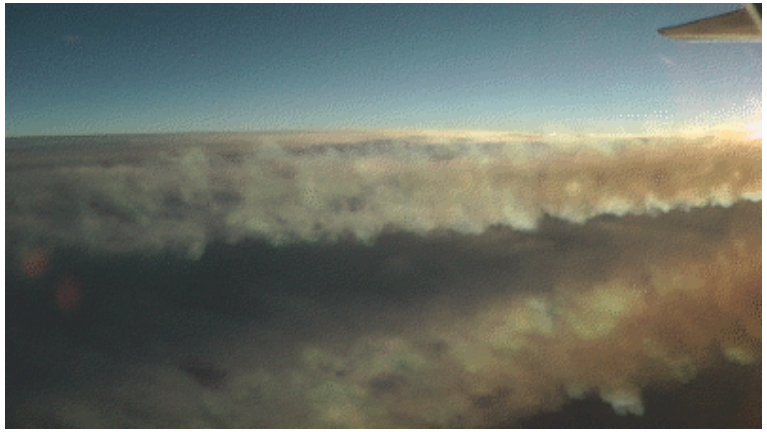
Impact of Turbulence and Ground on Wake Vortex Evolution
-
Towing Tank Studies

Reinhard Geisler, Robert Konrath, Janos Agocs

Deutsches Zentrum
für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

Wake Vortices in Real Life: Exemplar Contrail of an Airliner



Condensation behind engines
(view from window of a Boing 747,
tail plane to the upper right)

Roll-in of condensate
into wake vortices

Natural decay of wake vortices
(Crow-instability)

Experimental Study on Wake Vortices:

Measurements in a Water Towing Tank

Object:

Wake (2-vortex-system) of a F-13 model in the water towing tank Göttingen („Wasserschleppkanal Göttingen“, WSG)

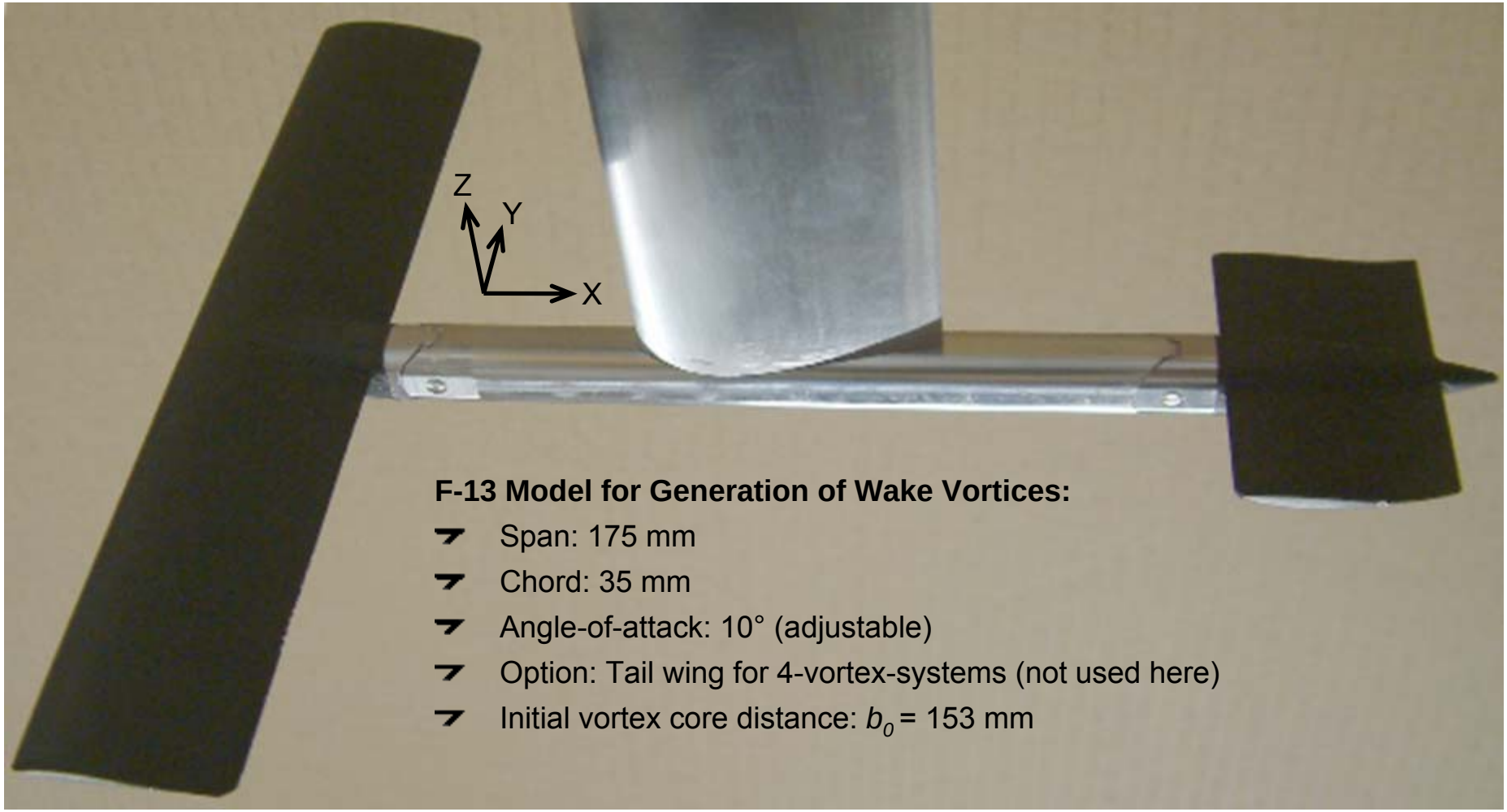
Methods:

- Time-resolved stereo Particle Image Velocimetry (PIV)
- Time-resolved vortex core visualization
- Turbulence generation: Pilot carriage with grid, selectable velocity / delay

Configurations:

- Wake with / without turbulent environment
- Wake close to ground surface with / without ground obstacles

Experimental Study on Wake Vortices: The Model

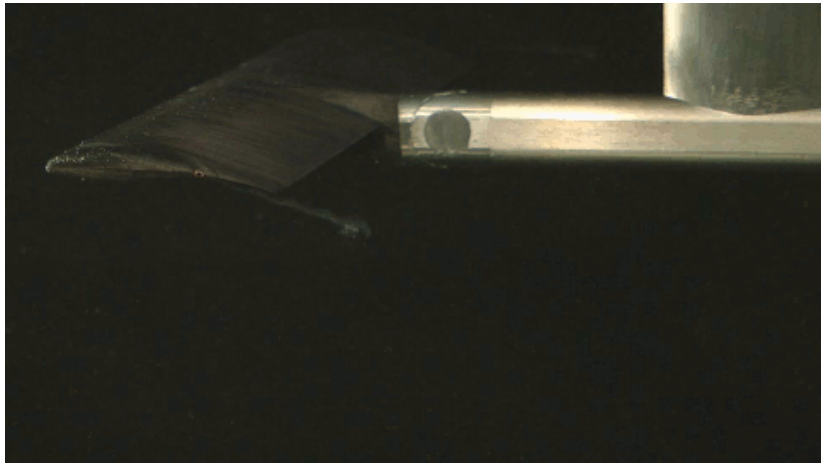


F-13 Model for Generation of Wake Vortices:

- Span: 175 mm
- Chord: 35 mm
- Angle-of-attack: 10° (adjustable)
- Option: Tail wing for 4-vortex-systems (not used here)
- Initial vortex core distance: b_0 = 153 mm

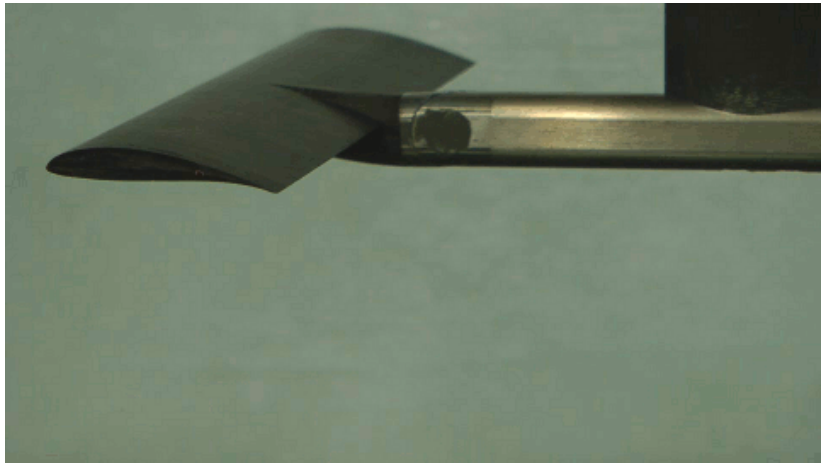
Experimental Study on Wake Vortices: The Model

a)



Wing tip with outlet

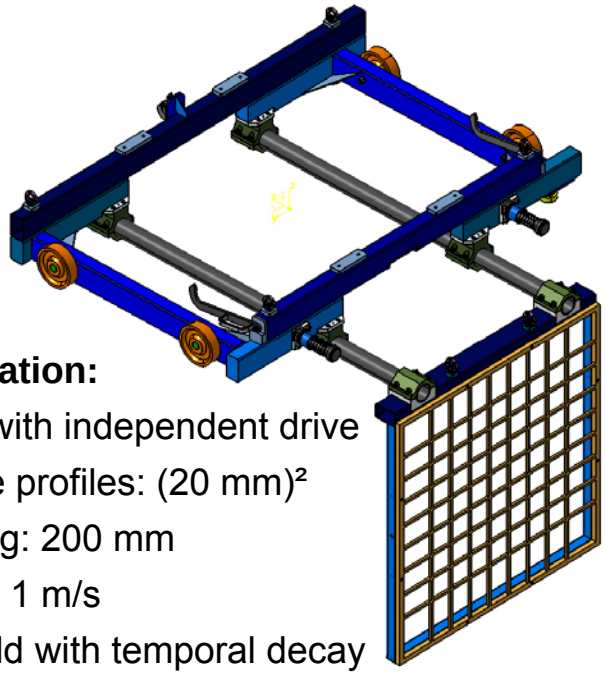
b)



Visualization of Vortex Cores:

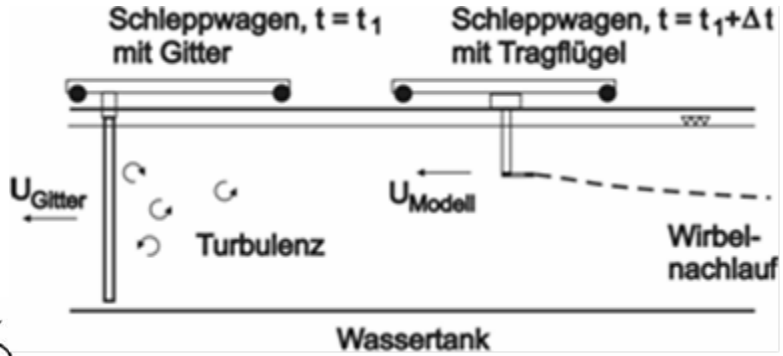
- Outlets at wing tips
- Contrast agent fed from vessel 0.5 m above water surface
- Gravity-driven flow without additional forcing
- Contrast agent (high concentration):
  - a) Polyamide particles in water (scattering), side illumination
  - b) Ink (absorbing), back-illuminated

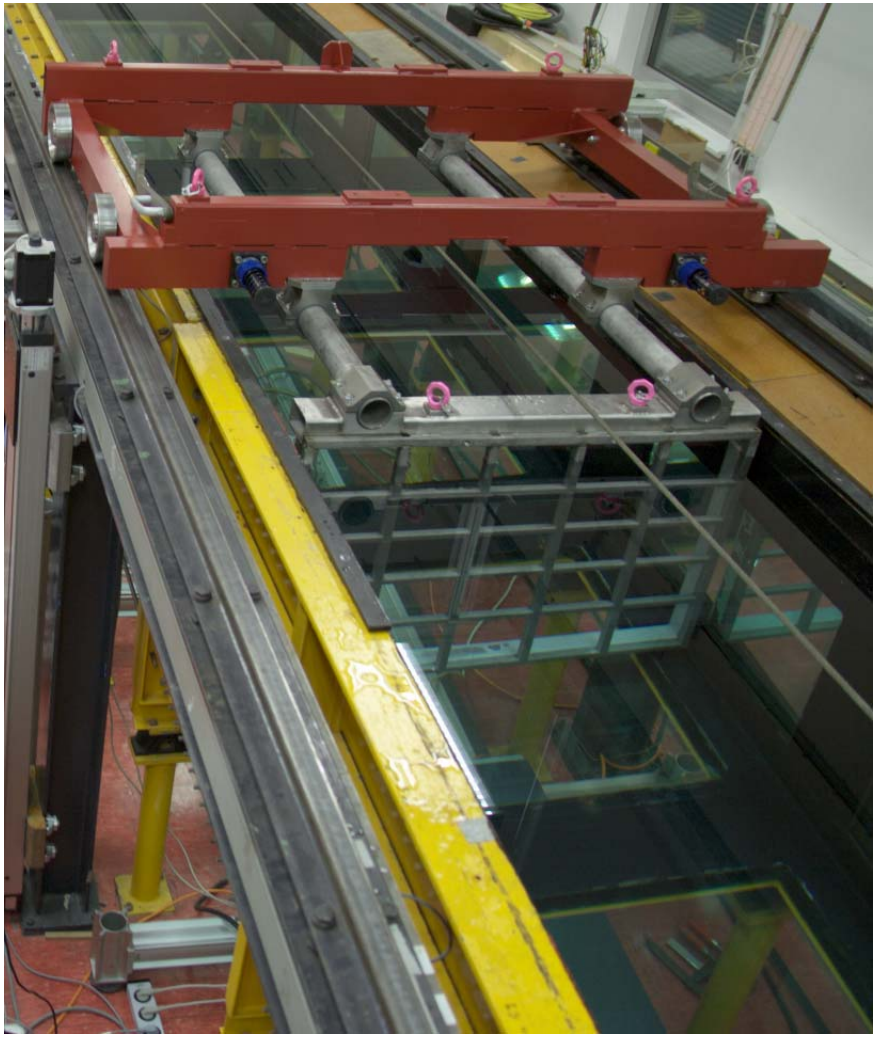
Turbulence Generation: Pilot Carriage



Turbulence Generation:

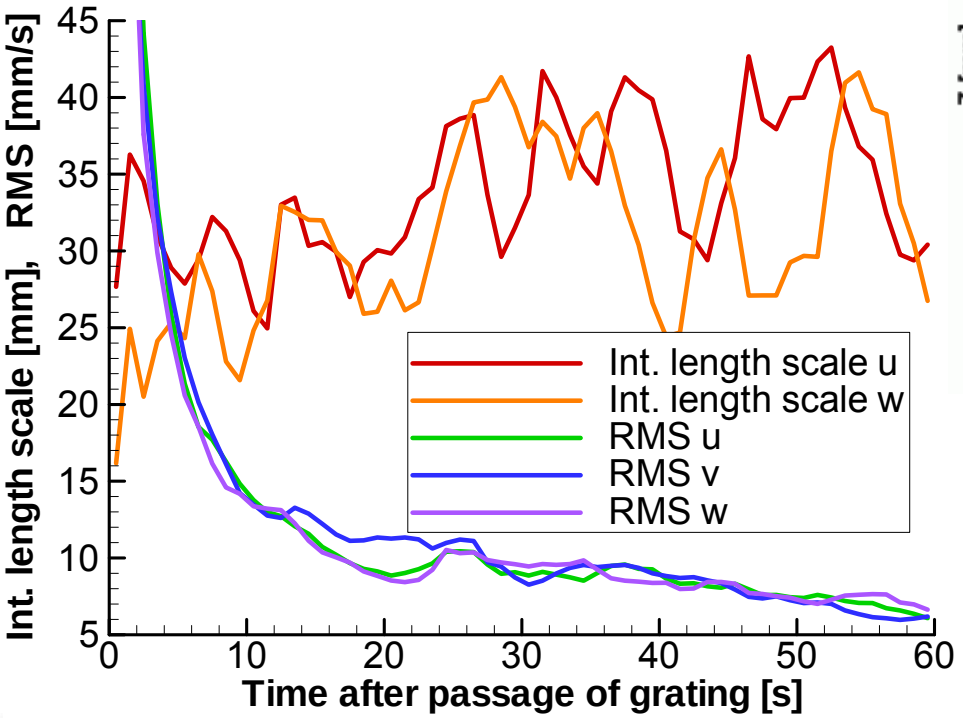
- Pilot carriage with independent drive
- Grating square profiles: (20 mm)²
- Grating spacing: 200 mm
- Velocity: Up to 1 m/s
- Turbulence field with temporal decay

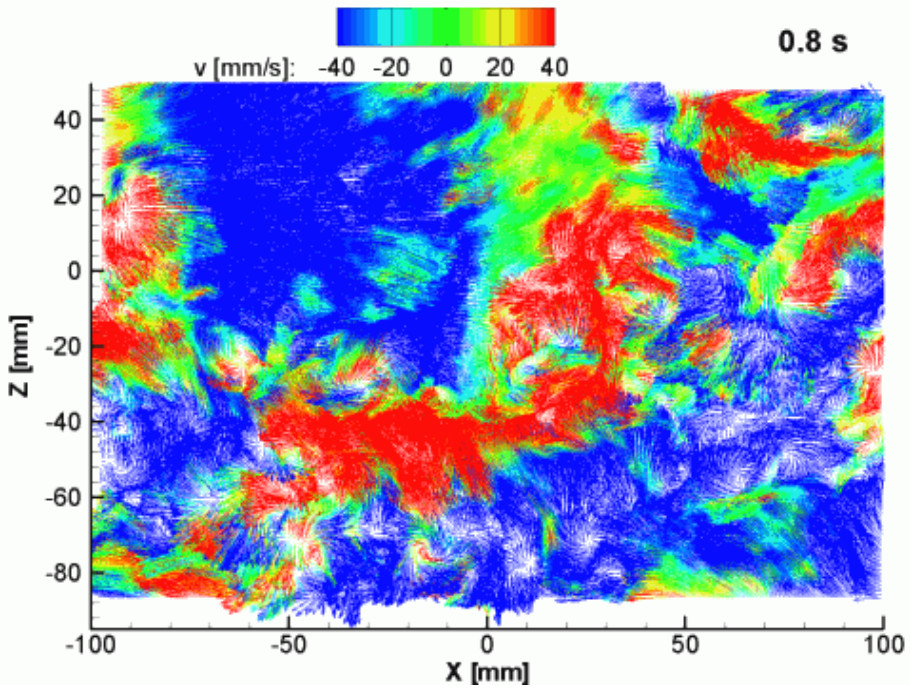




Turbulence Generation: Characterization

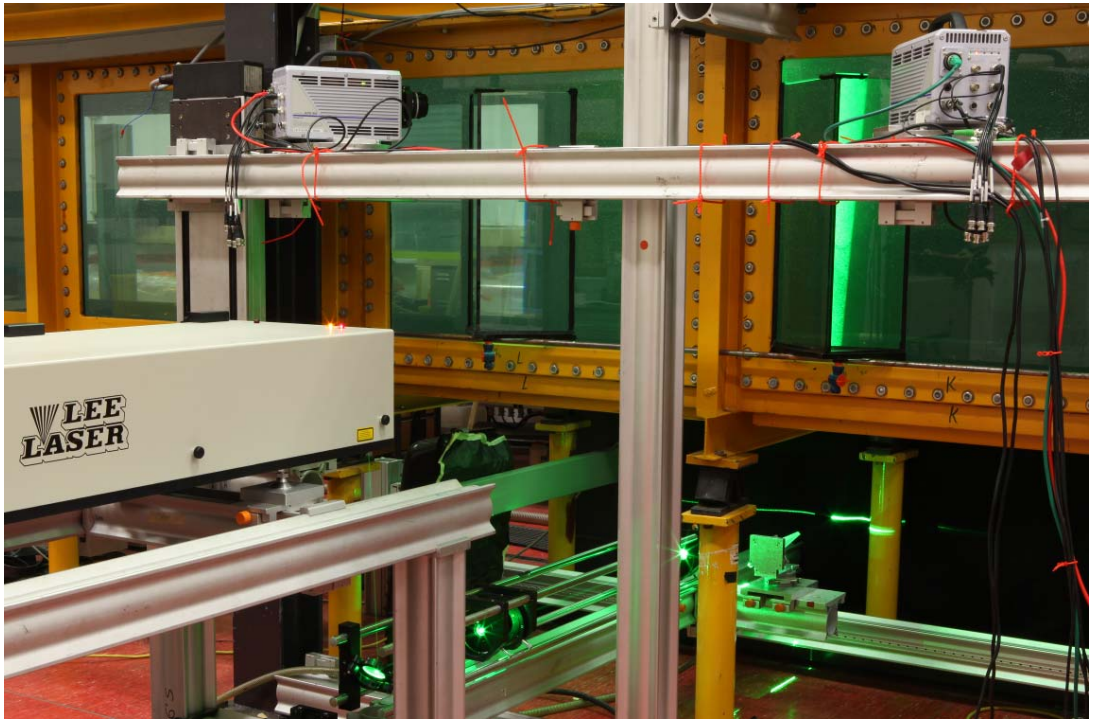
- Grating velocity: 1 m/s
- Stereo PIV measurement
- PIV correlation window size:
  - 3.2 mm @ field of view 190 x 130 mm²
  - 1.6 mm @ field of view 100 x 70 mm²





Turbulence field behind grating

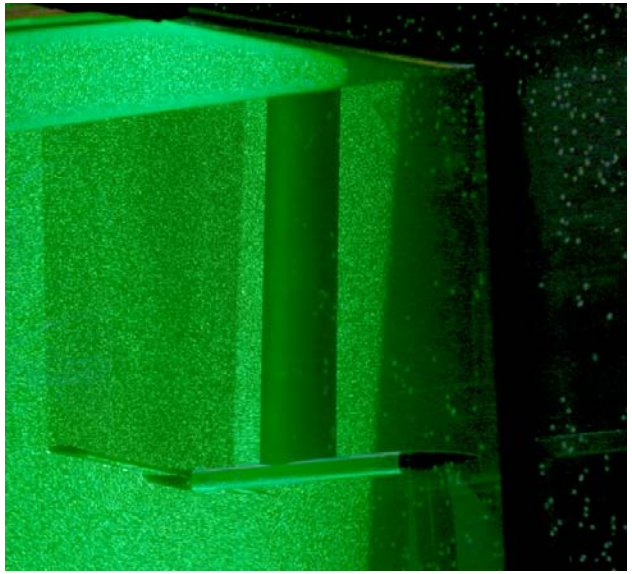
Stereo PIV: Setup



- Laser: Lee LDP 200-MQG @ 1 kHz, 25 mJ / pulse
- Cameras: Photron APX-RS @ 1kHz, 1 mega pixel
- Lenses: Nikkor 1.8/50 @ F# 5.6 , Distagon 2.8/21 @ F# 8
- Imaging: Scheimpflug-condition, prisms optimize interface to water
- Camera system on vertical translation stages, selectable velocity

Stereo PIV: Calibration and Evaluation

View from left prism to calibration grid



View from right prism to light sheet and model

Calibration:

- Light sheet perpendicular to flight direction
- Cameras on both sides of light sheet
- Transparent calibration grid on glass carrier
- Grid spacing: 10 mm
- Disparity correction based on particle images

PIV Evaluation:

- Multigrid cross correlation evaluation, image deformation
- Correlation window size 24 * 24 pixels
- PIV delay 2 – 20 ms, automatic adaptation according to outlier rate (< 0.5%)
- Time resolution 50 ms

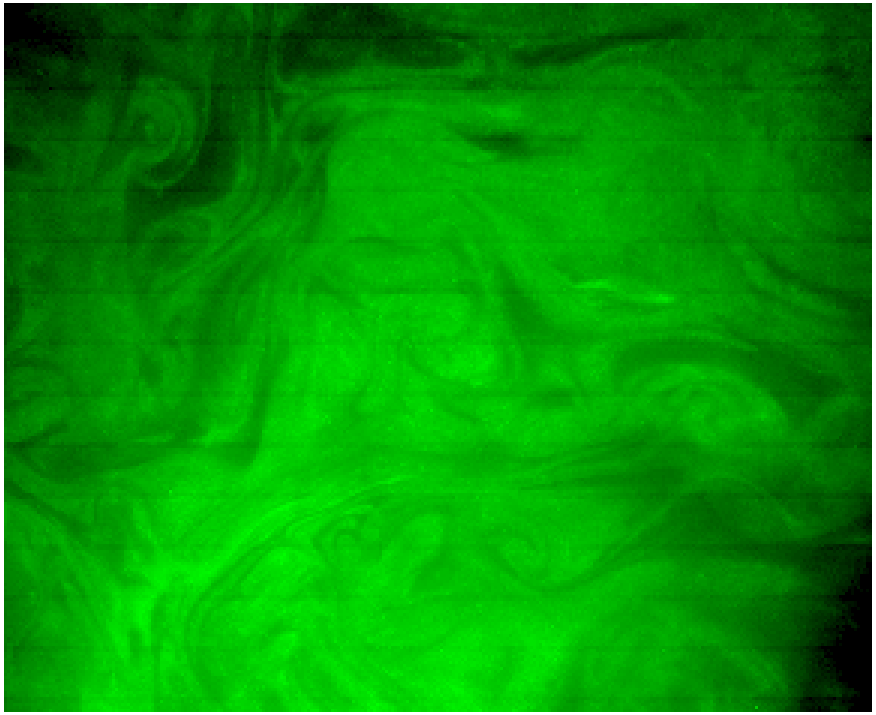
Wake Vortices Impacted by Turbulence: Properties

Requirements / Features:

- Undisturbed vortex pair descents with approximately constant velocity and constant core distance
- Vortices impacted by turbulence change velocity / direction in non-predictable way
- Field of view should capture vortices as long as possible

Measurement:

- Translation stages move cameras with descent rate of undisturbed vortices
- Field of view: 340 x 190 mm²
- Correlation window size: 4.8 mm (24 pixels)

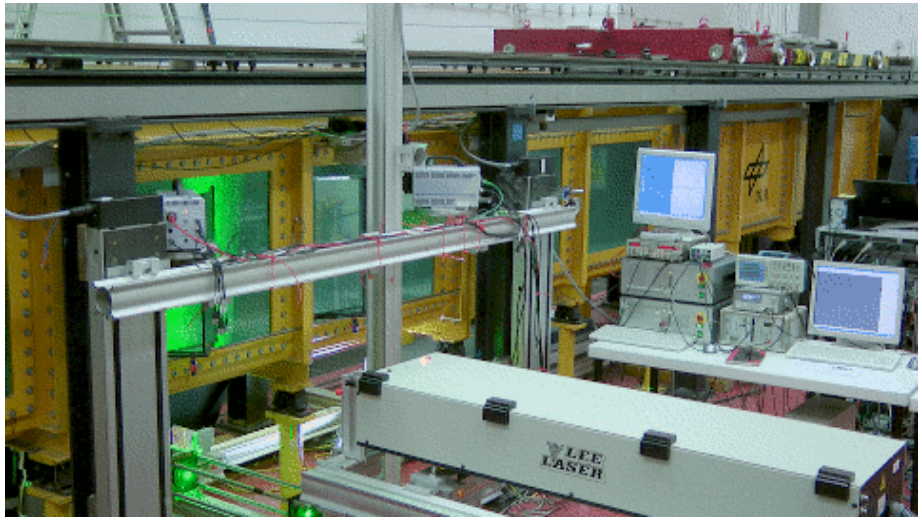


Descent of vortex pair

Reference time: $t_0 = b_0 / w_0$
Vortex age: $\tau = t / t_0$

(b_0: vortex core distance, w_0: descent rate)

Wake Vortices Impacted by Turbulence: PIV Measurement Sequence



Measurement sequence (time lapse)

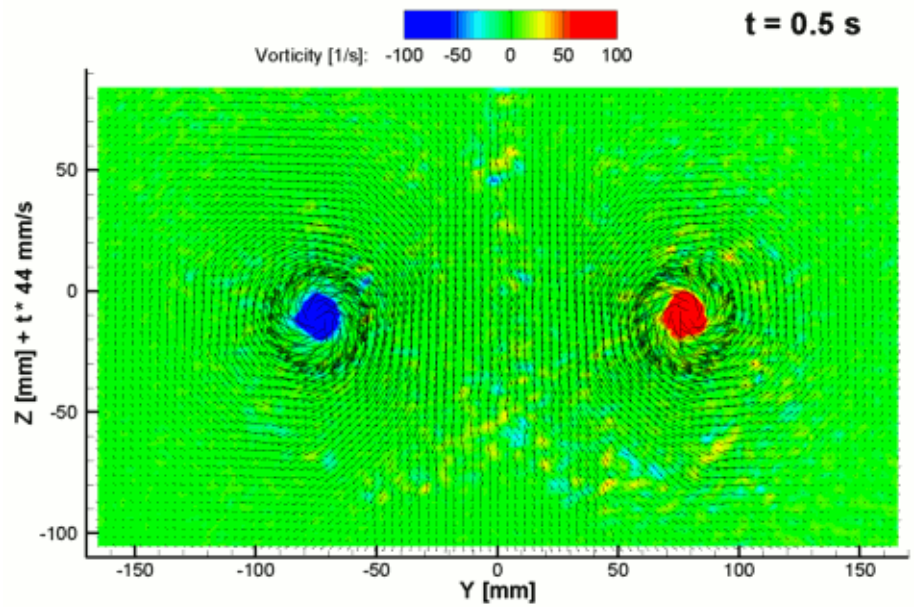
Measurement Sequence:

- Settling time for turbulence inside tank > 20 minutes
- Start of pilot carriage with grid, velocity 1 m/s
- Time at rest, duration defined by delay between grid and model
- Start of model carriage
- Model carriage passing PIV plane triggers measurement sequence:
  - Cameras start recording
  - Translation stages follow vortex descent
- Both carriages transported back to start position
- Transfer of image data from cameras to computer

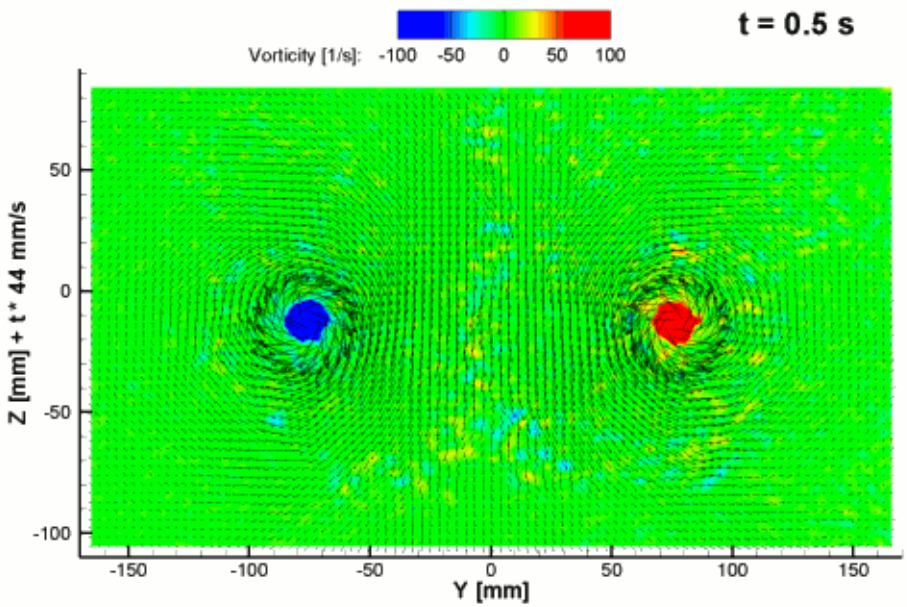
Wake Vortices Impacted by Turbulence: Configurations

Configuration	**1**	**2**	**3**	**4**	**5**	**6**
Time after grid passing [s]	**without grid**	**without grid**	**80**	**80**	**40**	**40**
Turb. RMS [mm/s]	0	0	5	5	8	8
Model velocity [m/s]	**1**	**2.44**	**1**	**2.44**	**1**	**2.44**
Reynolds number: Chord based	35000	85000	35000	85000	35000	85000
Circulation based	17000	52000	17000	52000	17000	52000
Initial circulation [m²/s]	0.017	0.052	0.017	0.052	0.017	0.052
Descent rate [mm/s]	18	44	18	44	18	44
Reference time t_0 [s]	8.5	3.5	8.5	3.5	8.5	3.5

Wake Vortices Impacted by Turbulence: PIV Results



Low turbulence



With grid turbulence (example)

Parameters:

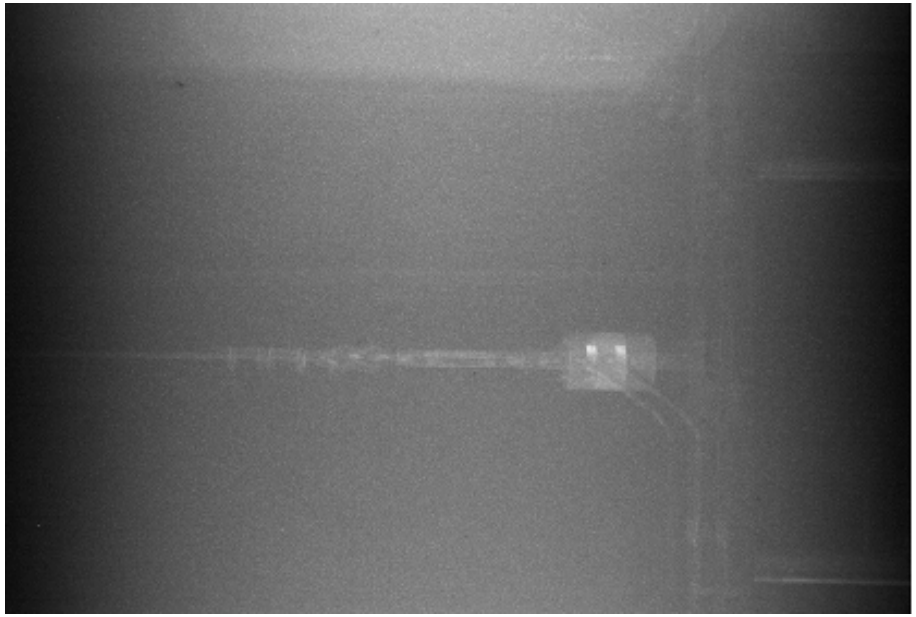
- Model velocity: 2.44 m/s
- Moving coordinate system: 44 mm/s descent rate
- Time delay grid – model: 80 s (turb. RMS: 5 mm/s)
- Circulation: 0.052 m²/s
- Here in display: 10 s ($\tau = t / t_0$ = 2.9 resp. 159 b_0)

Vortex Core Visualization: Setup

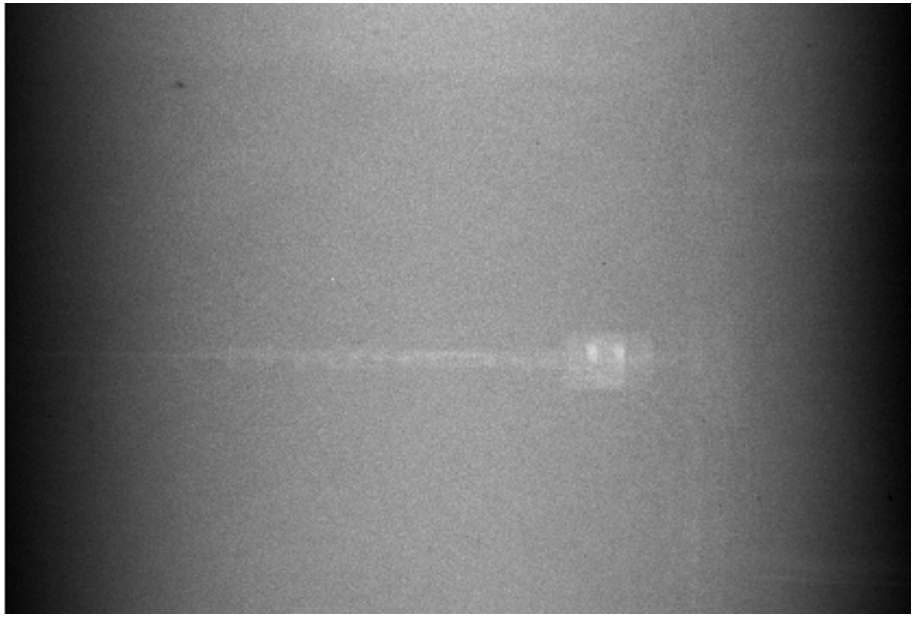
- Three cameras (PCO.4000, 11 mega pixel) in linear arrangement under towing tank
- Lenses: Distagon 2.8/21, Nikkor 2.8/28 @ F# 8
- Side cameras under Scheimpflug-condition
- Recording rate: 2 frames / s
- Captured volume: min. 700 * 360 * 600 mm³

- Background above tank darkened by black fabric
- Illumination by xenon flash lamps (Rapp OptoElectronic NGW10) on both sides of tank
- Release of polyamide particles from wing tips into vortex cores
- Recording of flash illuminated particles

Vortex Core Visualization: Results (Qualitative)



Low turbulence

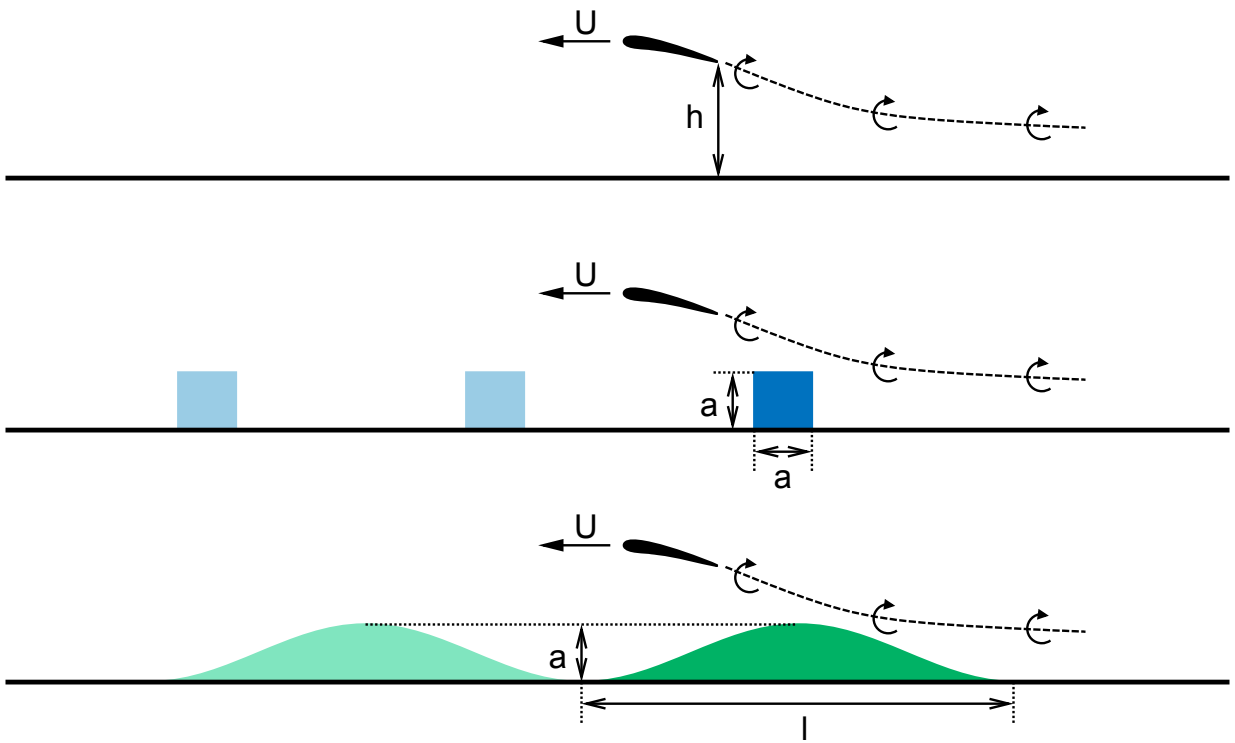


With grid turbulence (example)

Parameters:

- Model velocity: 2.44 m/s
- Time delay grid – model: 80 s (turb. RMS: 5 mm/s)
- Recording rate: 2 frames / s
- Here in display: 15 s (τ = 4.3 resp. 239 b_0)

Wake Vortices in Proximity to Surfaces: Properties



Flat ground

Ground with square profile(s)

Ground with sine wave(s)

Parameters:

- Model at constant distance *h* above flat ground
- Optional 2D obstacles perpendicular to flight direction on ground in front of / behind measurement plane:
  - Square profiles with side length *a* = 10 mm, 20 mm, 30 mm
  - Sine wave, height *a* = 40 mm, wave length *l* = 1300 mm
- Ground and obstacles made from PMMA (acrylic glass, „Perspex“)

Wake Vortices in Proximity to Surfaces: Properties

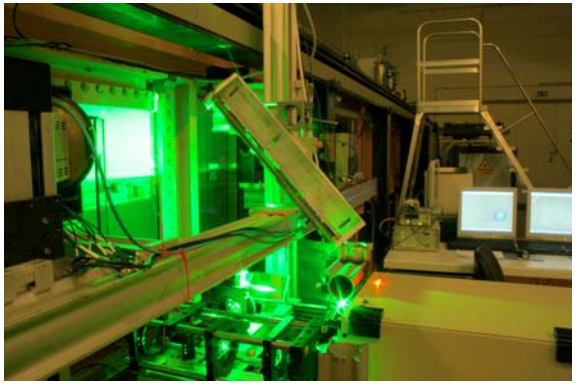
Towing tank with installed intermediate ground

Requirements / Features:

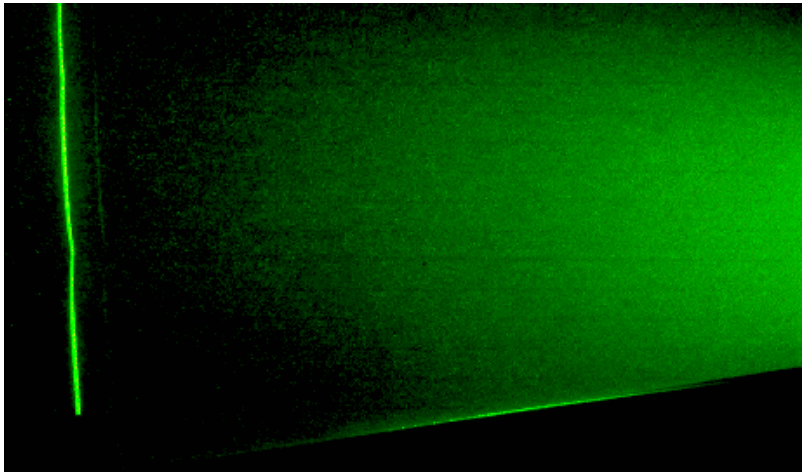
- Wake vortices decelerated by ground
- Wake vortex path diverted sideways by ground
- Ground topology influences vortices

Measurement:

- Flat intermediate ground installed in towing tank
- Model distance to ground adjustable by translation stage
- Field of view covers complete vortex path of one side
- Video visualization for qualitative analysis

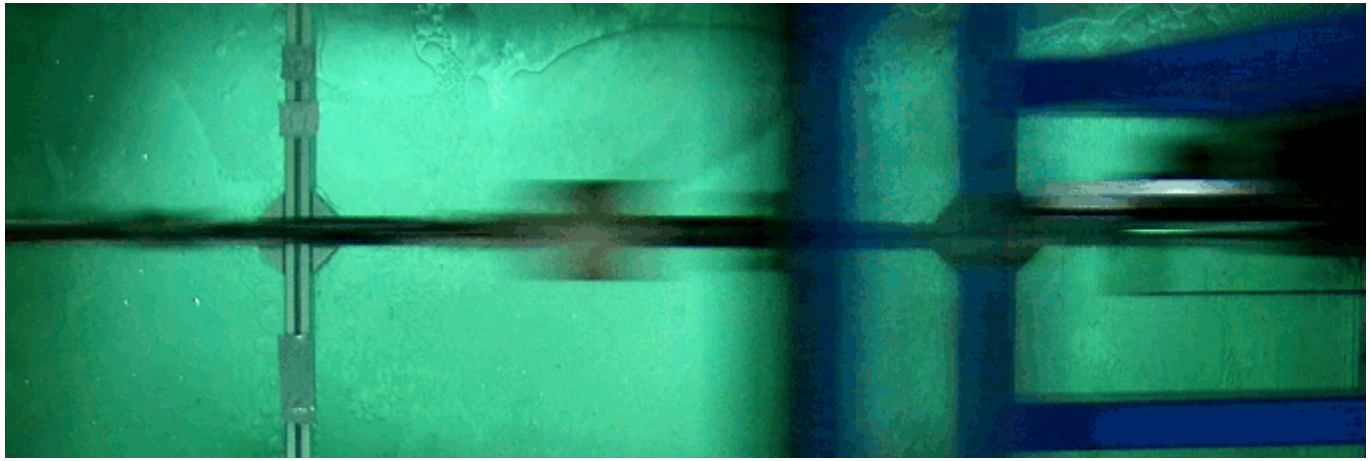


Light sheet enters tank from the side

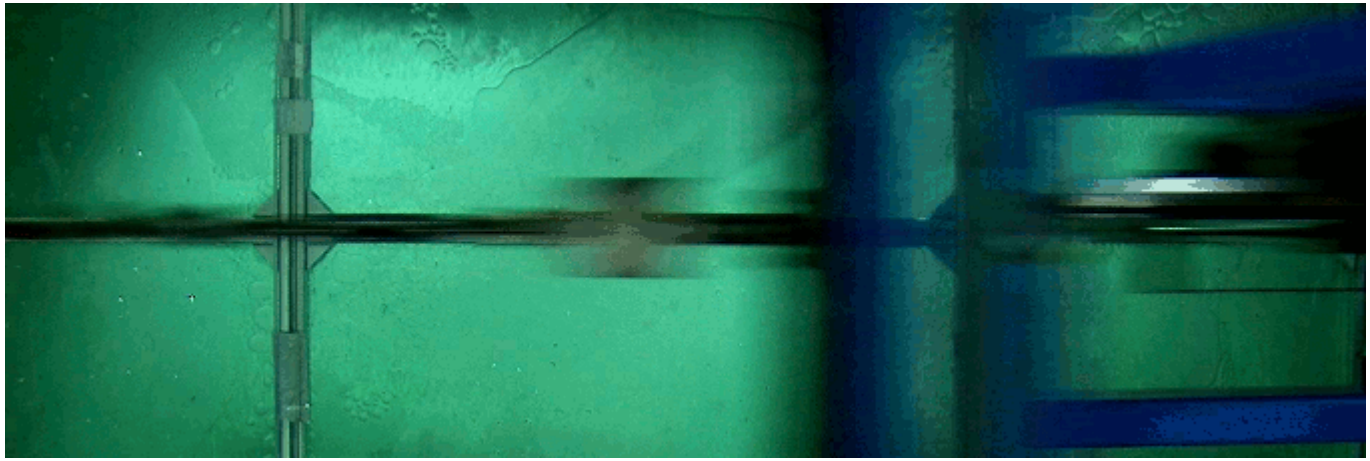


Visualization of wake vortices

Wake Vortices in Proximity to Surfaces: Visualization



Flat ground



Ground with 2 square profiles (30 mm)² perpendicular to flight direction

X = -550 mm
profile position 1

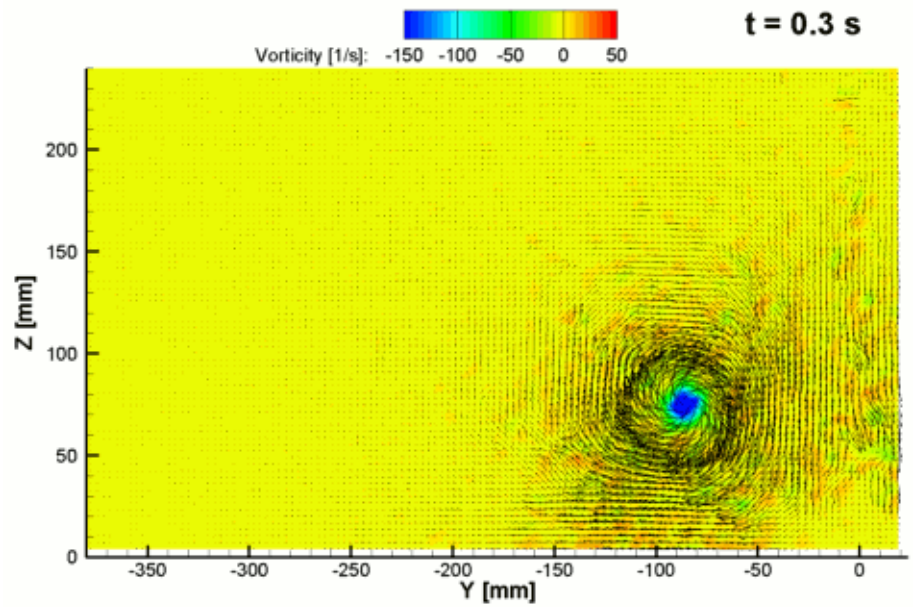
X = 0 mm
PIV position

X = 550 mm
profile position 2

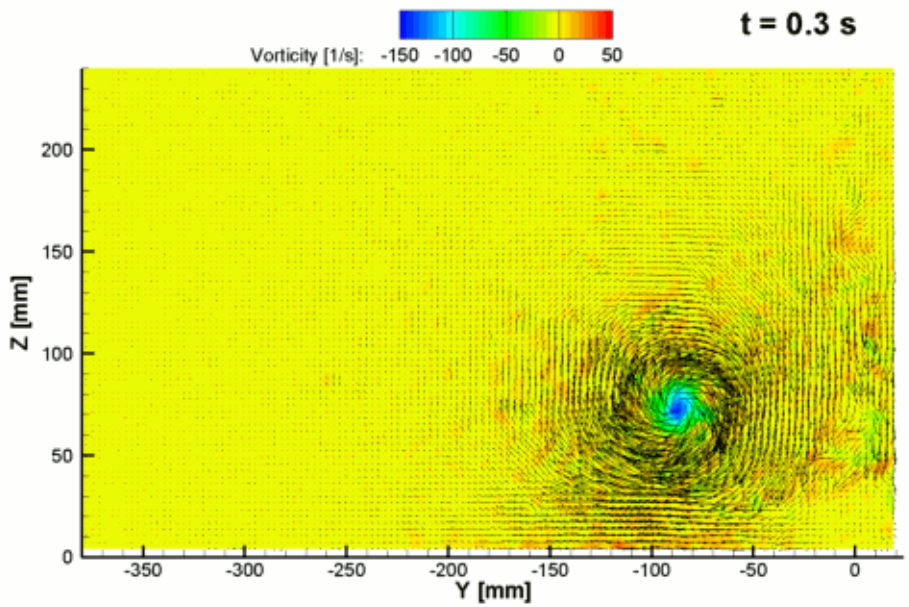
Parameters:

- Model velocity: 2.44 m/s
- Distance to ground: 80 mm (0,5 b_0)
- Here in display: 5 s (τ = 1.4 resp. 80 b_0)

Wake Vortices in Proximity to Surfaces: PIV Results



Flat ground

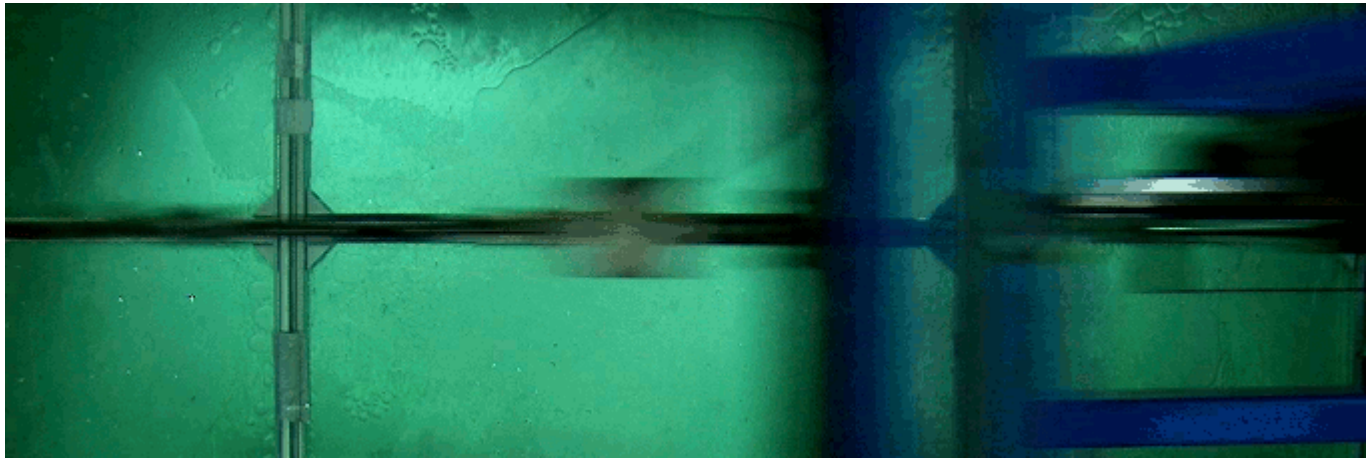


Ground with square profile (30 mm)²
in front of and behind PIV plane at X = +/- 550 mm

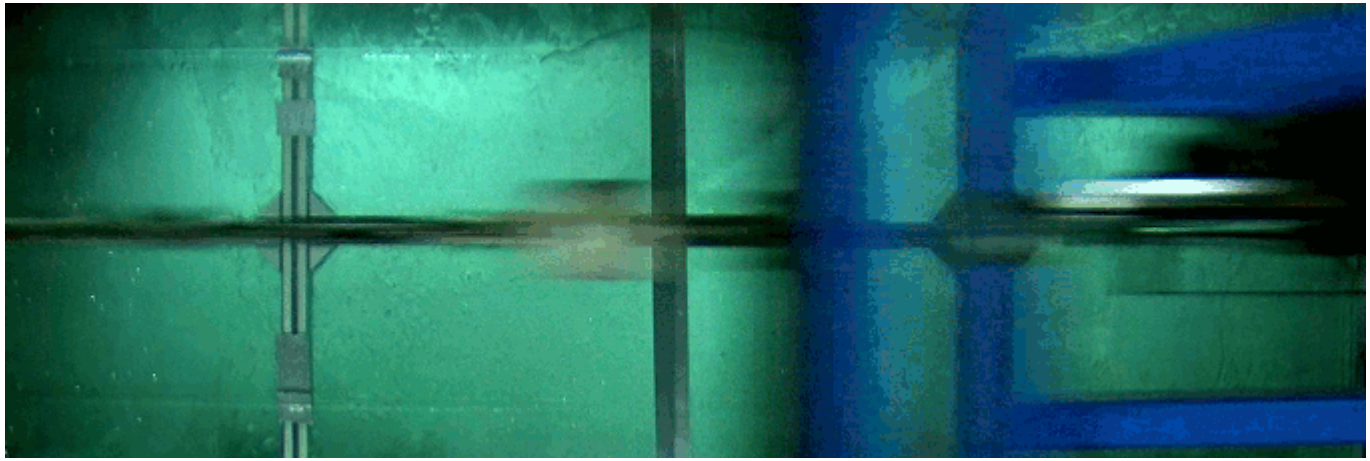
Parameters:

- Model velocity: 2.44 m/s
- Distance to ground: 80 mm (0.5 b_0)
- Option: Profile perpendicular to flight direction on ground in front of and behind PIV plane
- Field of view: 400 x 240 mm²
- Correlation window size: 6.4 mm (32 pixels)
- Here in display: 15 s (τ = 4.3 resp. 239 b_0)

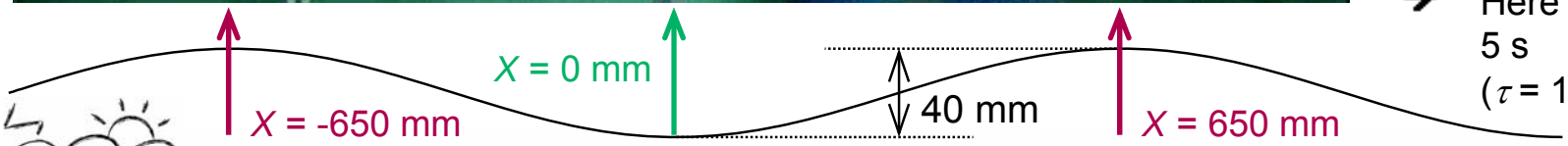
Wake Vortices in Proximity to Surfaces: Visualization



Ground with two square profiles



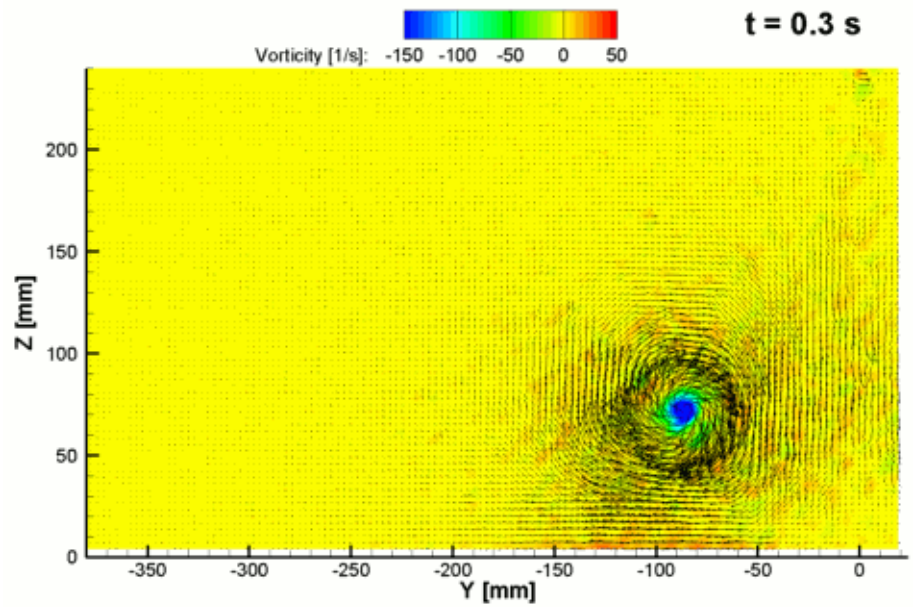
Ground with double sine wave



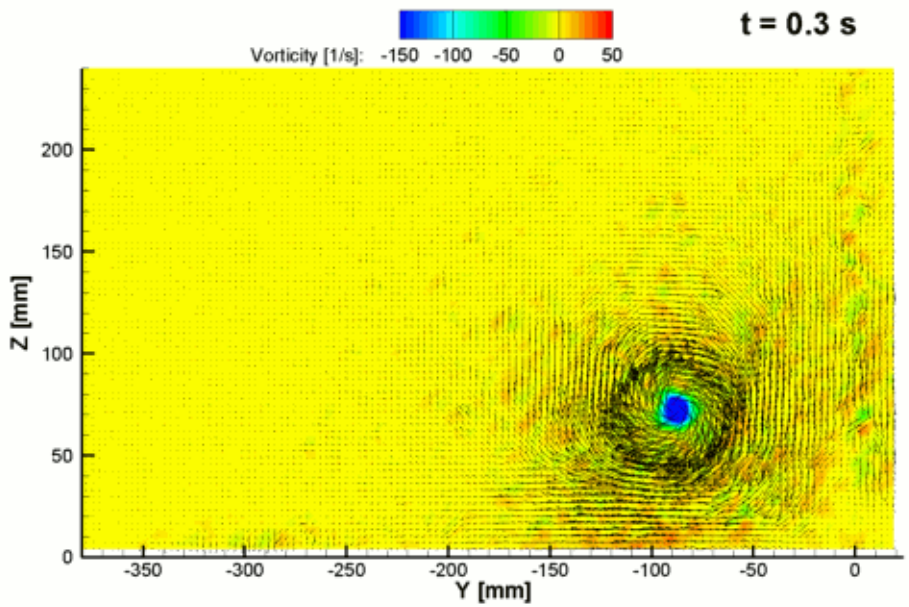
Parameters:

- Model velocity: 2.44 m/s
- Distance to ground: 80 mm (0.5 b_0)
- Here in display: 5 s (τ = 1.4 resp. 80 b_0)

Wake Vortices in Proximity to Surfaces: PIV Results



Ground with square profile (30 mm)²
in front of PIV plane X = 550 mm

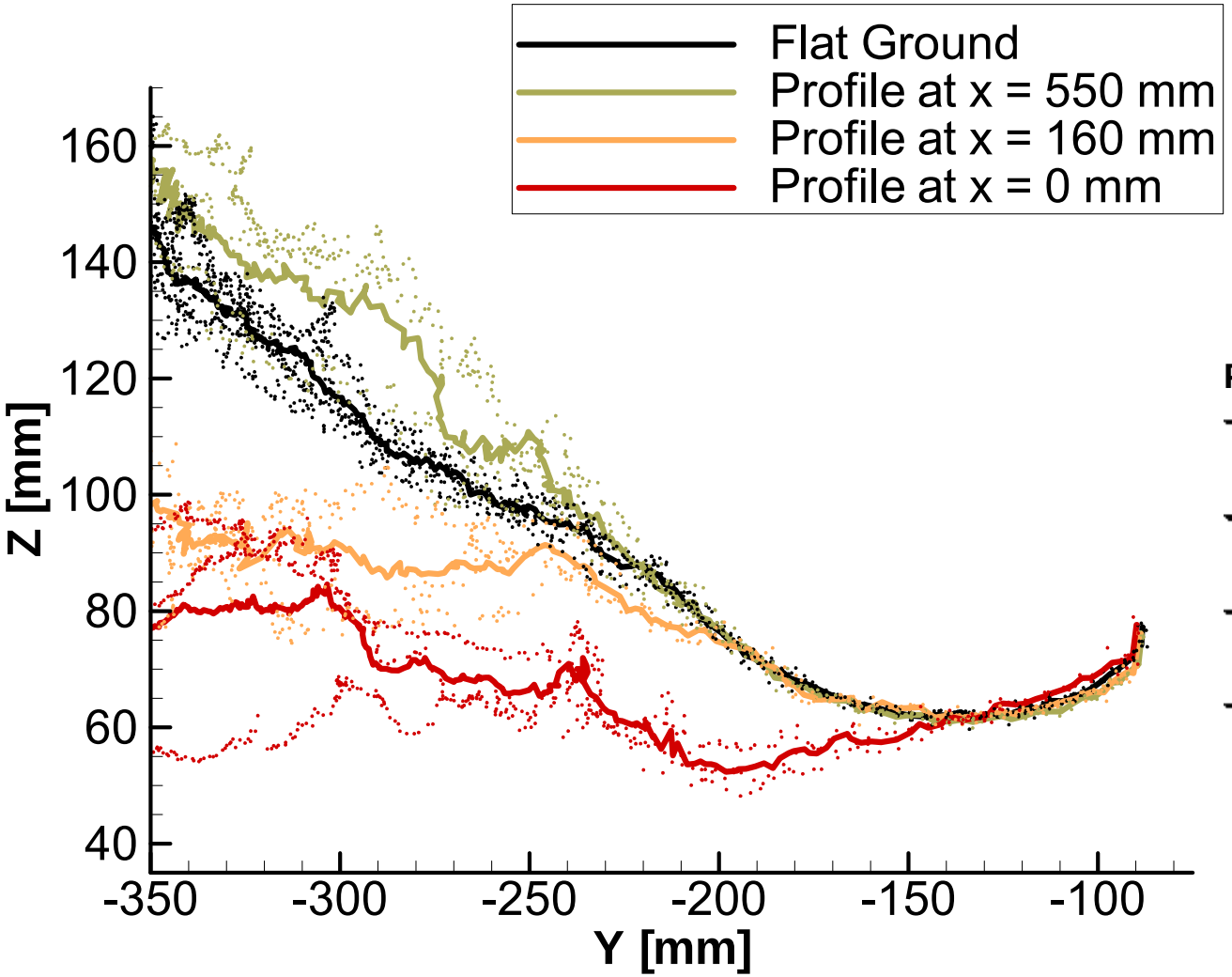


Ground with sine wave (2π),
maximum (4 cm) at X = 650 mm

Parameters:

- Model velocity: 2.44 m/s
- Distance to ground: 80 mm (0.5 b_0)
- Profiles perpendicular to flight direction in front of PIV plane
- Field of view: 400 x 240 mm²
- Correlation window size: 6.4 mm (32 pixels)
- Here in display: 15 s (τ = 4.3 resp. 239 b_0)

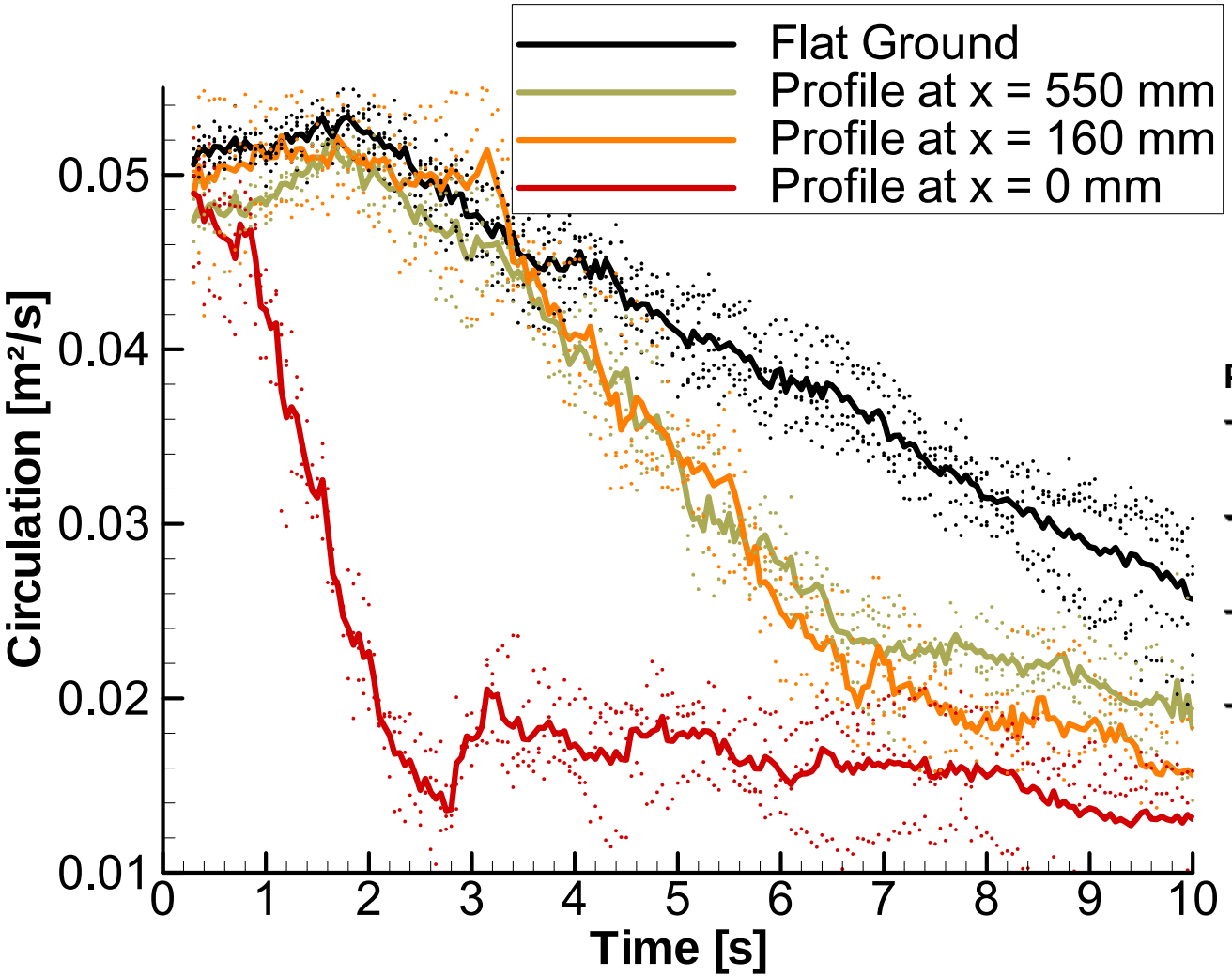
Wake Vortices in Proximity to Surfaces: PIV Results — Vortex Position



Parameters:

- Model velocity: 2.44 m/s
- Distance to ground: 80 mm (0.5 b_0)
- Profile perpendicular to flight direction in front of PIV plane
- Disturbance propagates in flight direction

Wake Vortices in Proximity to Surfaces: PIV Results — Circulation



Parameters:

- Model velocity: 2.44 m/s
- Distance to ground: 80 mm (0.5 b_0)
- Profile perpendicular to flight direction in front of PIV plane
- Disturbance propagates in flight direction

Conclusions / Outlook:

Conclusions:

- Investigation of wake vortices from F-13 Model in the water towing tank Göttingen (WSG) with
  - time-resolved stereo PIV
  - time-resolved vortex core visualization
- Wake vortices in turbulent environment
- Wake vortices in proximity to (ground) surfaces
- Influence of selected 2D ground obstacles
- Data base for numeric vortex models

Future Work:

- Quantitative evaluation of visualizations
- Evaluation / analysis of vortex bending
- Investigation of additional ground topologies (3D topologies)
- 3-dimensional (tomographic) PIV measurement of vortex development at ground obstacles