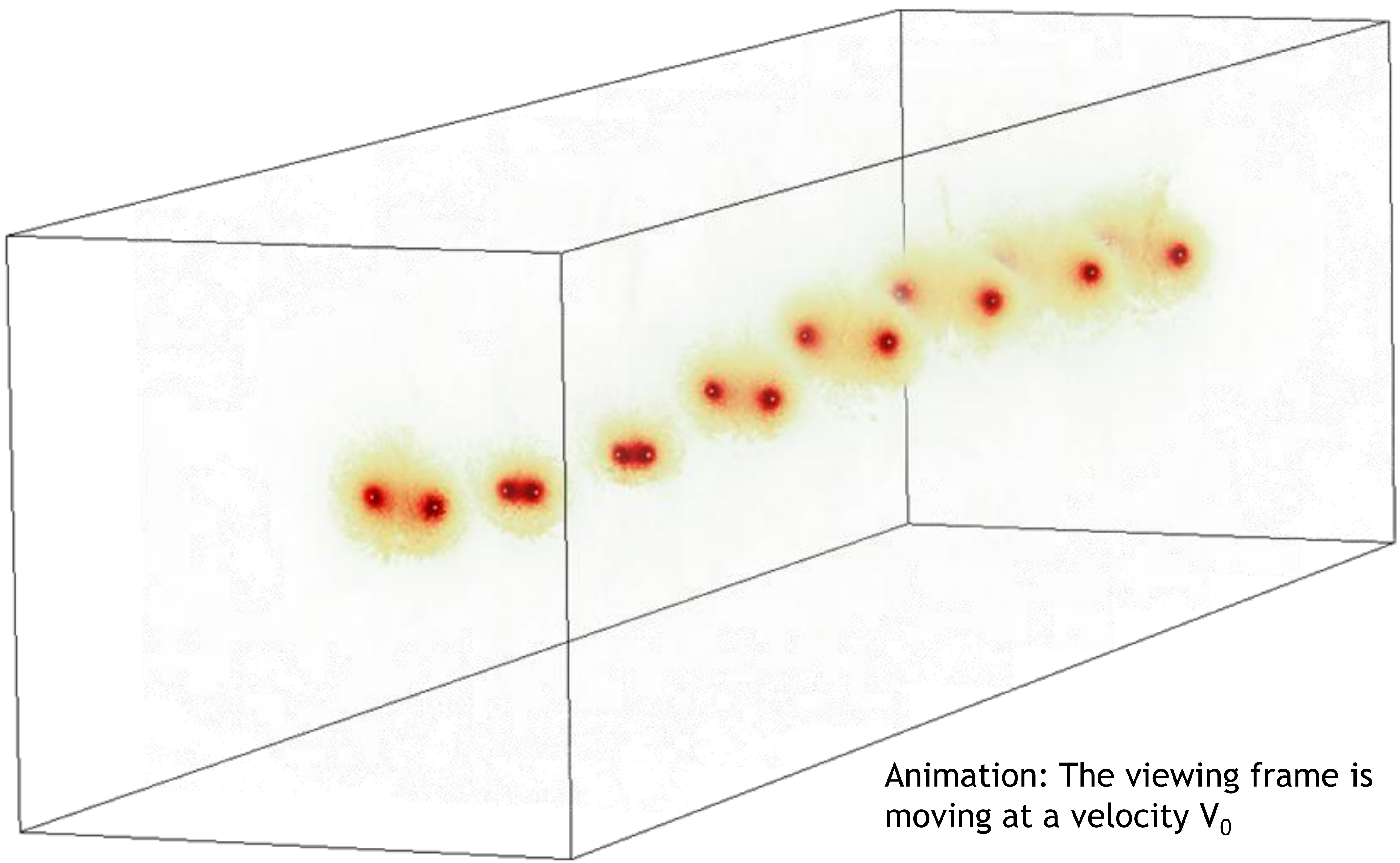
$\tau = 6.0$



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

Velocity norm in several planes (LES results)

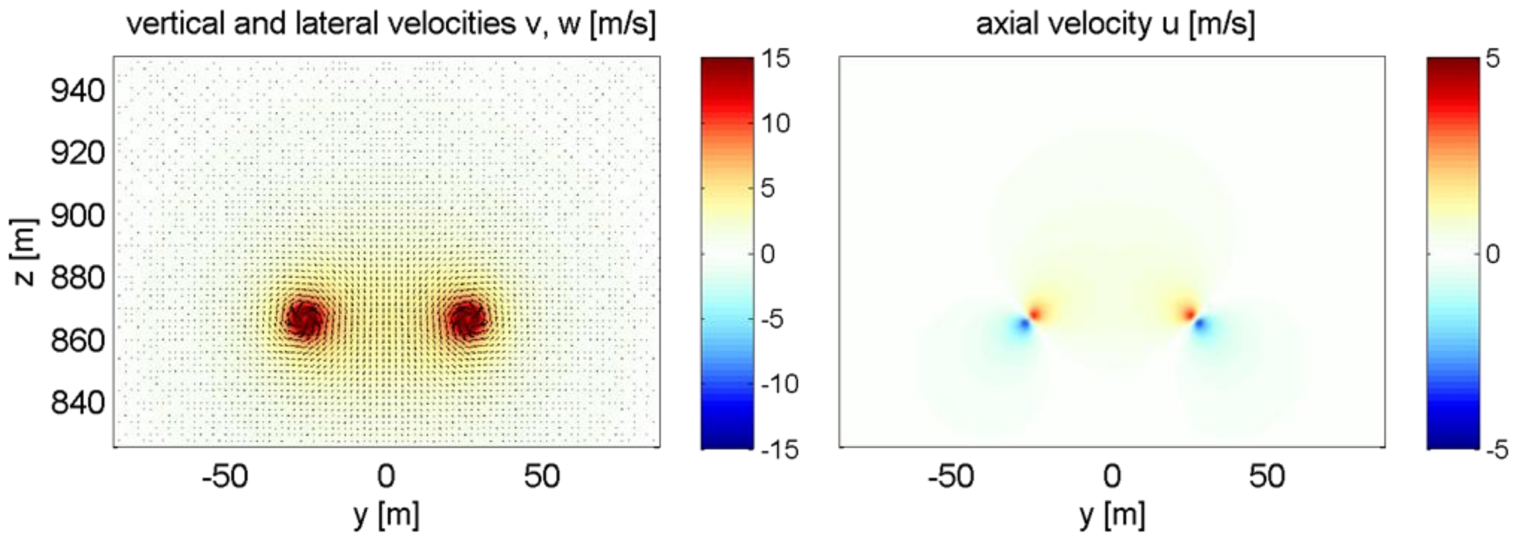
- Pseudo Spectral Code
- very high Re
- ~130 millions grid points
- ~ 1 month on 64 CPU's

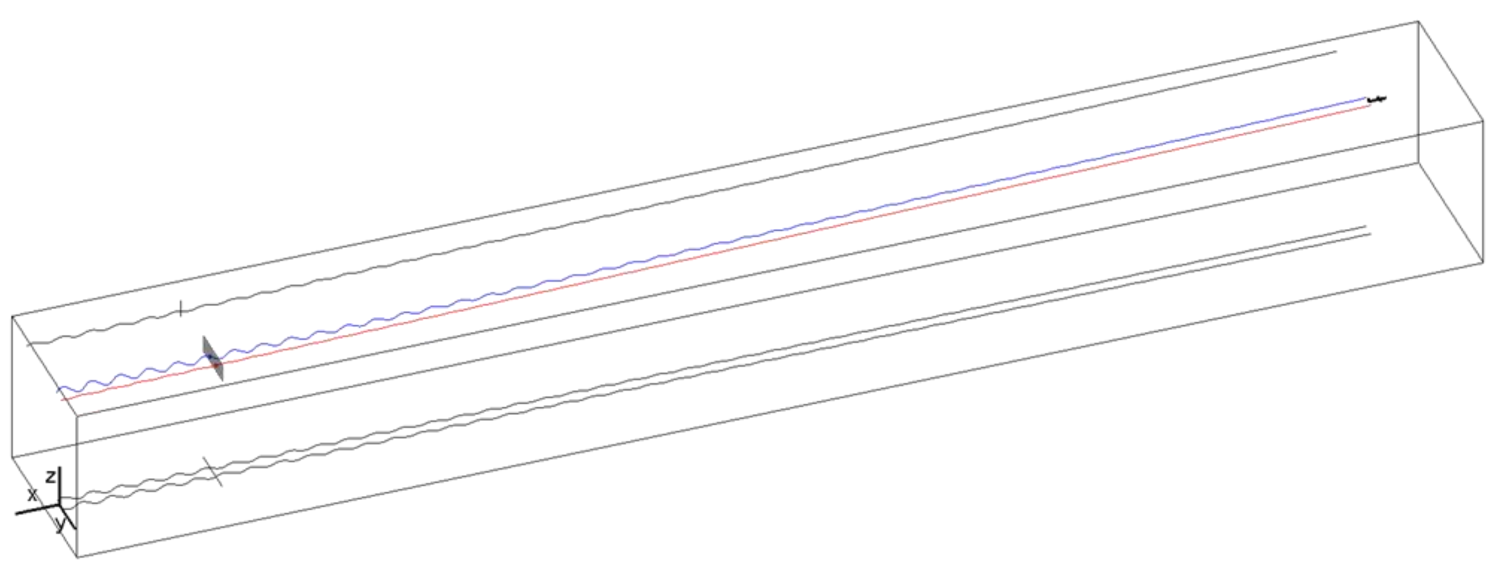


Animation: The viewing frame is moving at a velocity V_0

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

- The deformed 3-D wake is rebuilt using the Crow instability amplitude as predicted in each computational gates.
- As post-processing, the velocity field induced by the deformed vortices can be evaluated, in real-time, using a vortex filaments approach with efficient Biot-Savart velocity evaluation
- This approach is useful for OGE conditions (also cruise) where Crow effects are important





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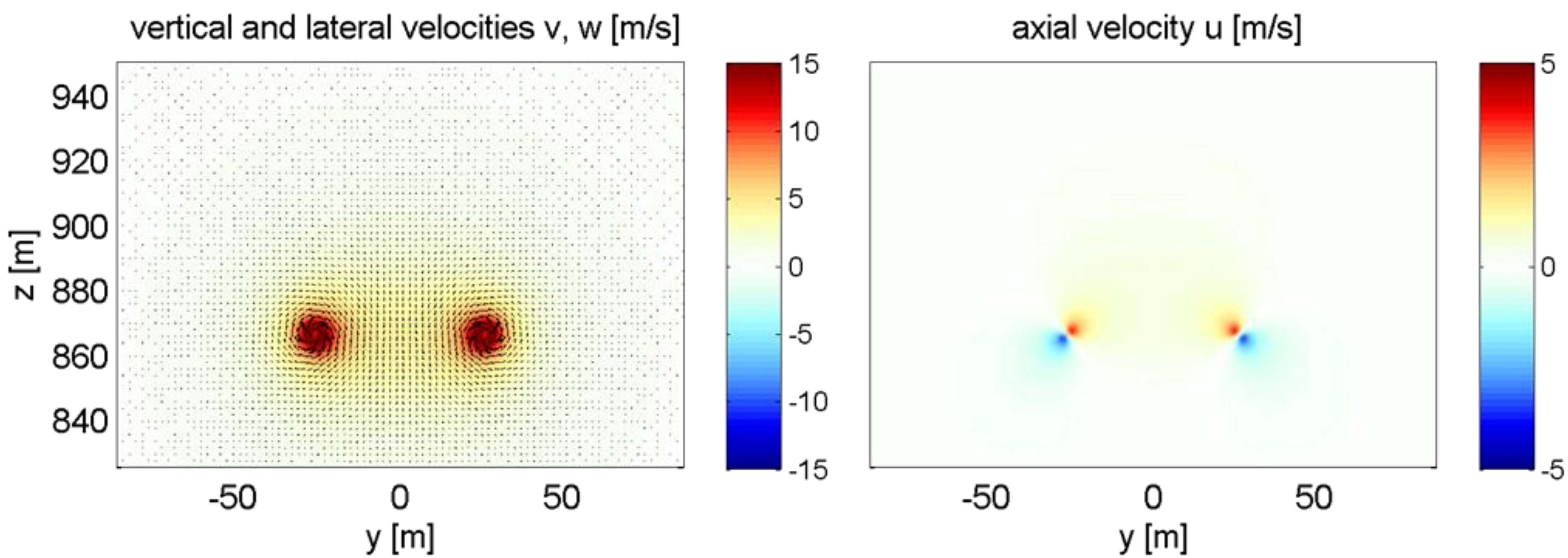
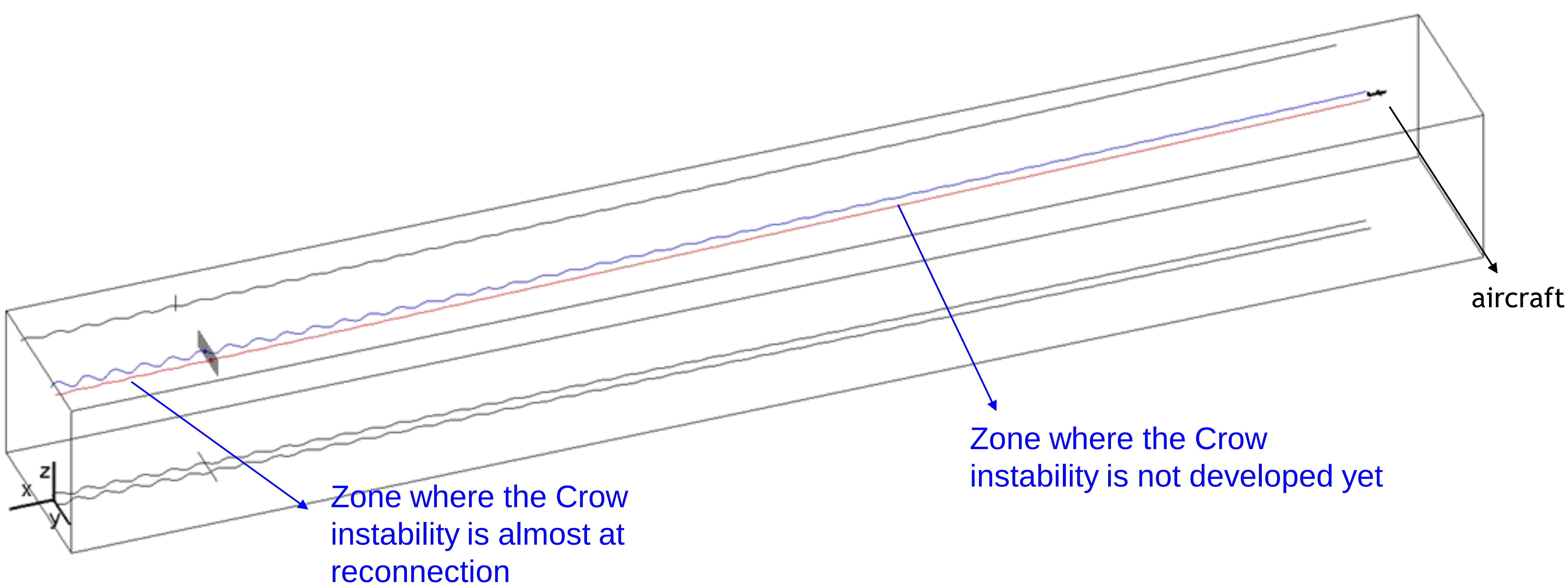
Induced velocity field evaluation using the WAKE4D-DVM results with Crow instability effect : example





Investigation of a Time-based Separation (TBS) concept using the WAKE4D-PVM (Eurocontrol TBS project)

- New concept of operation applied to the arrival phase of flights with significant headwind.
- The current distance-based separations (DBS) are to be replaced by time intervals.
- The WAKE4D-PVM was used for a comparative risk analysis between DBS in still air conditions and TBS with headwind:

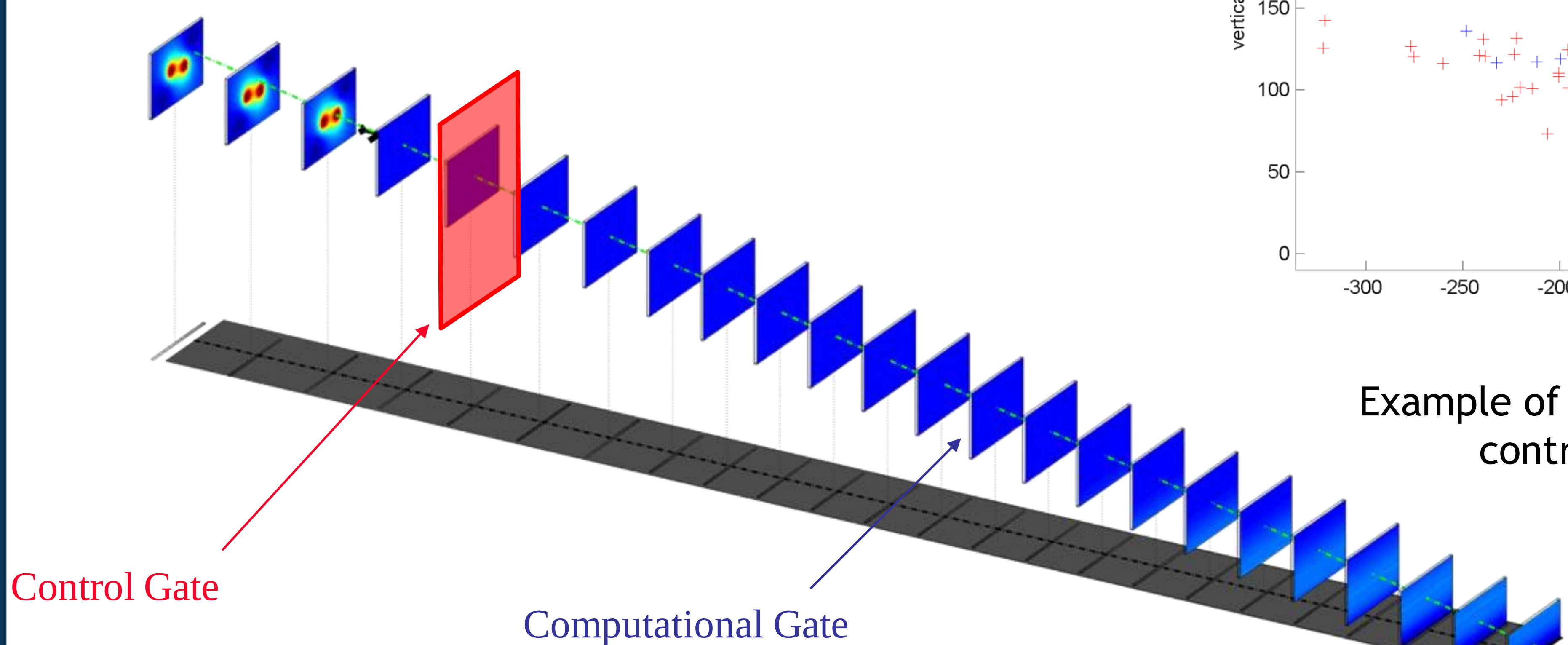
1. Simulation of the 3-D wakes generated :
    - by various aircraft (with variations on their trajectories)
    - in various wind conditions (with variations)

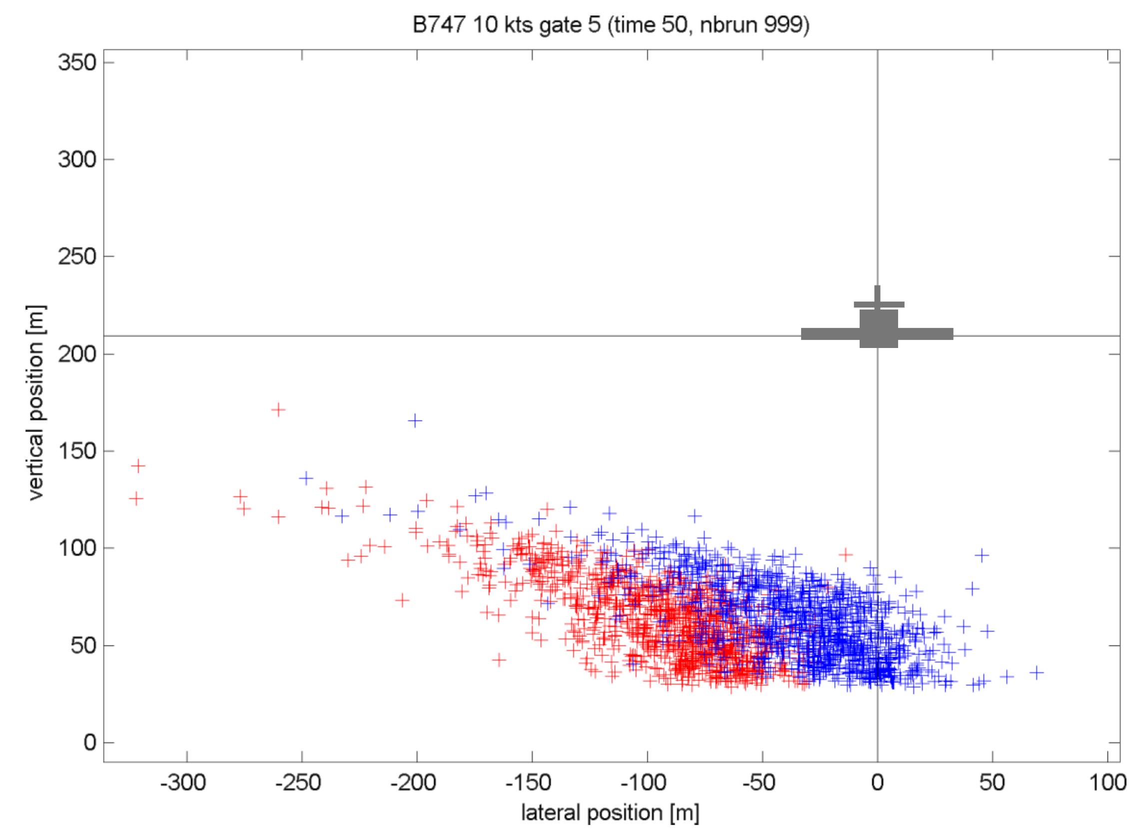
2. Interpolation of the results in several control gates along the flight trajectory.

Investigation of a Time-based Separation (TBS) concept using the WAKE4D-PVM (Eurocontrol TBS project)

In each of the control gates, computation of:

- the distance between the WV (both left and right) and the following aircraft (with uncertainties on its trajectory)
- the PDF of the circulation of the potentially encountered WV

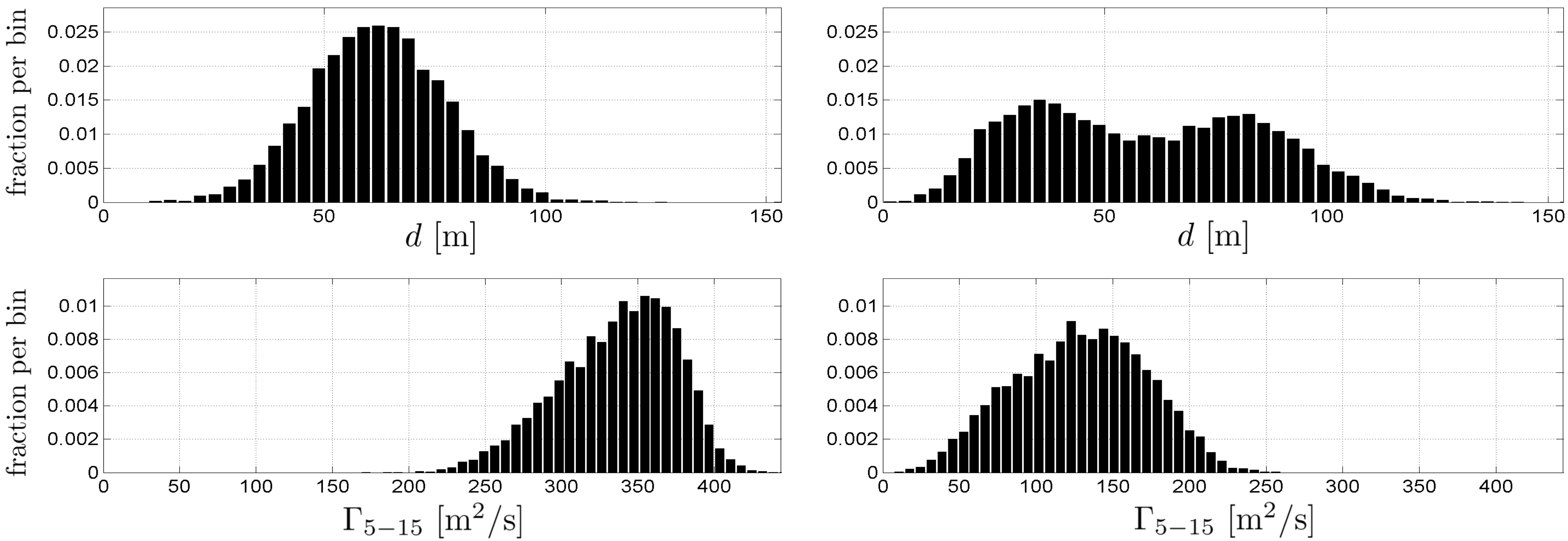




Example of predicted positions in a certain control gate at a certain time

Example of WAKE4D-PVM results for a 90 s TBS in a gate IGE (ILS altitude = 65 m)

Without wind | 10kts headwind at 10 m height



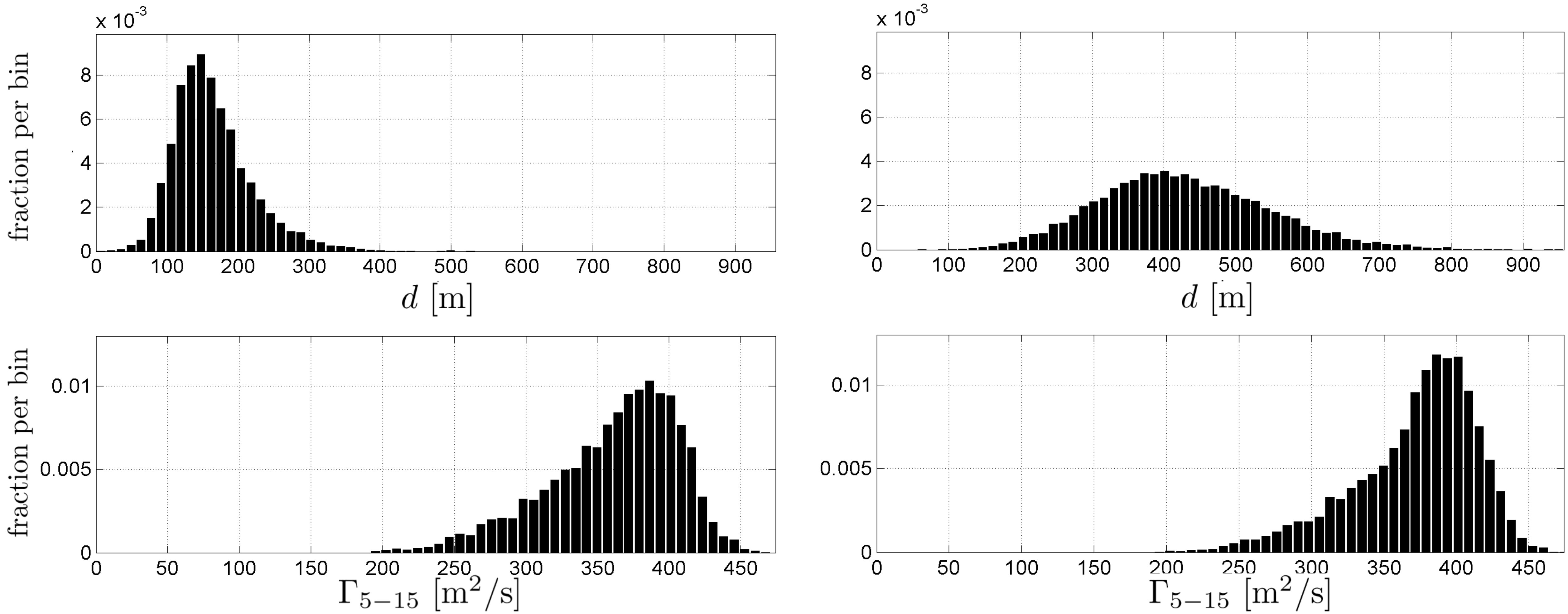
Close to the ground:

- the wind enhances the decay IGE
- the vortices rebound due to IGE and thus do not move away from the ILS

Example of WAKE4D-PVM results for a 90 s TBS in a gate OGE (ILS altitude = 915 m)

Without wind

10kts headwind at 10 m height

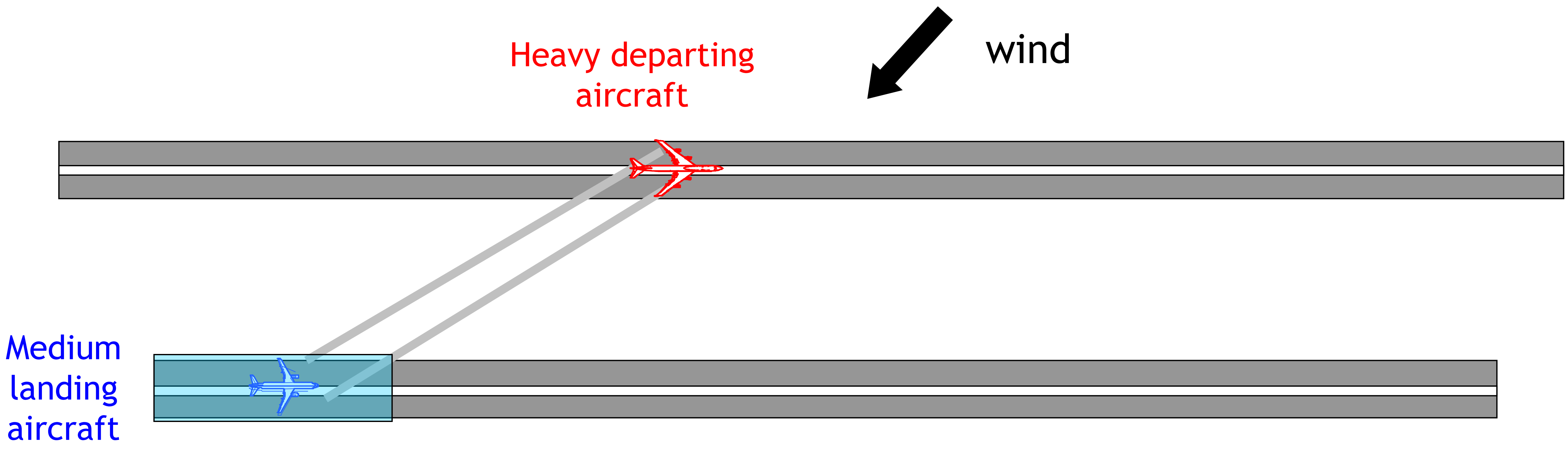


Away from the ground:

- the headwind tends to bring younger vortices in the control gate
- the crosswind component tends to move those WV away from the ILS

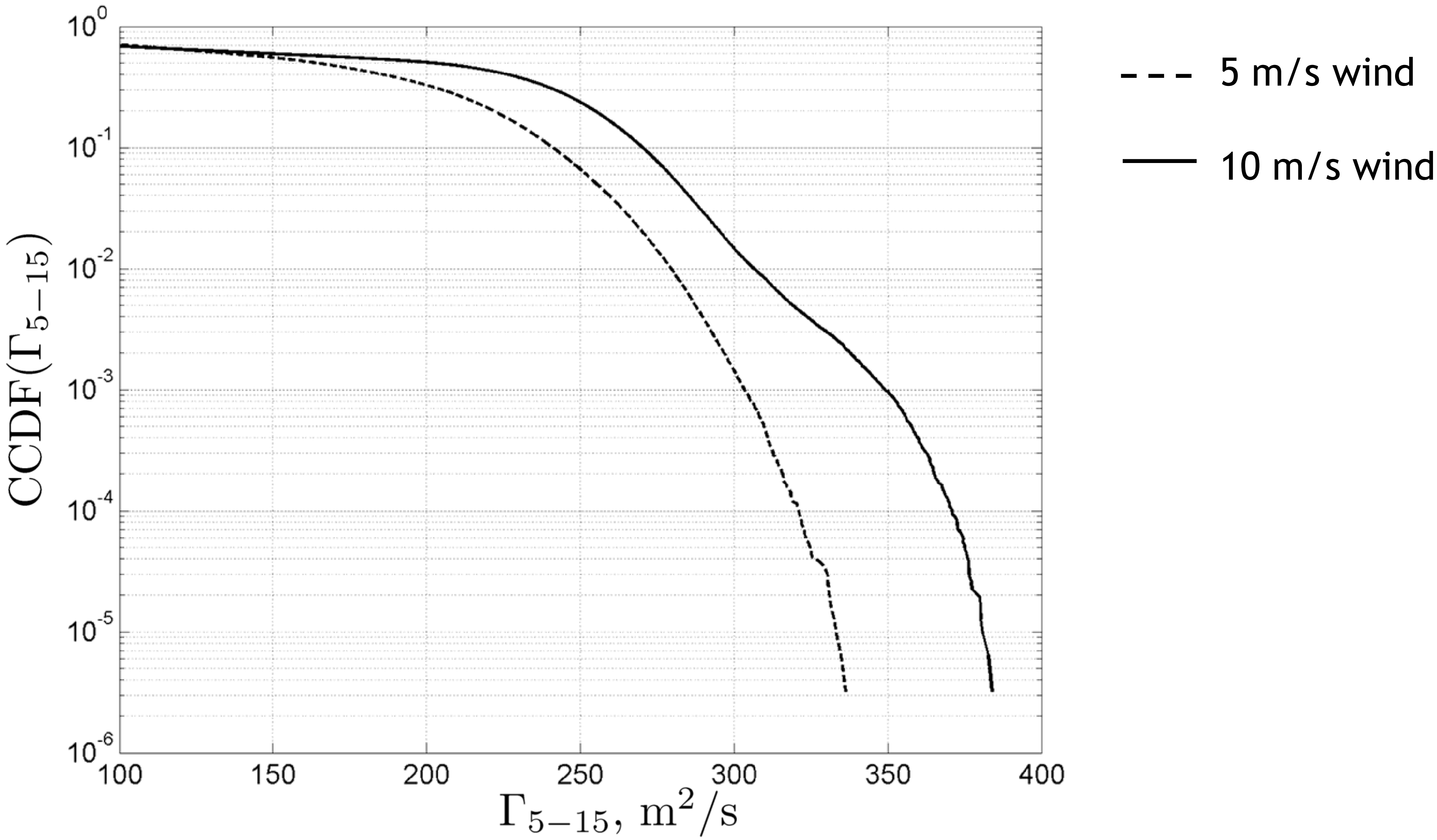
Investigation of the impact of the wind on potential WVE for a pair of parallel runways.

- WV generated by heavy departing aircraft
- WV blown by the wind in the landing aircraft region of the parallel runway (="control box").
- Two cases of wind are investigated:
  - a mean wind profile with a 5 m/s wind at 10 m height
  - a mean wind profile with 10 m/s wind at 10 m height.
- The wind direction is at 45 degrees w.r.t. the runway.
- Variations of 0.5 m/s are assumed around these mean profiles, with a uniform distribution.



Comparison of the frequency-severity curves

The complementary cumulative density function ($\mathrm{CCDF}(\Gamma_{5-15})$) is defined as the probability to observe a vortex with a circulation higher than Γ_{5-15}



- As expected, the wind blows the vortices on the arrival runway.
- A higher wind leads to younger potentially encountered vortices with higher circulation.
- Note : the wind direction was here chosen so that the vortices always come in the arrival zone;
  => the probabilitity to observe a vortex with any circulation is almost unity.

Conclusions

- The WAKE4D and its sub-components, DVM/PVM:
  - constitute a well mature and operational WV predictor
  - enable to simulate realistically complex WV behaviors depending on met conditions and a/c trajectory

- Concerning the DVM
  - The physical models have been established, improved, calibrated, assessed and used for the past 15 years in several projects => can be considered as reliable
  - The software is modular and can easily be modified (e.g., to use other models)

- Concerning the PVM
  - The real Monte-Carlo approach enables to perform relevant statistical analysis, taking into account input variations and uncertainties
  - The resampling technique enables to obtain conservative statistics while limiting the number of runs

- Concerning the WAKE4D
  - It is a usable WV predictor for off-line fast-time studies (e.g., potential WVE, reconstruction of accidents, and risk assessment)
  - It enables to compute in real-time, as post-processing, the induced 3-D velocity field
  - It is usable as a WV predictor for practical real-time operational system