The Japan Society of
Fluid Mechanics

50th Anniversary Symposium, Osaka, 4 Sept 2018

Recent advancements towards large-scale flow diagnostics by robotic PIV

Fulvio Scarano

Delft University of Technology, Aerospace Engineering Department

Collaborators: A. Sciacchitano, C. Jux, J. Schneiders, D. Engler-Faleiros, F. Donker-Duyvis

Partners

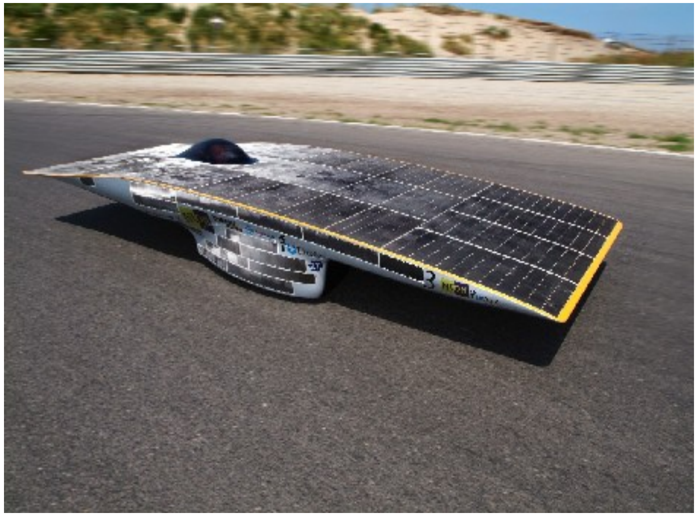
The need for large-scale aerodynamics

Investigation approaches, from lab scale detail to full scale systems

Civil aviation constantly growing

Renewable energy by wind farms

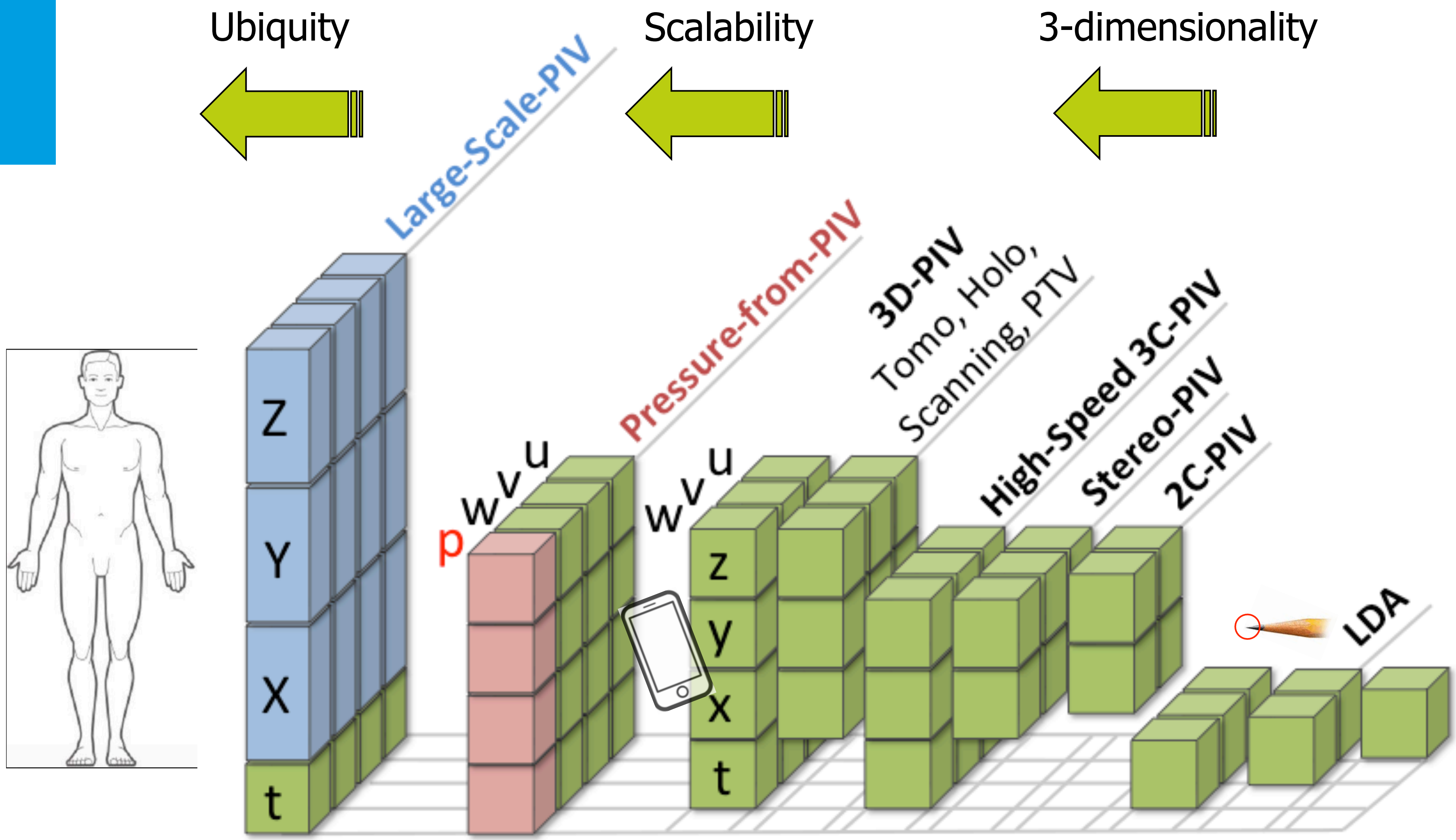
Novel concepts for personal air mobility



Advanced concepts for green transport

Developments of Laser velocimetry

4-D velocimetry, flow pressure, measurement upscale, versatility

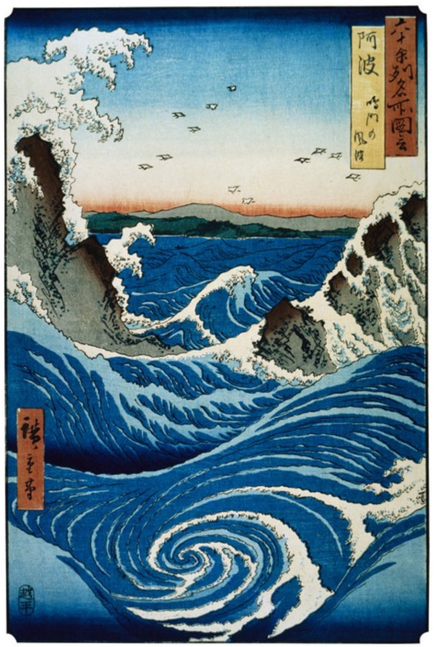


Early, seminal activities in Japan

Art of flow visualisation, large scale flow analysis, from art to measurement science

1855

Ukiyo-e, Hiroshige



1967

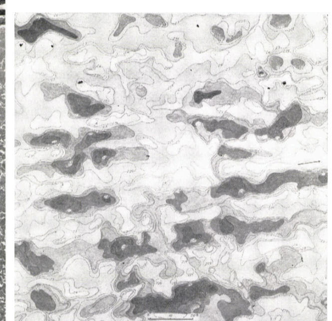
航空写真による洪水流の解析

その乱流構造と表面の流れかたの特性について

木下良作*

An Analysis of the Movement of Flood Waters by Aerial Photography, Concerning Characteristics of Turbulence and Surface Flow

Ryosaku Kinoshita



1987

計測自動制御学会論文集
Vol. 23, No. 2
(昭和62年2月)

相関を利用した流れ場の速度ベクトル分布の画像計測†

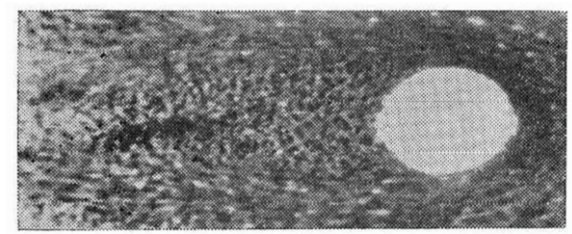
——円柱後流の変動渦への適用——

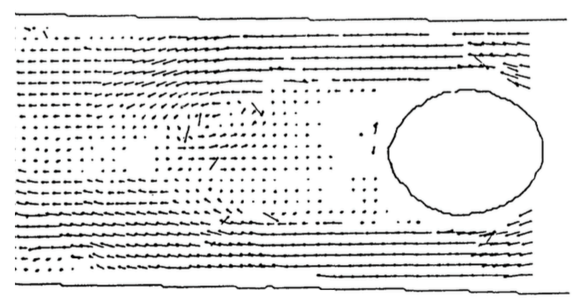
木村一郎*・高森年*・井上隆**

Image Processing Instrumentation of Flow Velocity Vector Distribution by Using Correlation Technique

——Application to Vortices in the Wake of a Circular Cylinder——

Ichiro KIMURA*, Toshi TAKAMORI* and Takashi INOUE**





Summary of PIV'97–Fukui and New Directions in PIV Development

1997

Yamamoto, F.*[1] and Kobayashi, T.*[2]

Outline

3 Dimensionality

- Tomographic PIV: working principle
- Momentum equation => Pressure-from-PIV
- Fundamental studies in fluid mechanics

Scalability and methods for large-scale experiments

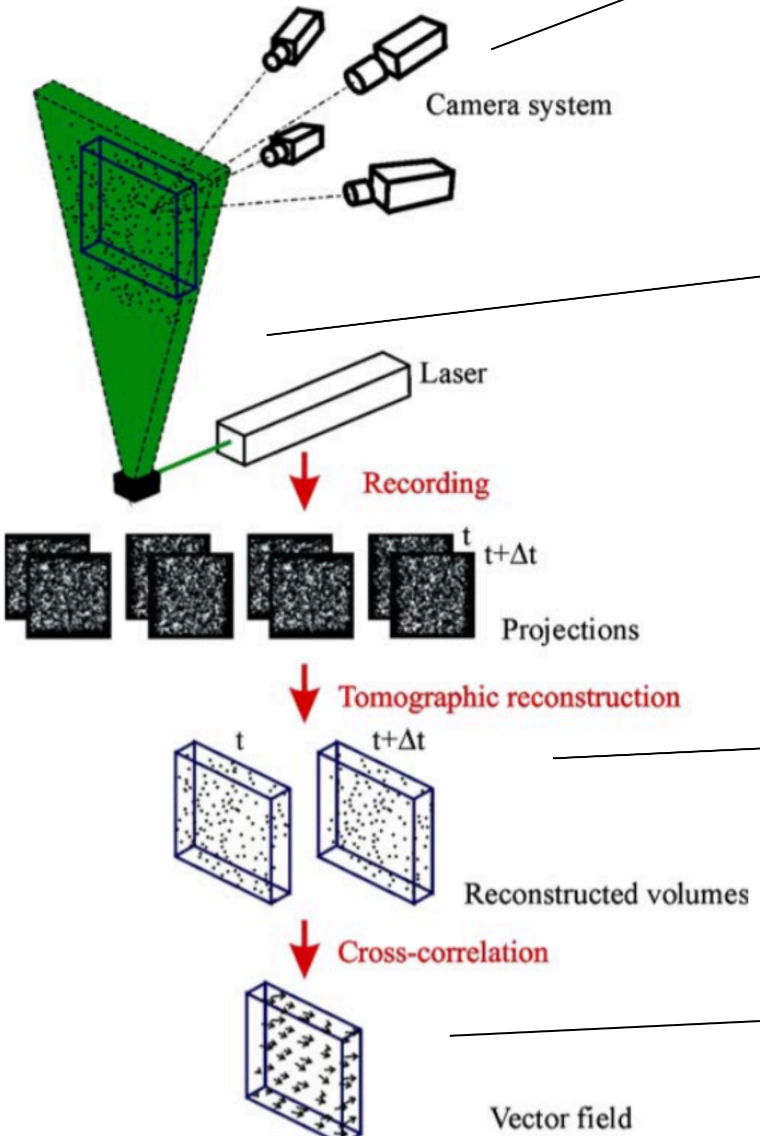
- Helium filled soap bubbles for aerodynamics
- Applications to vertical-axis wind turbine, ground vehicles, ships

Ubiquity and versatility

- Coaxial volumetric velocimetry
- Robotic PIV
- Applications in aviation and sport aerodynamics

Conclusions and perspectives

Tomographic PIV: working principle



Imaging

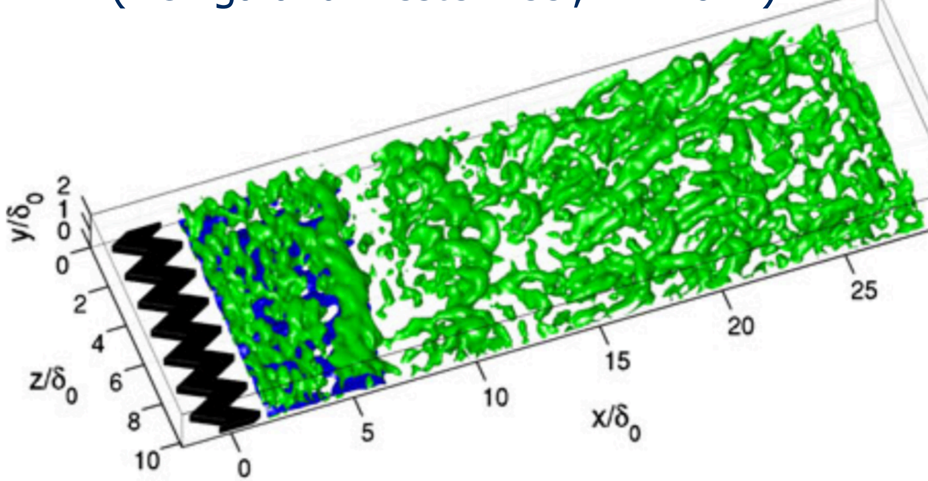
Volume illumination

Reconstruction (MART)

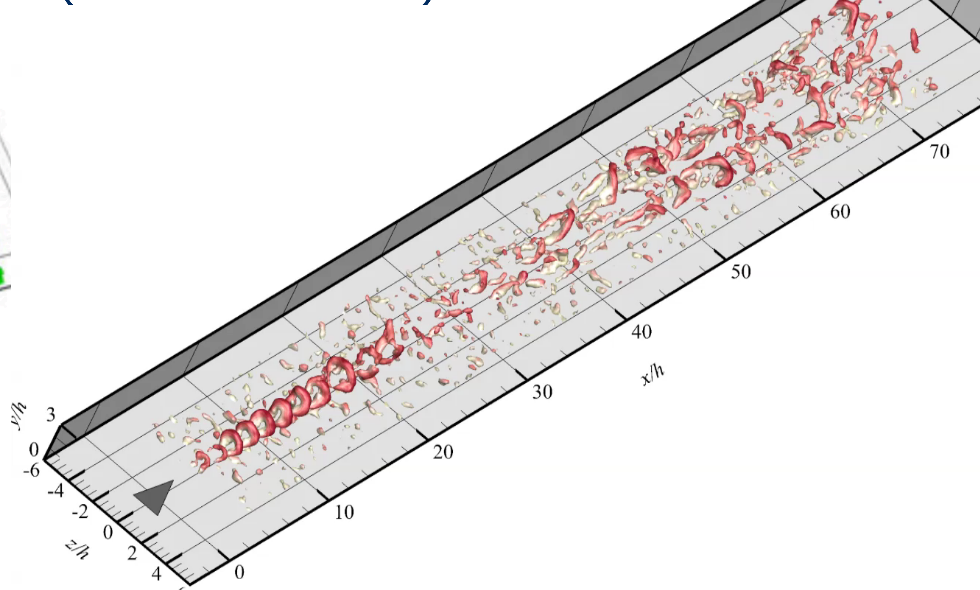
Object interrogation

Flow stability and vorticity dynamics

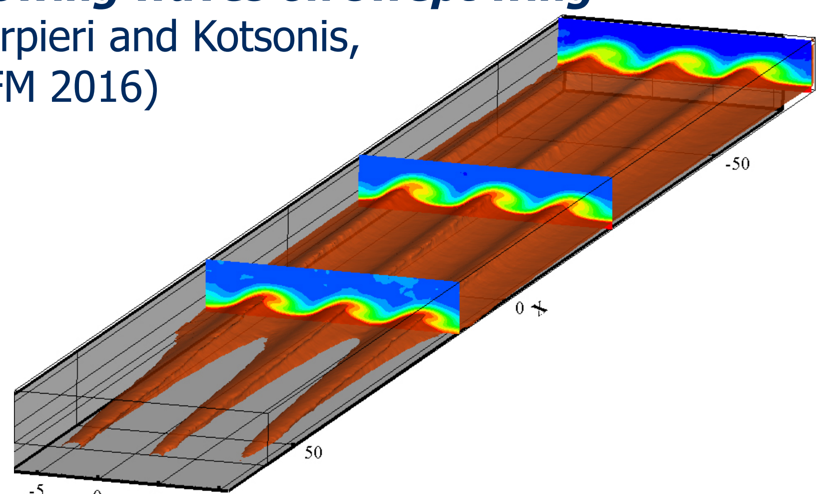
Forced transition by zig-zag device
(Elsinga and Westerweel, EiF 2012)



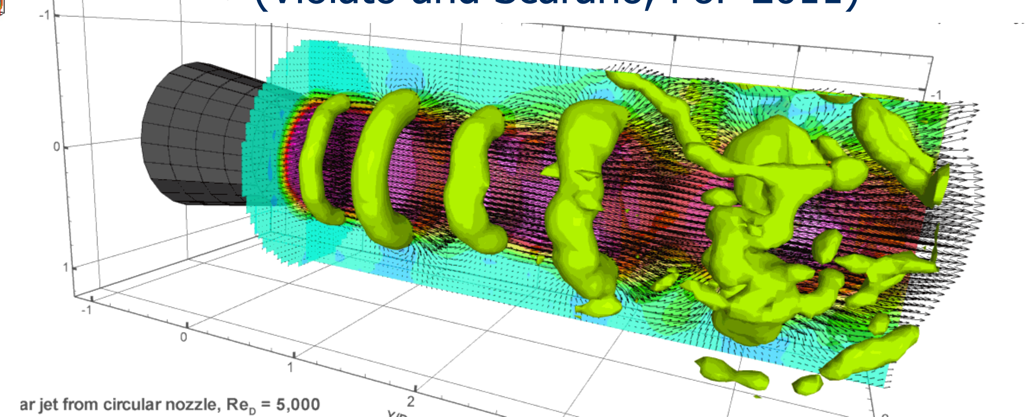
Roughness induced transition from micro-ramp
(Ye et al. JFM 2016)



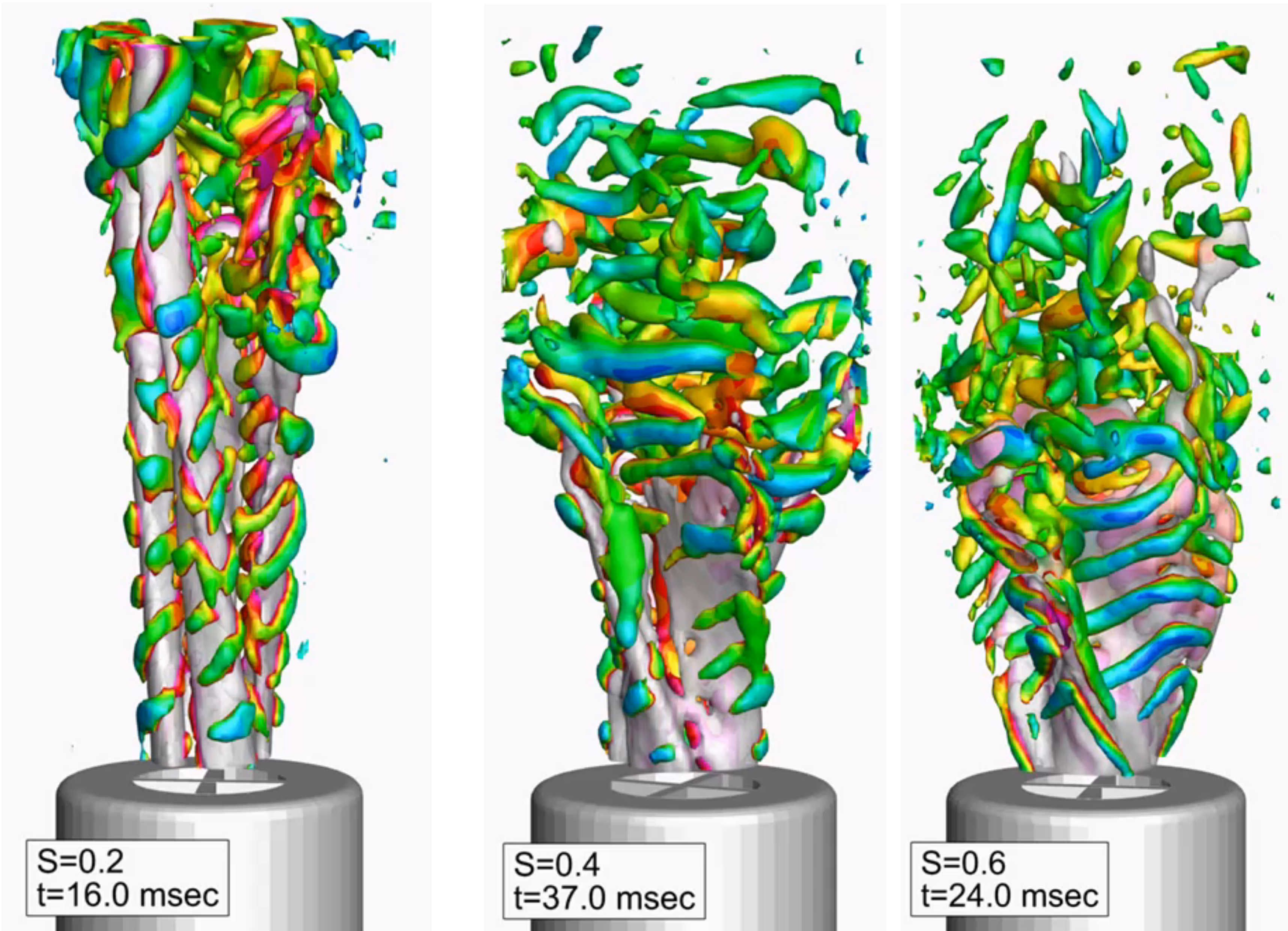
Growing waves on swept wing
(Serpieri and Kotsonis, JFM 2016)



Transitional jet
(Violato and Scarano, PoF 2011)



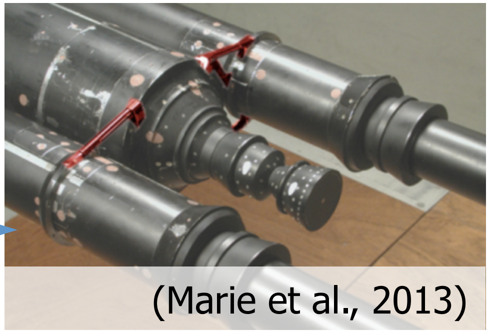
Complex flows: swirling jets (Ianiro et al., JFM 2018)

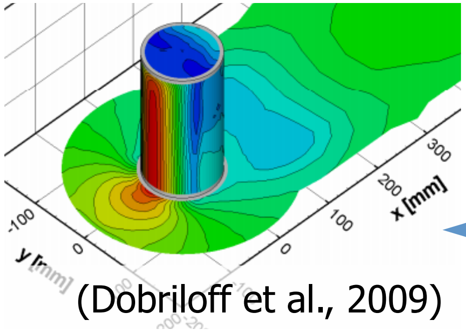


Pressure from PIV

Surface Pressure Transducers

Ariane 5 model with **112 pressure transducers**


(Marie et al., 2013)



(Dobriloff et al., 2009)

Mounted Cylinder **179 pressure transducers**

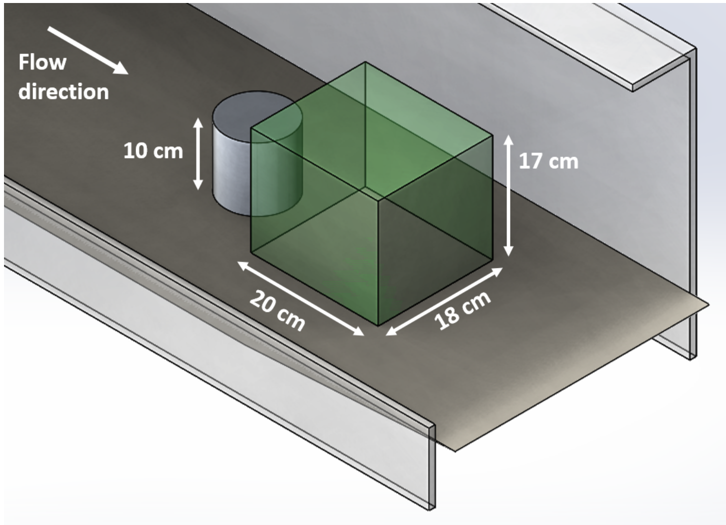
Pressure from PIV (van Oudheusden, 2013 among others)

$$\nabla p = -\rho \frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} + \mu \nabla^2 \mathbf{u} \longrightarrow \nabla^2 p = \nabla \cdot (\nabla p) = \nabla \cdot \left(-\rho \frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} + \mu \nabla^2 \mathbf{u} \right)$$

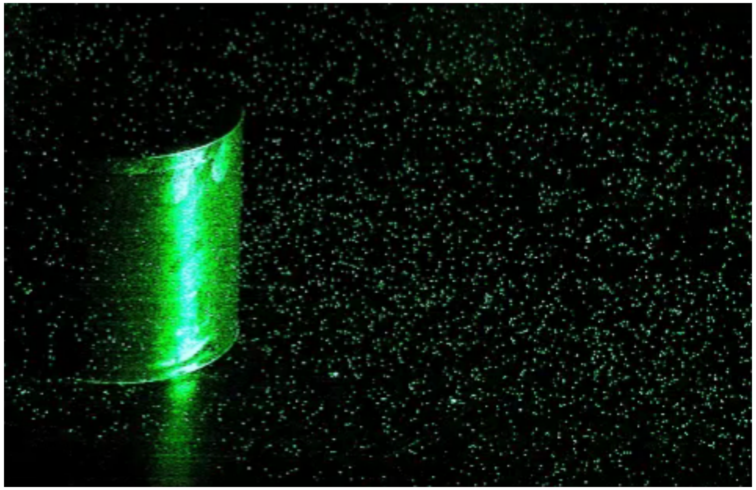
Time-resolved volumetric measurements required

Mounted Cylinder Experiment (Schneiders and Scarano, 2016)

Experiment Setup



Recording at 2 kHz

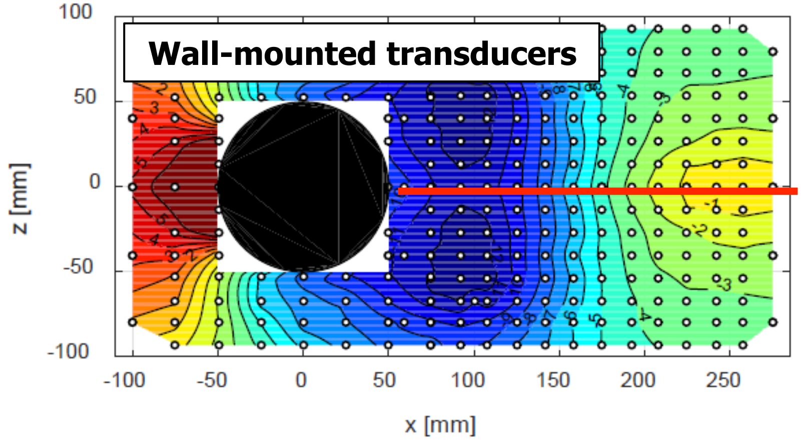


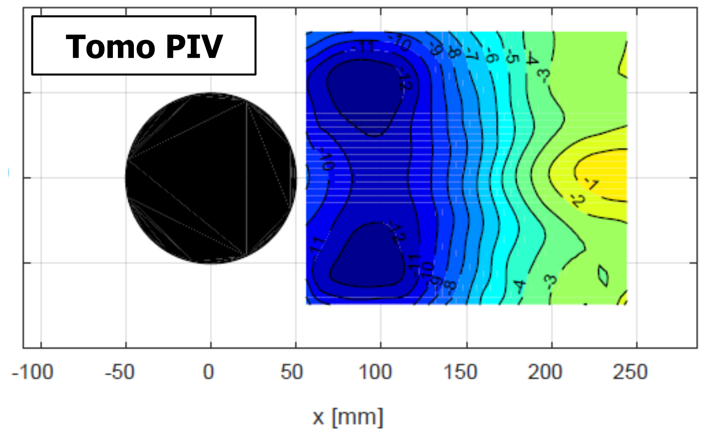
V_{inf}	5 m/s
Re_D	3.6×10^4
D	10 cm
H	10 cm

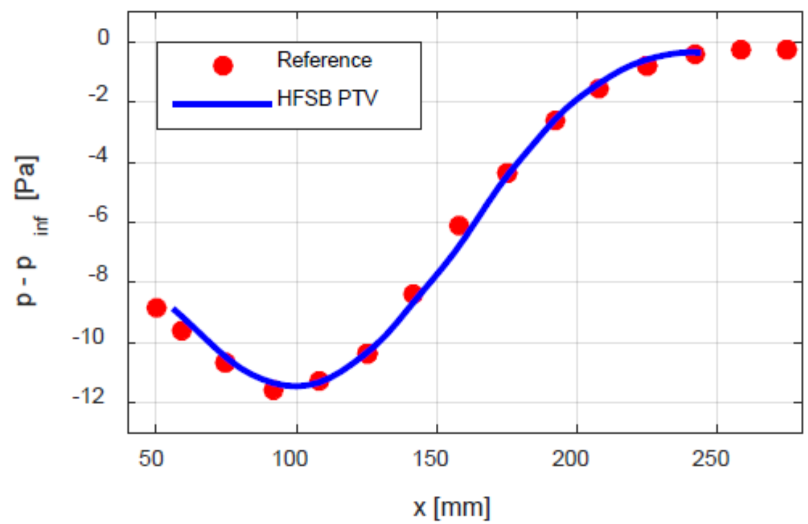
Seeding	Helium-Filled Soap Bubbles (0.5 mm)
Illumination	Quantronix Darwin-Duo Nd:YLF (2 x 25 mJ @ 1 kHz)
Imaging	4 x Photron Fast CAM SA1 CMOS, 1024x1024 px
Objectives	4 x 105-mm Nikkor, f/16
Acq. frequency	2,000 Hz

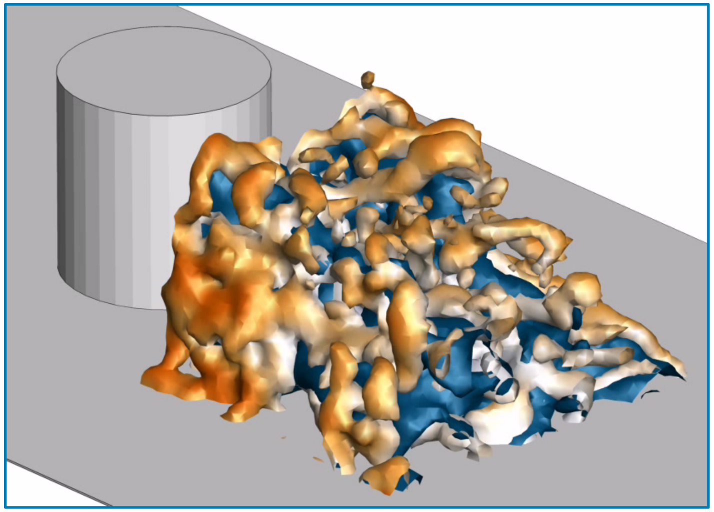
Surface pressure

Comparison between transducers and Pressure-from-PIV

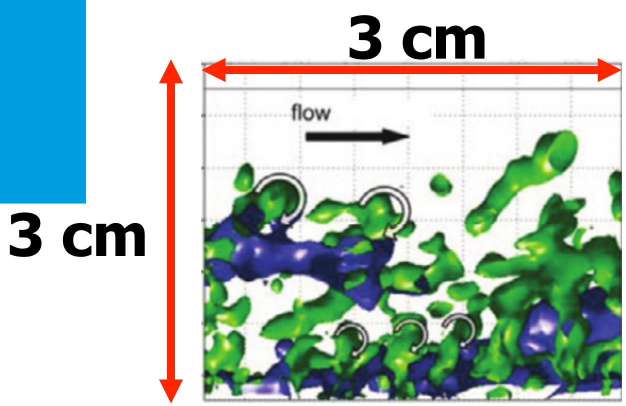




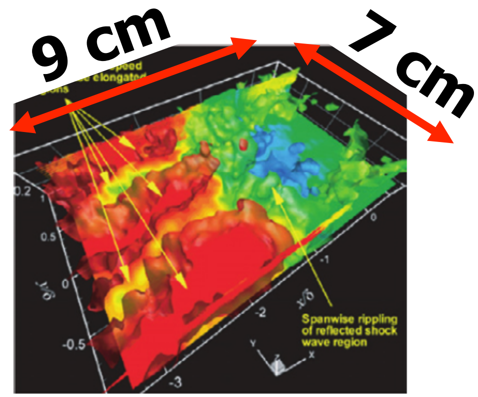




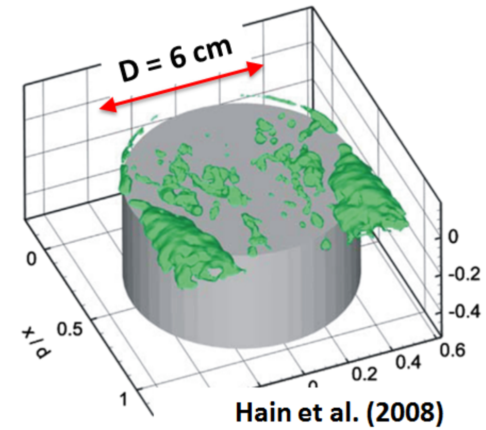
Experiment scalability: how to get there



Turbulent BL
Elsinga et al (2007)

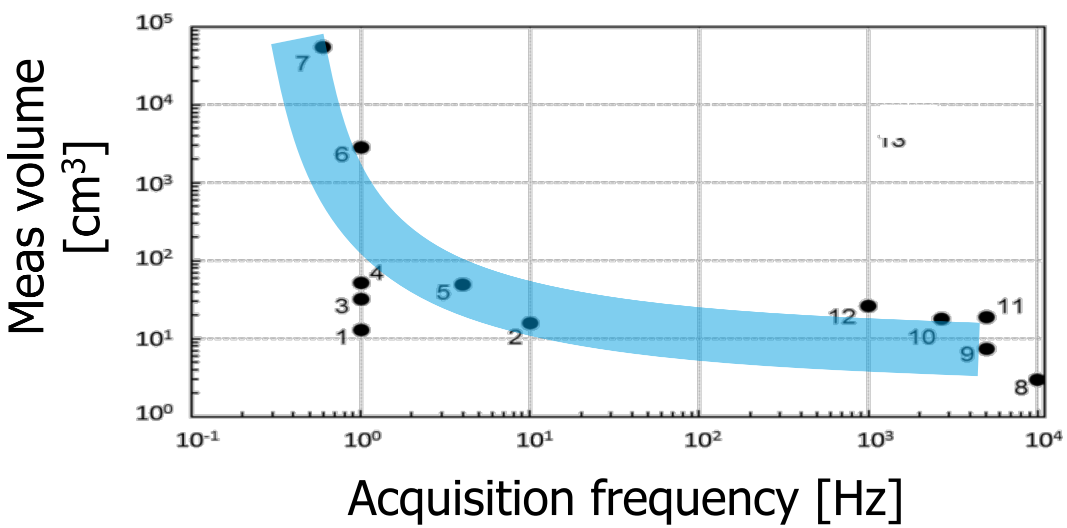


Shock wave - BL interaction
Humble et al (2007)



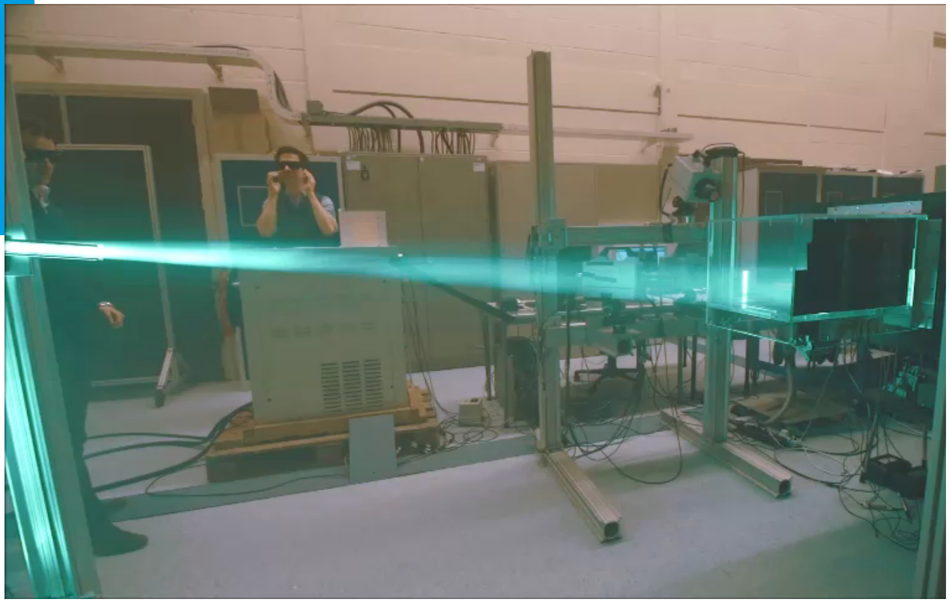
Surface-Mounted Cylinder
Hain et al. (2008)

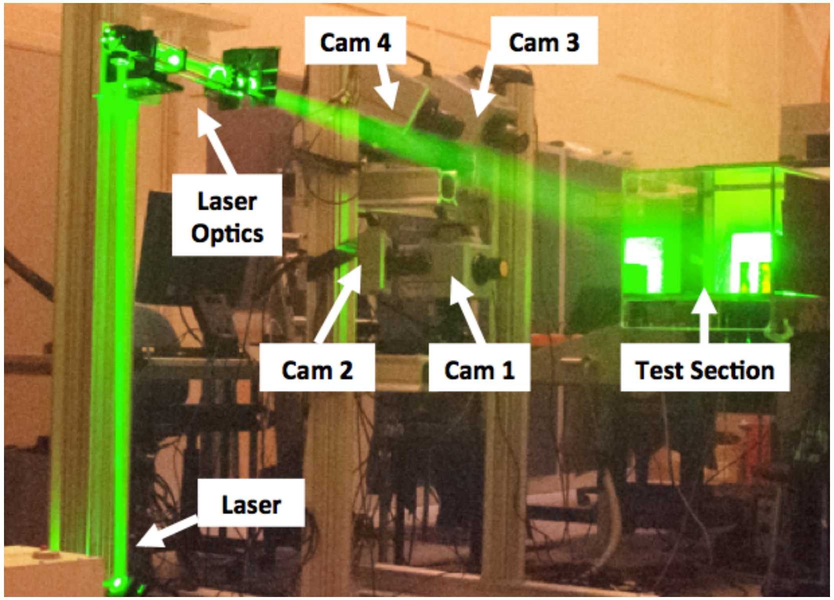
Typical measurement volume for time-resolved tomo-PIV ~ 20 cm^3

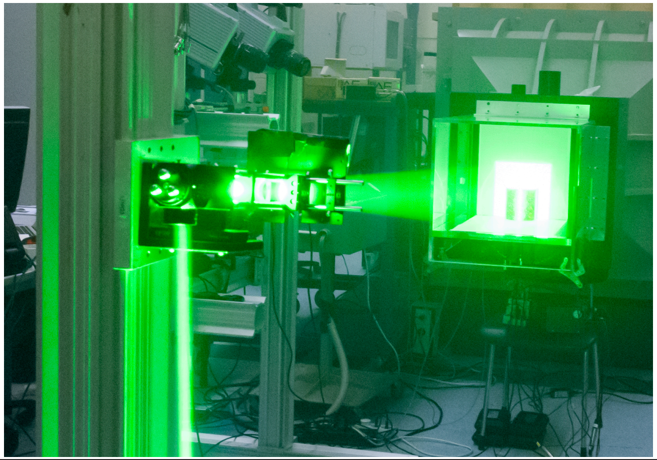


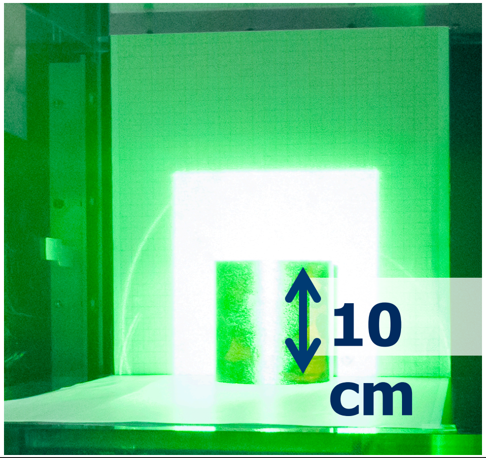
Caridi et al. (2015)

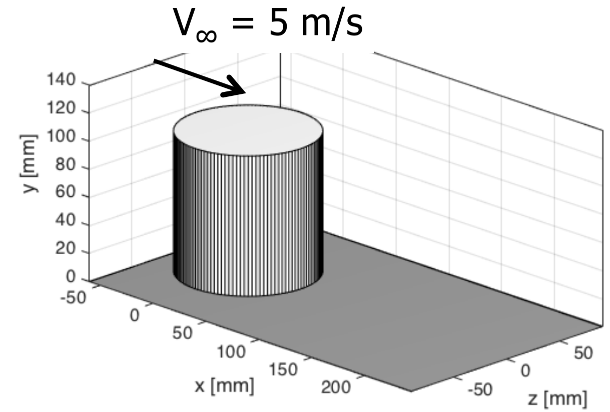
Large-Volume Tomographic PIV







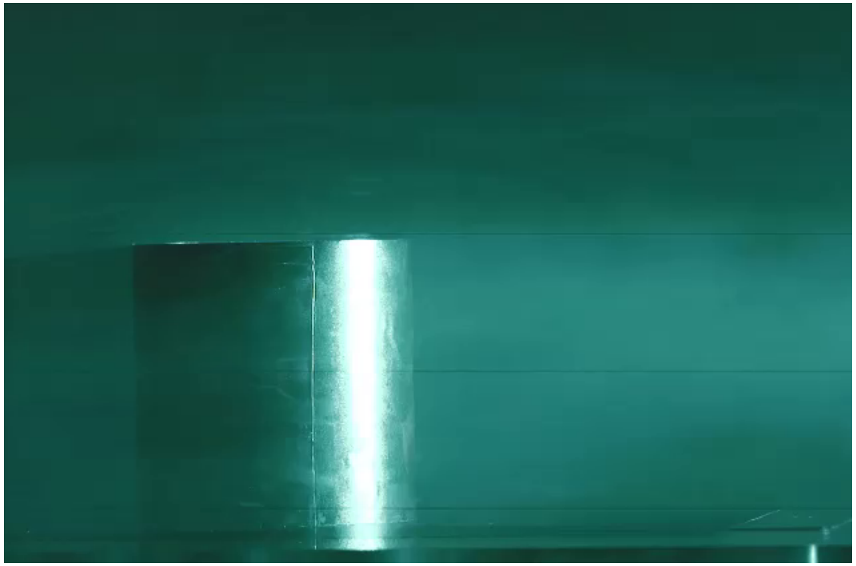




Large-Volume Tomographic PIV

Fog or oil droplets

- 1 μm diameter
- 2 μs response time



Particle-Image peak intensity

$$I_p \propto \frac{J_0\, \boxed{A^2}\, d_p{}^2}{Z_0\, d_\tau{}^2\, \boxed{\Delta X_0\ \Delta Z_0}}$$

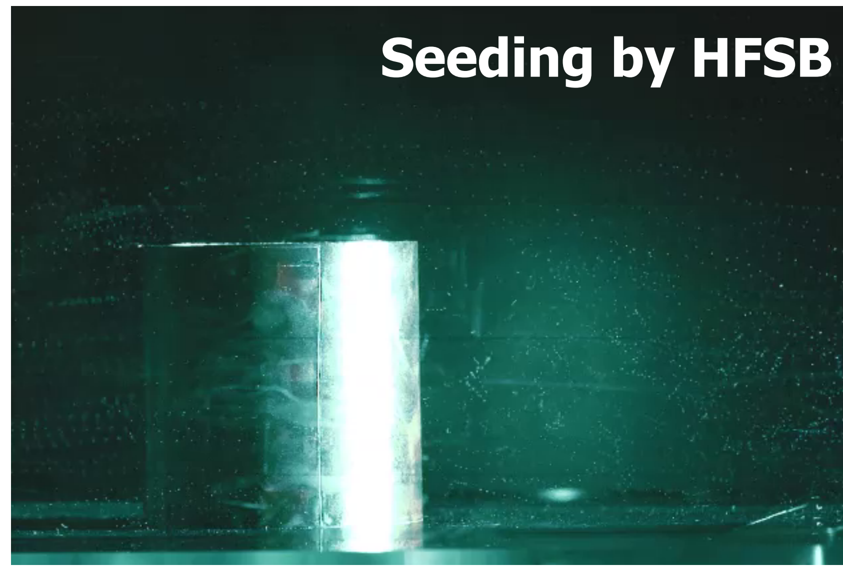
I_p	Particle peak intensity	Z_0	Object distance
J_o	Light pulse energy	d_τ	Particle image diameter
A	Objective aperture	ΔX_0	Laser sheet width
d_p	Particle diameter	ΔZ_0	Laser sheet thickness

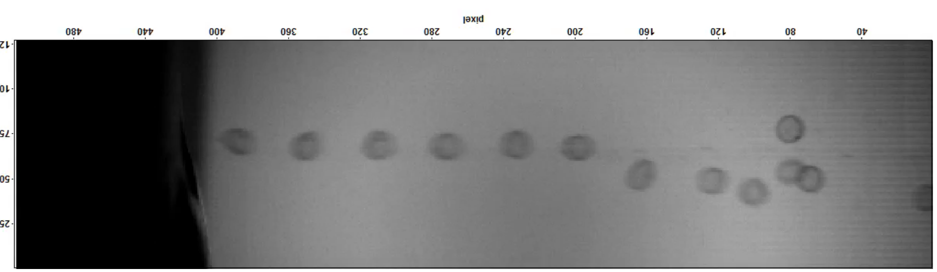
Particle time-response $\tau_p = d_p^2 \dfrac{\Delta\rho}{18\mu_f}$

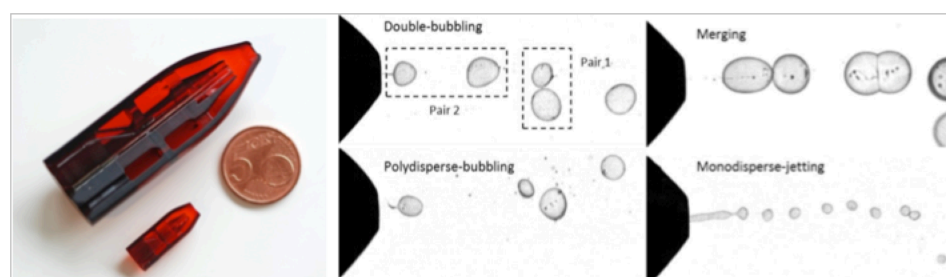
Large-Volume Tomographic PIV

Fog or oil droplets
- 1 μm diameter
- 2 μs response time

HFSB tracers
- 300 μm diameter
- 10 μs response time
- Neutrally buoyant

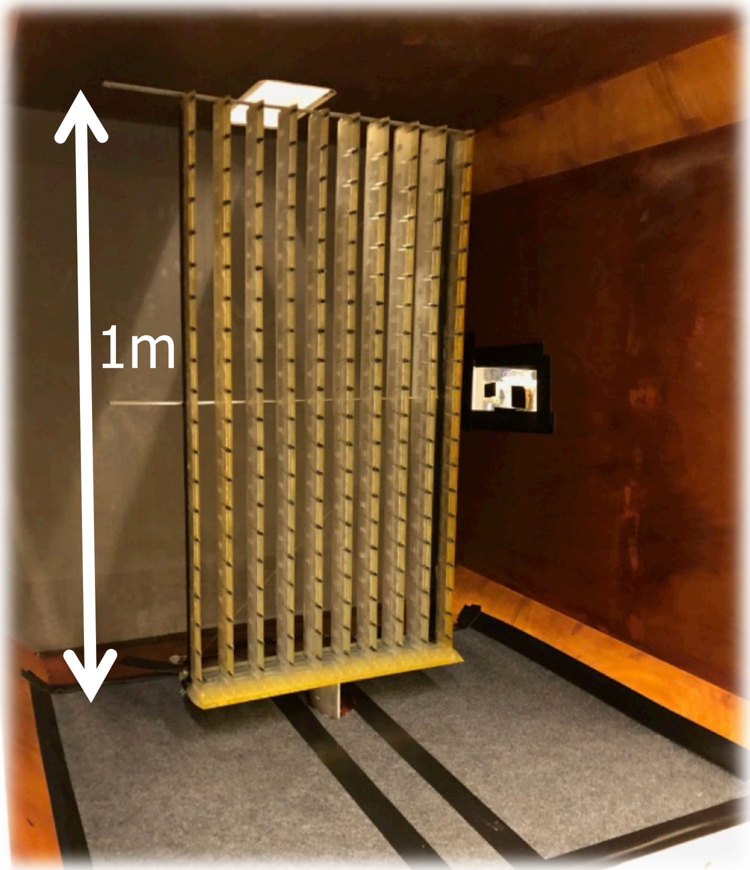




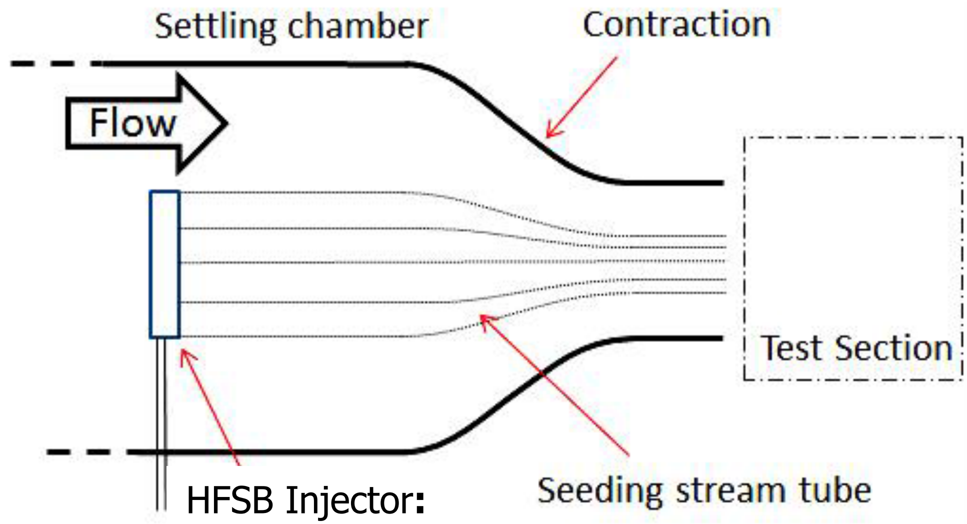


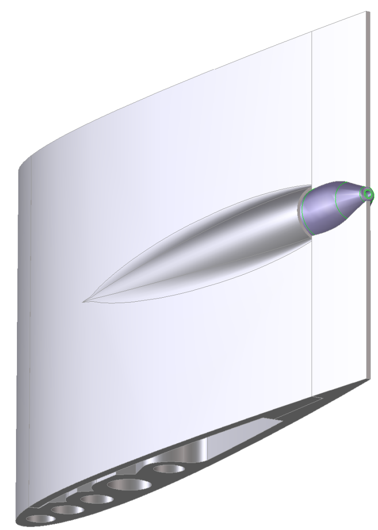
Large Scale PIV Seeding System

Injection of bubbles in wind tunnel stream



Aerodynamically shaped HFSB susyem with 200 generators in parallel

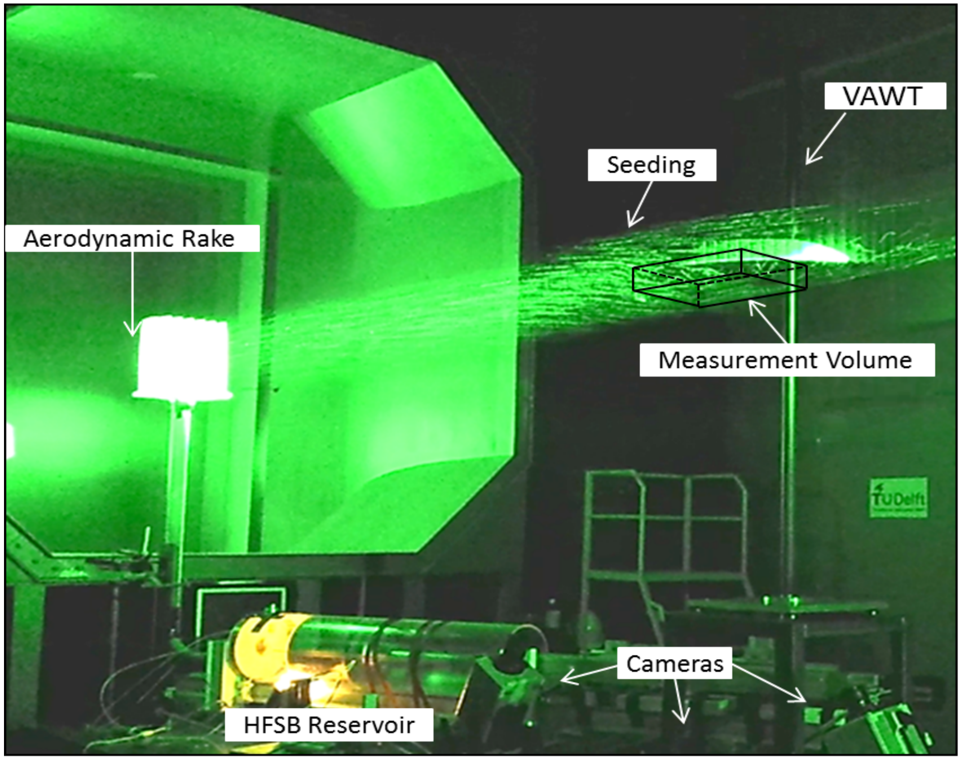


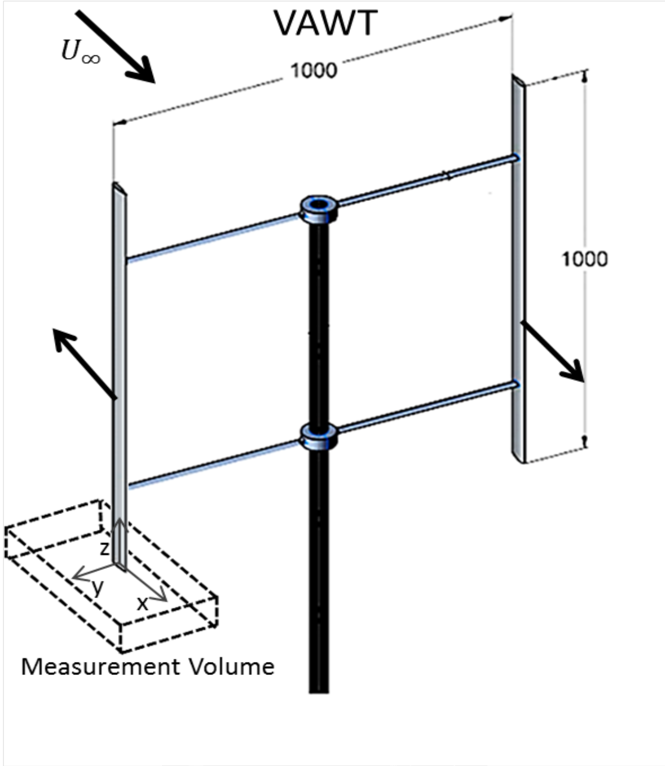


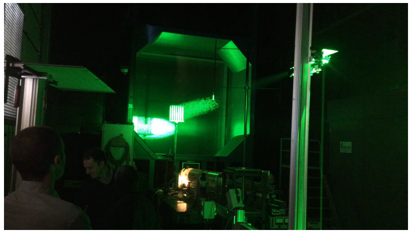
Detail of generator integration

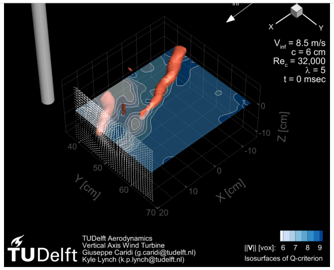
Large scale PIV experiments

Vertical axis wind turbine



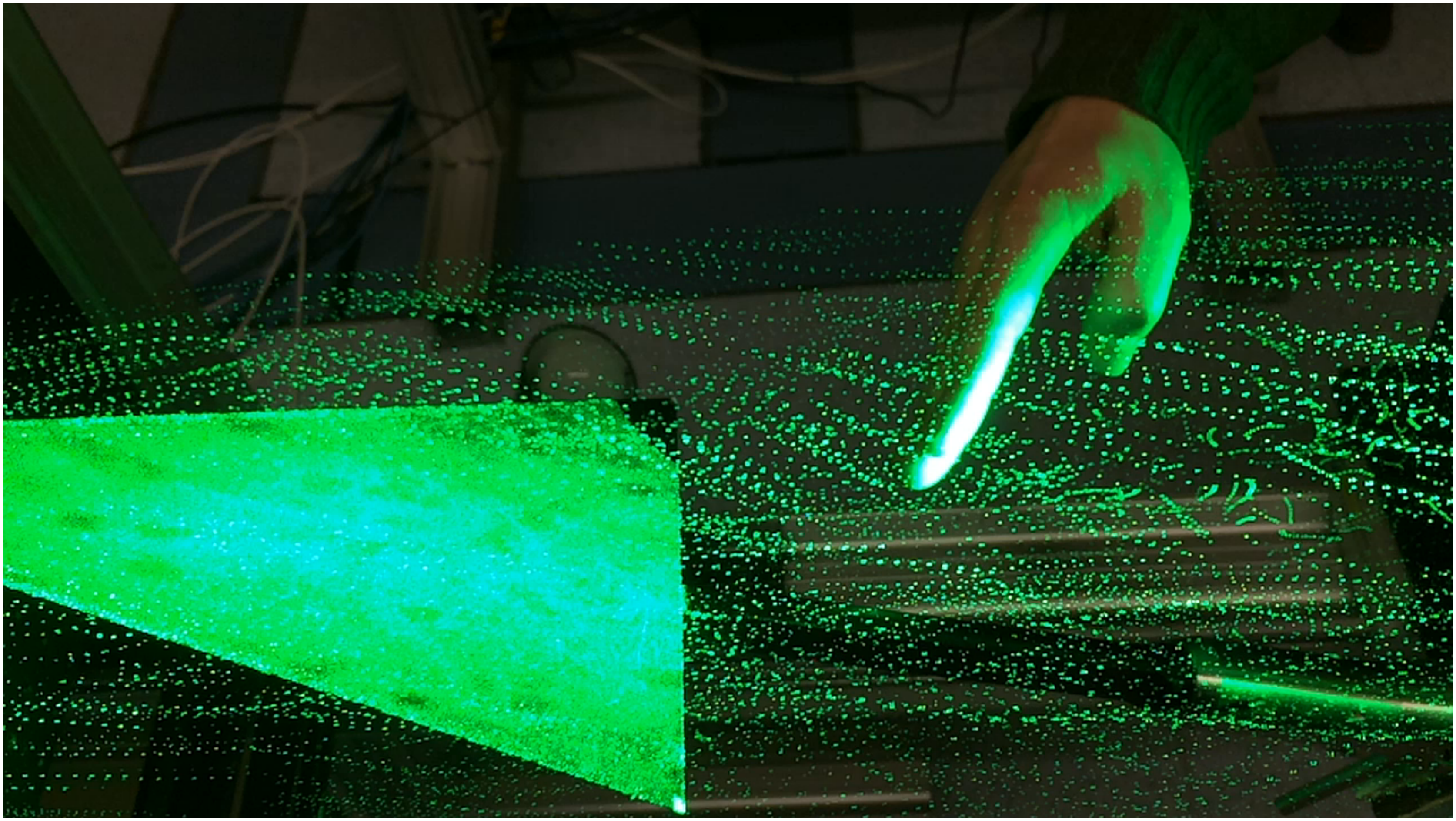






Flow visualization education

“hand made” vortex-breakdown



Towards industrial applications ?

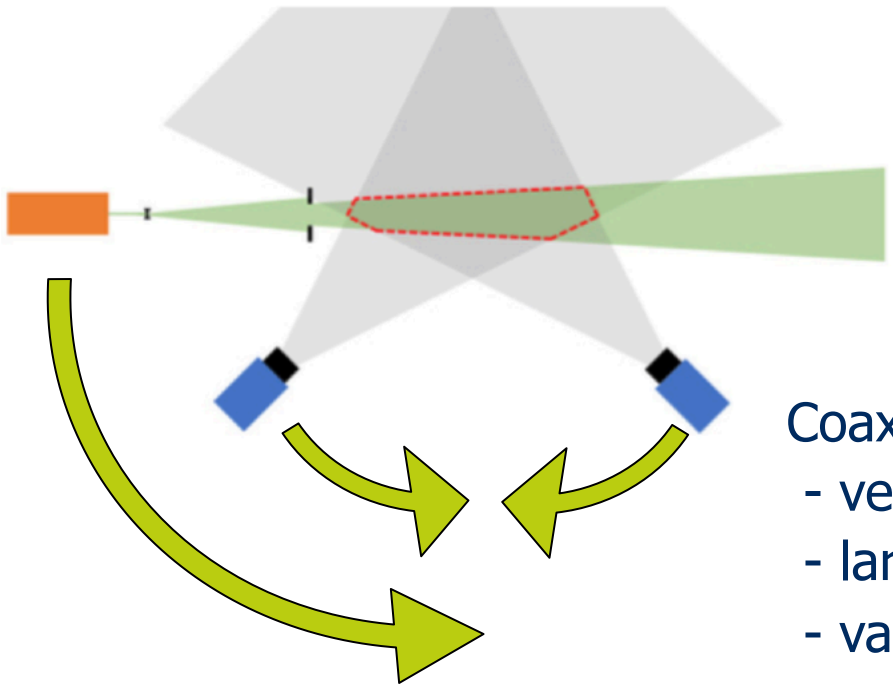
...We need a versatile technique that one can setup in less than one hour,
perform the measurements over a square meter domain
and deliver results within the day.
When you have such a technique, you can make me a call or send an e-mail...

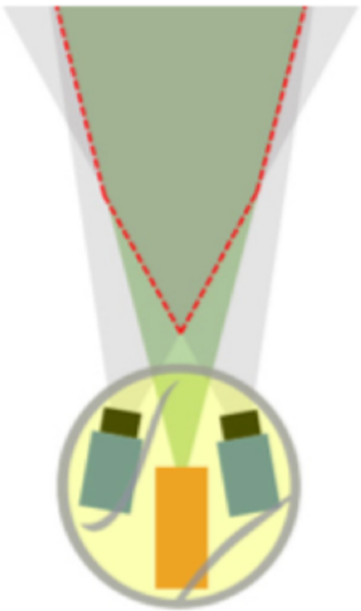
Antonello Cogotti,
Pininfarina industries

EUROPIV 2 progress meeting
~ 2002 somewhere in Europe

Coaxial Volumetric Velocimetry (Schneiders et al. 2018)

1) Reducing tomographic angular aperture
2) Aligning illumination with imaging

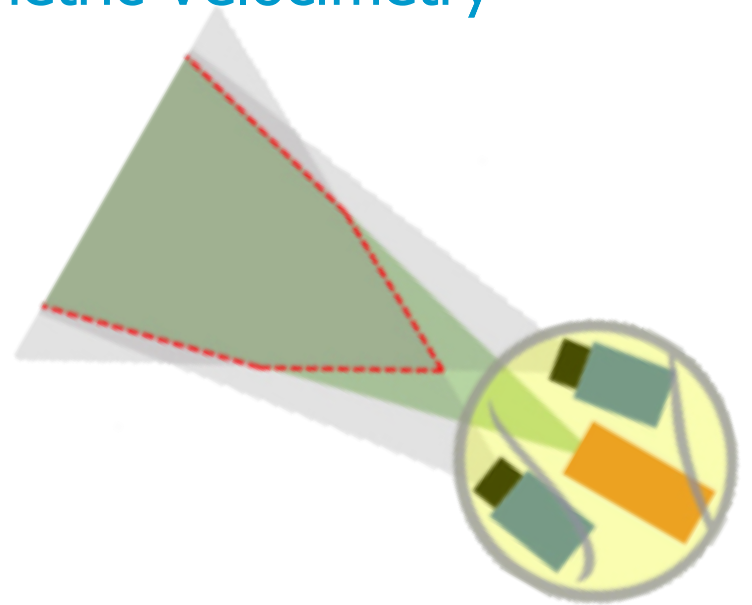




Coaxial => compact configuration
- very small aperture
- large range along depth
- varying optical magnification
- rapidly decaying light intensity

Principal features of Coaxial Volumetric Velocimetry

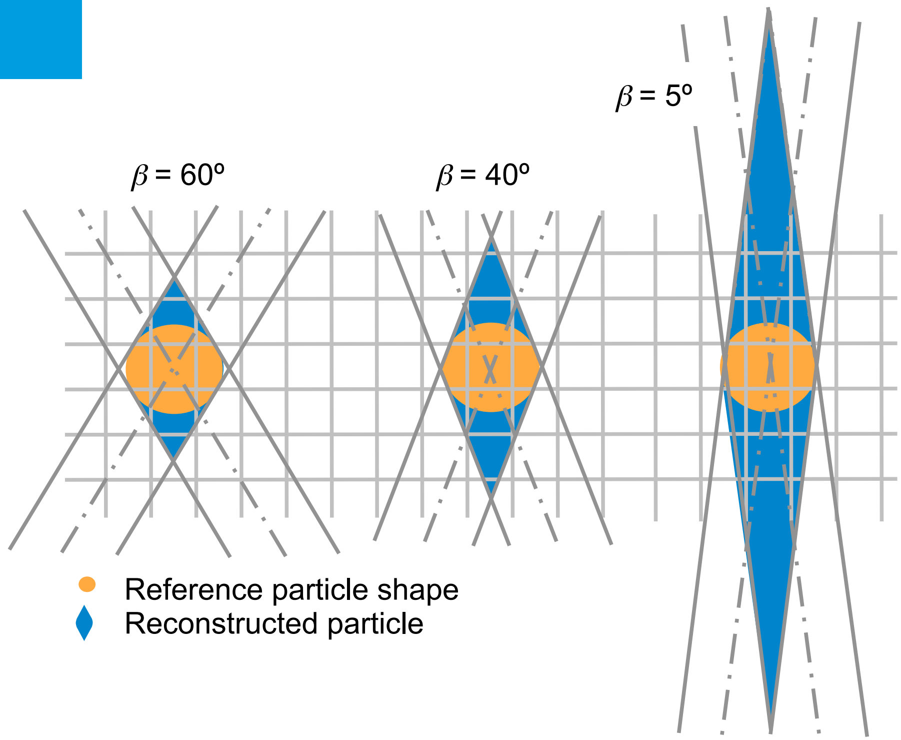
Main idea:
3D velocimeter like a torch light



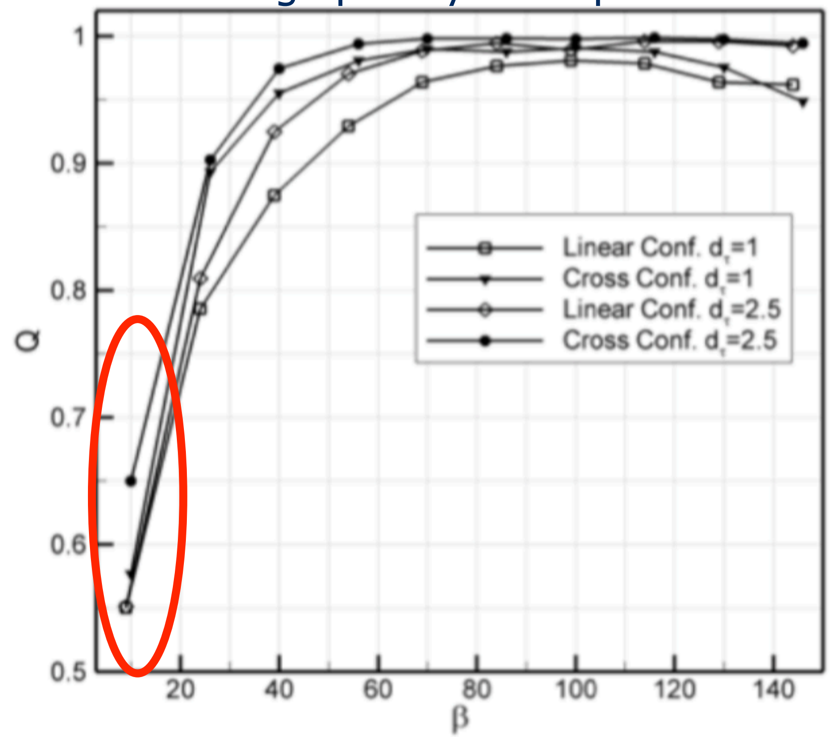
1) CVV : tomographic PIV system at small aperture
2) Probe in the flow (robot arm) with a finite depth range (~ 60 cm)
3) HFSB needed as flow tracers
4) High-speed recording (STB particle tracks analysis)
5) Ensemble-averaged velocity on cartesian bins

Tomographic aperture of CVV

1) The small aperture entails a large uncertainty along depth $\mathcal{E}_z$
2) Effect is compensated by long particle trajectory with $\boldsymbol{N}$ frames

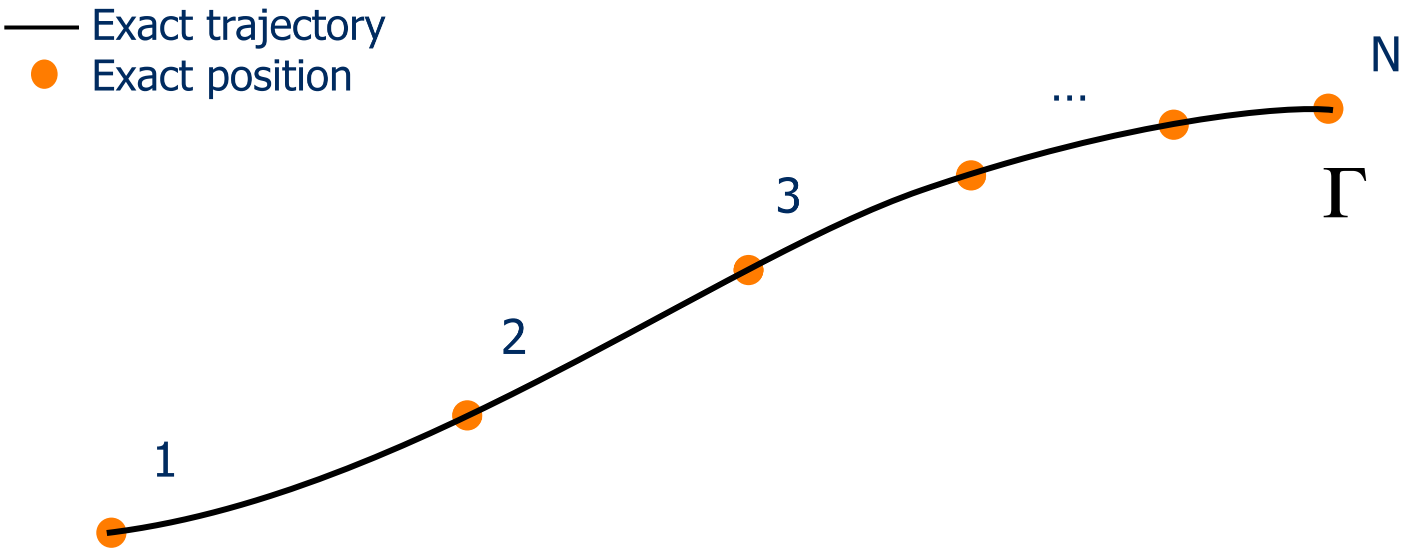


Reconstruction accuracy vs.
tomographic system aperture



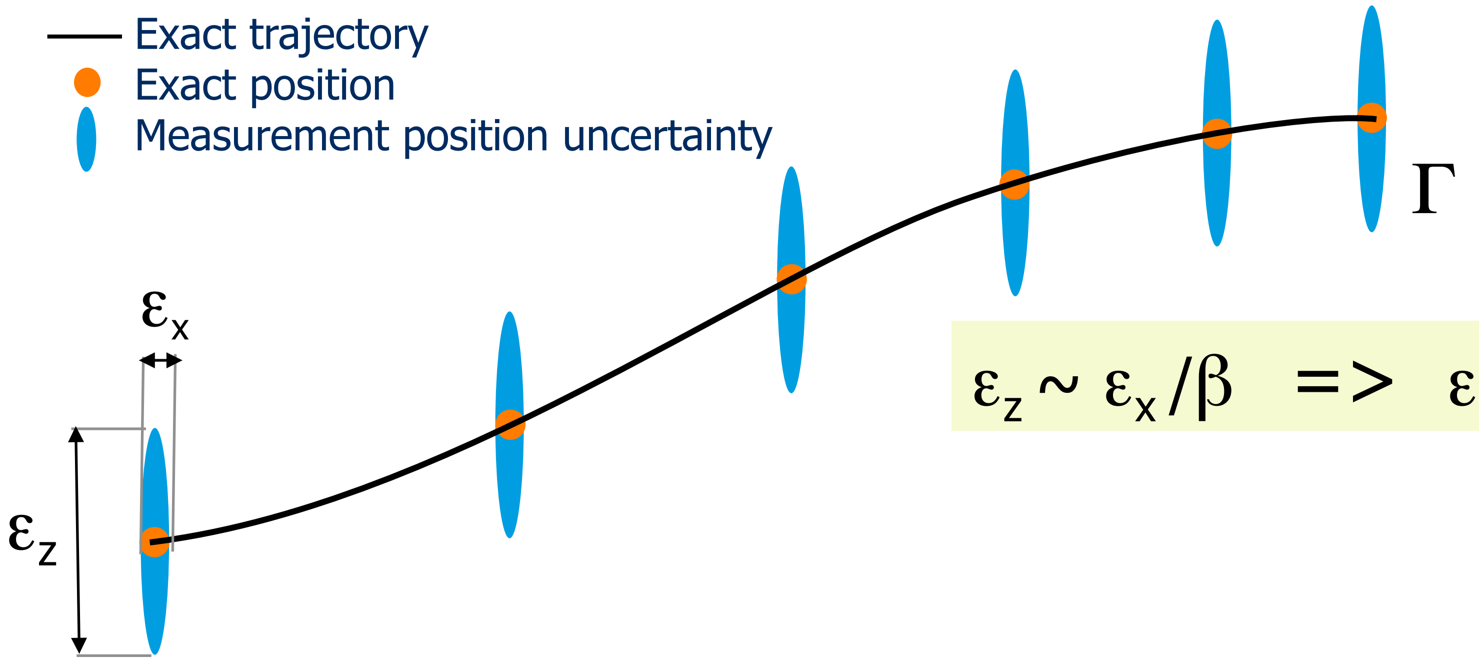
Velocity dynamic range

- Consider a particle trajectory Γ
- N sample positions are taken in a time-series of recordings



Velocity dynamic range

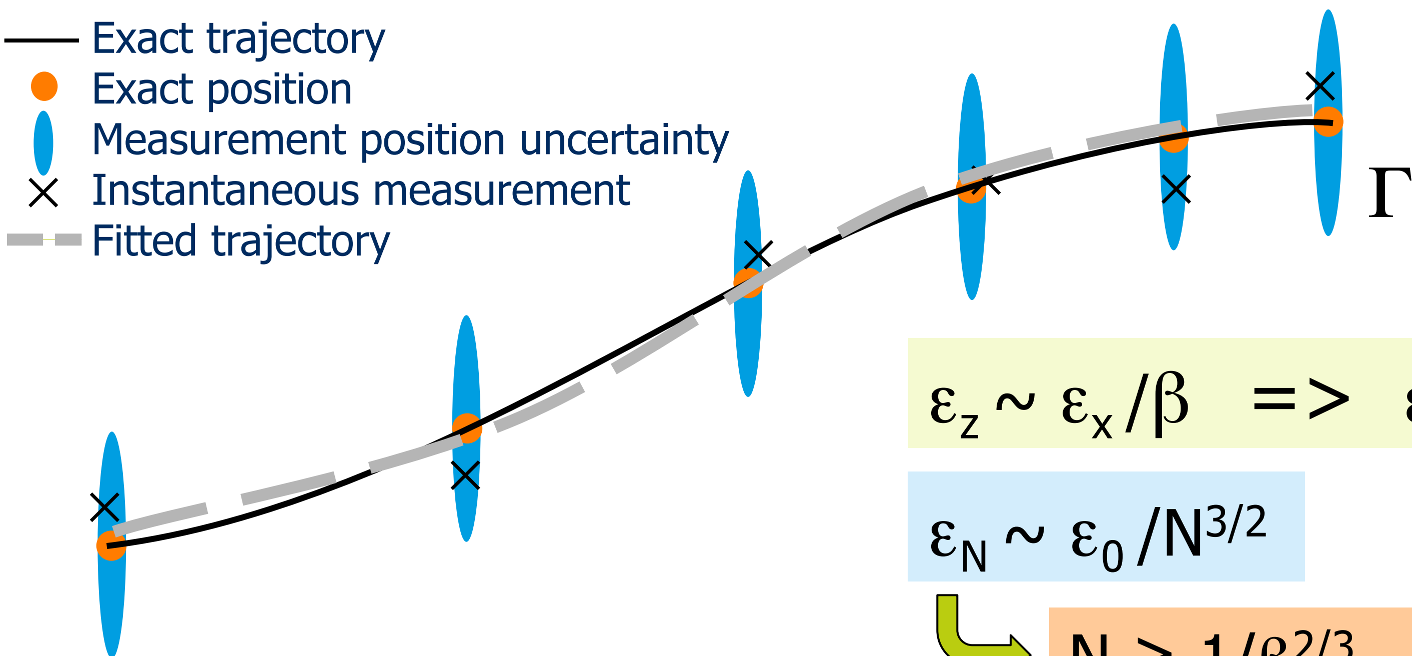
- The reconstructed particle positions have large uncertainty along z



$$\varepsilon_z \sim \varepsilon_x / \beta \quad => \quad \varepsilon_z >> \varepsilon_x$$

Velocity dynamic range

- Polynomial fitting over N points regularizes velocity estimation
- In particular w-component requires sufficiently large N (typ. N~10)



$$\varepsilon_z \sim \varepsilon_x / \beta \quad => \quad \varepsilon_z >> \varepsilon_x$$

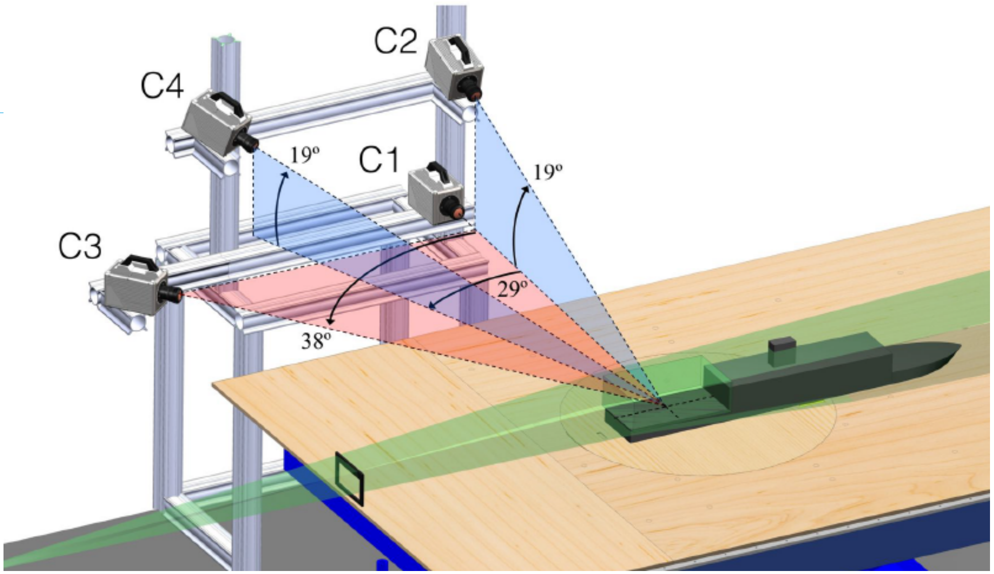
$$\varepsilon_N \sim \varepsilon_0 / N^{3/2}$$

$$N \geq 1/\beta^{2/3}$$

Lynch and Scarano (2013) A high-order time-accurate interrogation method for time-resolved PIV. *Meas. Sci. Technol.*

Optical configuration of CVV

Conventional tomographic PIV system



- Large aperture
- Calibration procedure
- Meas. Domain defined by illumination
- Instantaneous 3D velocity field

Coaxial velocimeter

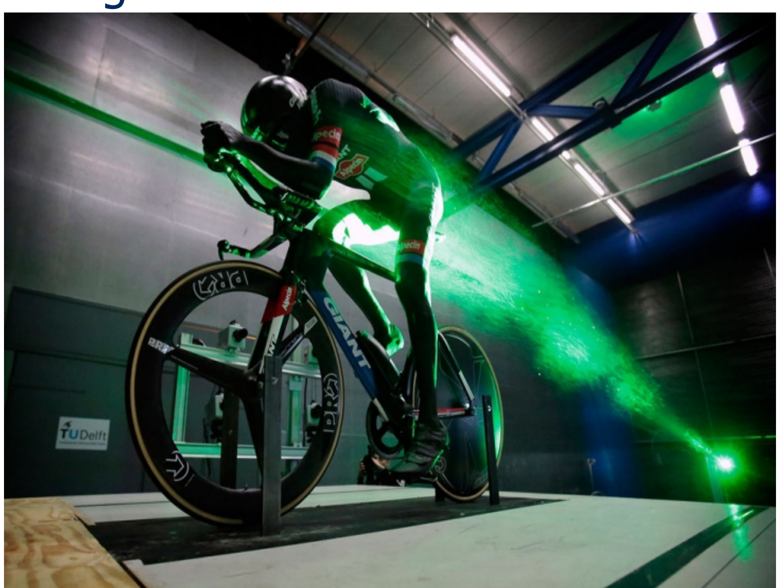
- Small aperture + laser optic fiber
- No calibration
- Meas. Domain defined by light decay
- Ensemble-averaged 3D velocity

Aerodynamic survey of full scale cyclist

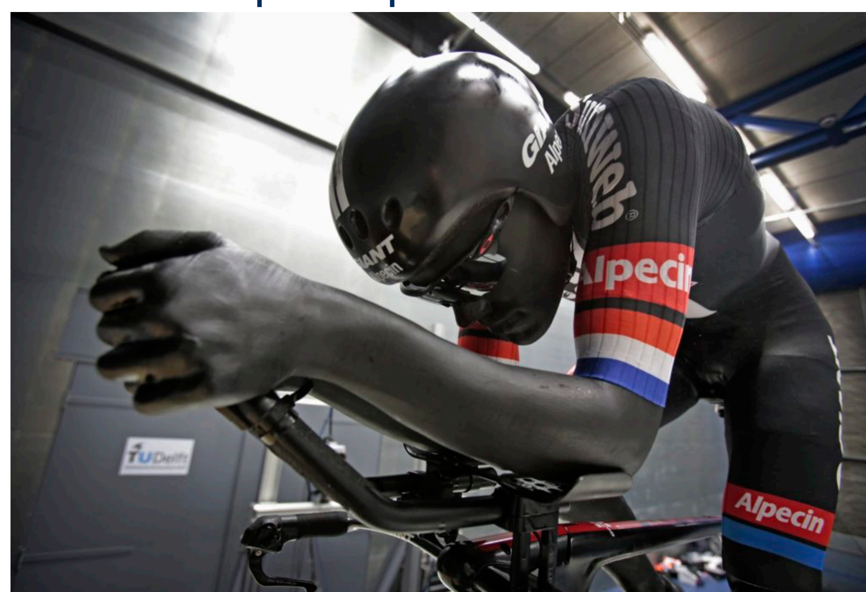
Dutch cyclist Tom Dumoulin (winner of *Giro d' Italia* 2017)

3D scan of athlete in time-trial position

Large-scale Tomo-PIV



Mannequin replica in wind tunnel



Aerodynamic survey of full scale cyclist

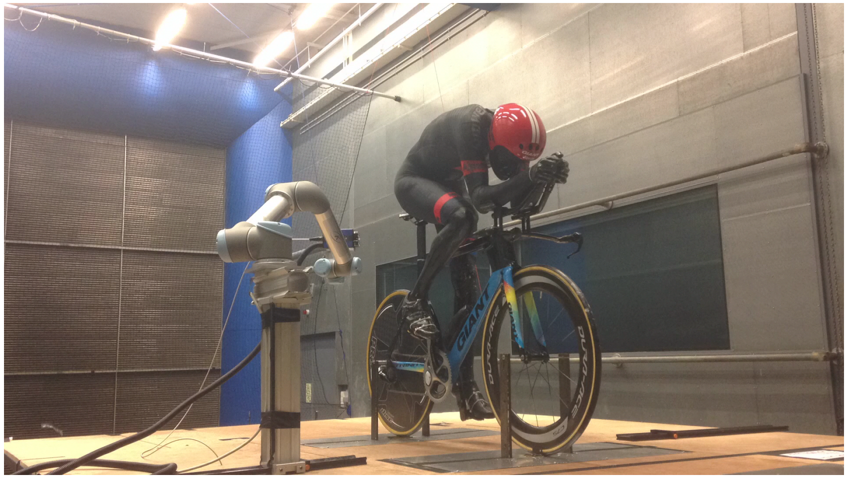
Robotic PIV experimental layout

(Jux et al. 2018)

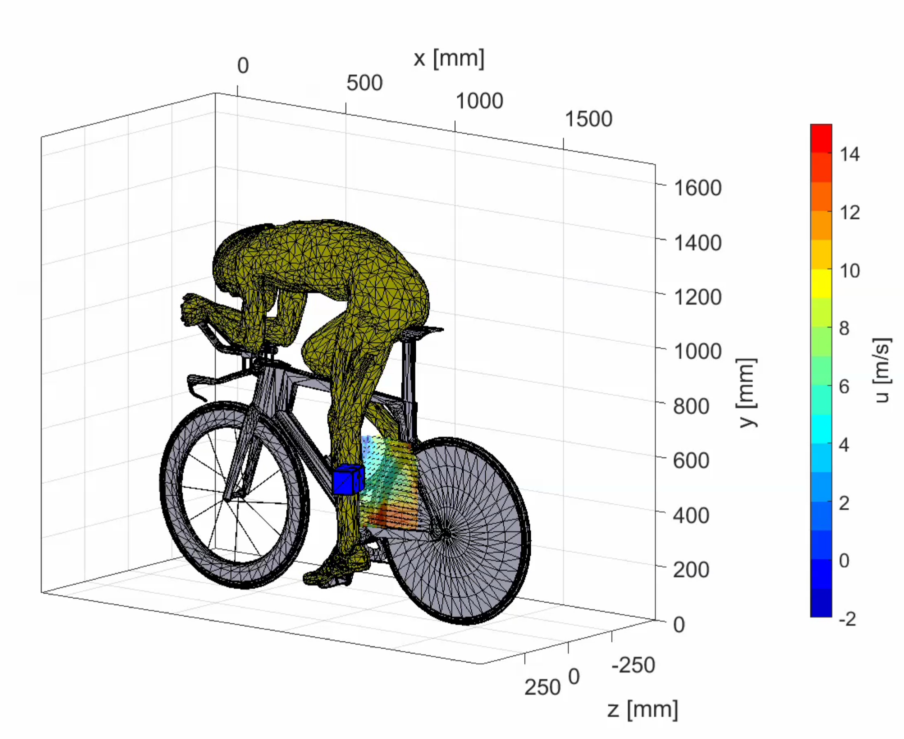
CVV is manouvered by a collaborative robot arm (UR5)

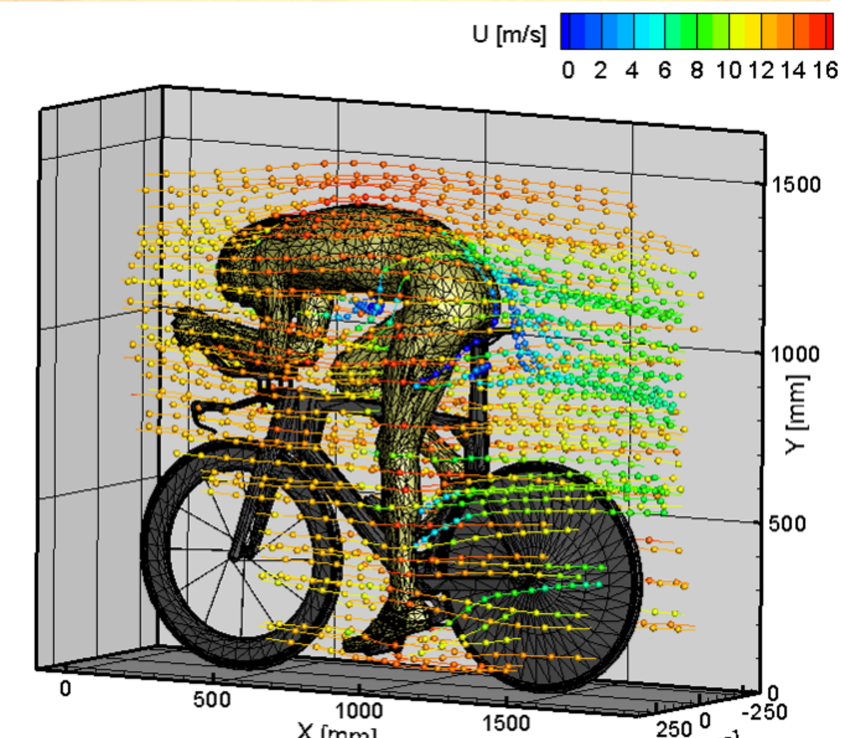
3D evaluation by robotic scan using CVV

Robot setup and positioning



Detail of leg wake



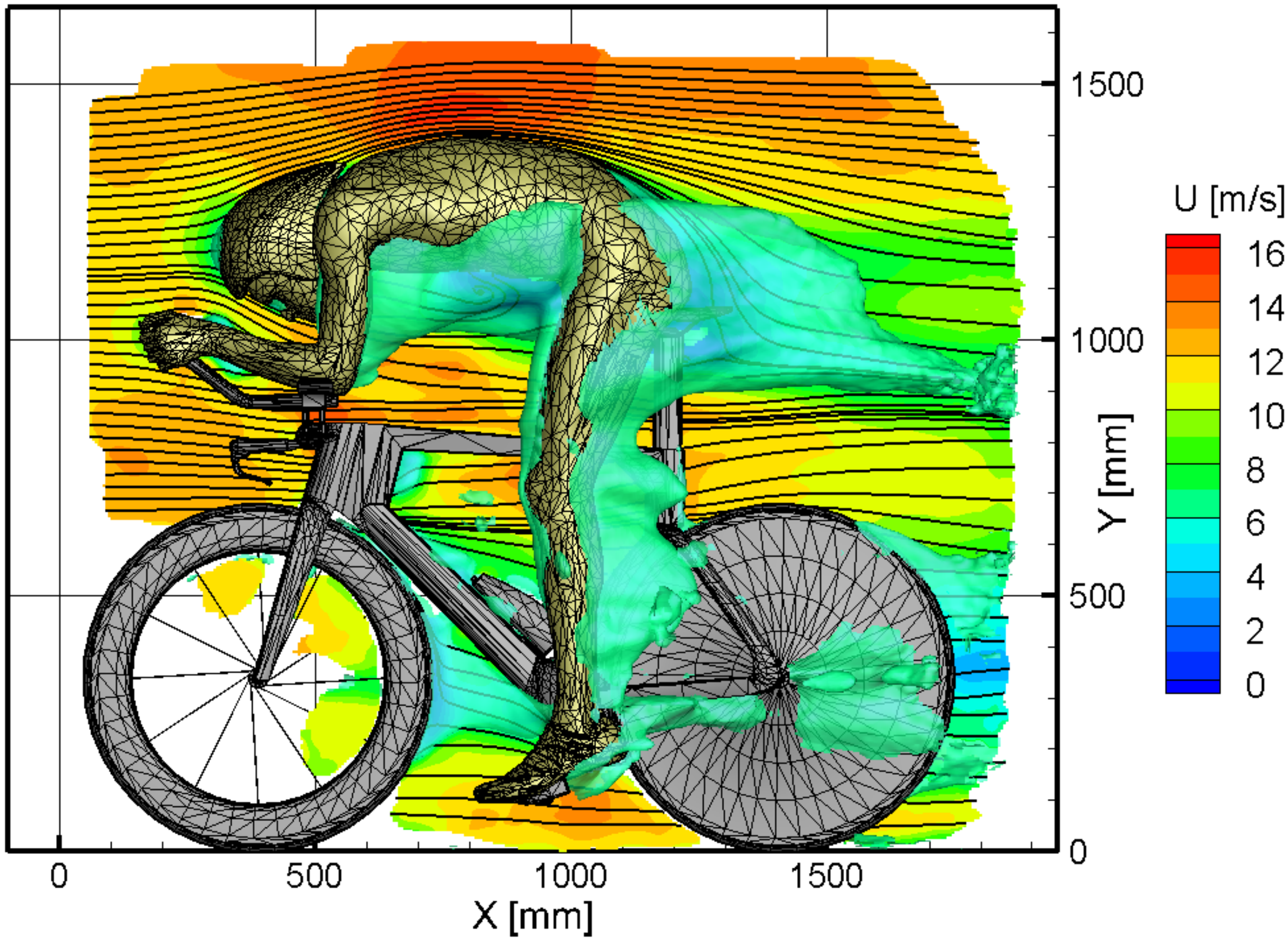


Cyclist velocity field survey

Building the global velocity field from individual sets (views)

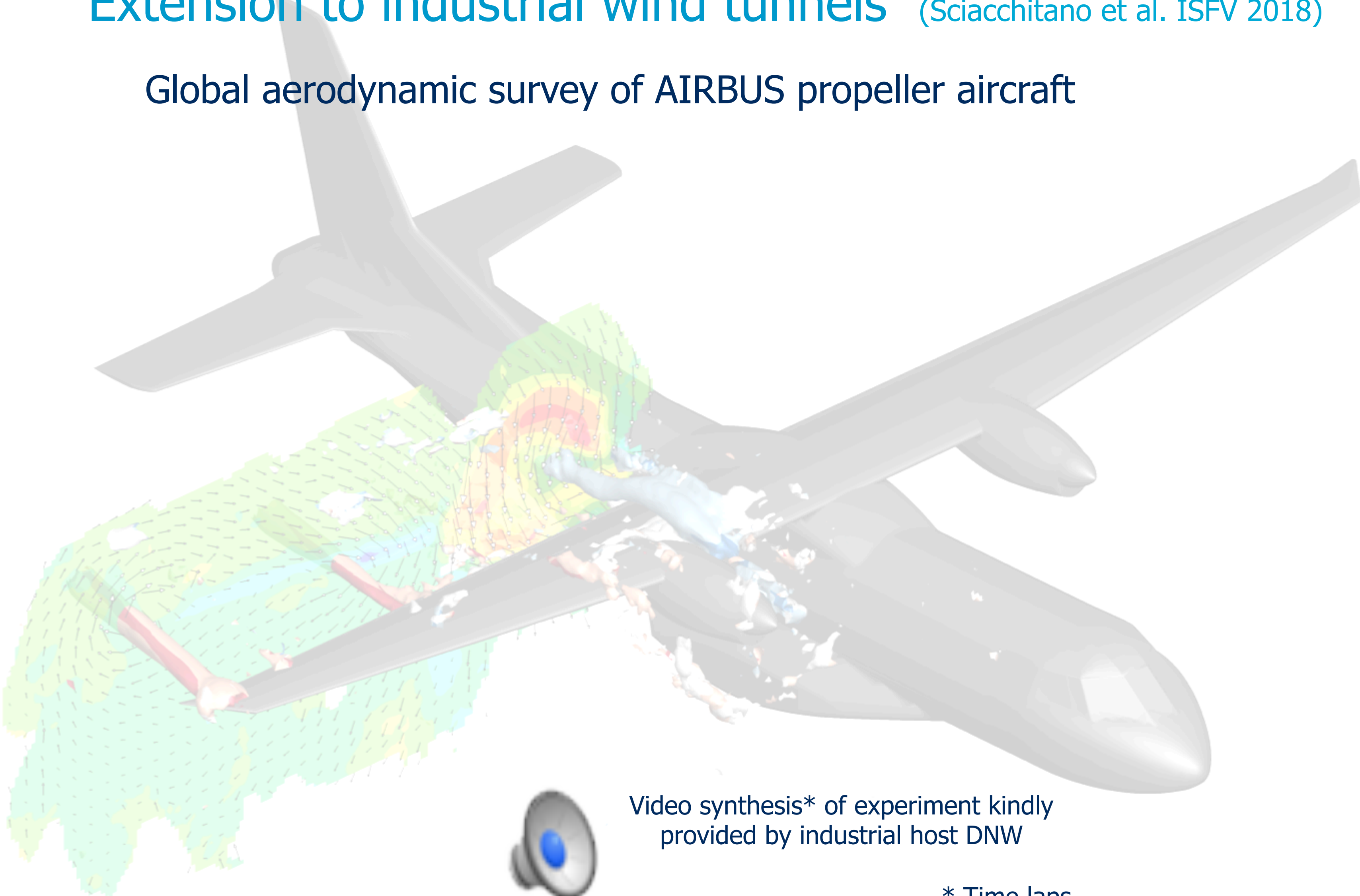
Local measurement
20 liters volume
5,000 recordings (8 s)
150,000 particle tracks

Global measurement
2,000x1,600x700 mm^3
400 views (both sides)
2x2x2 cm^3 bin size
vector spacing 5 mm
18,000,000 vectors



Extension to industrial wind tunnels (Sciacchitano et al. ISFV 2018)

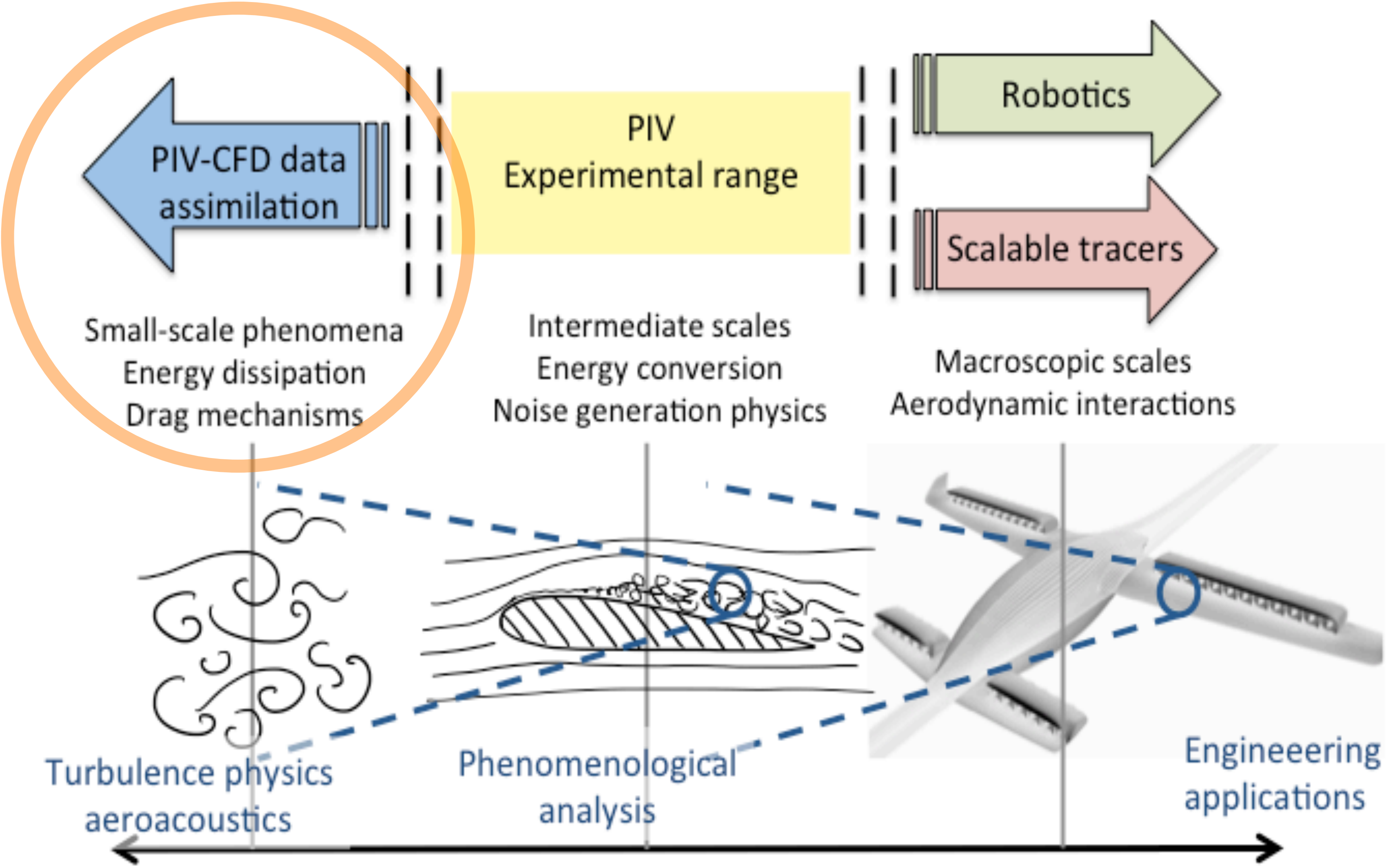
Global aerodynamic survey of AIRBUS propeller aircraft



Video synthesis* of experiment kindly provided by industrial host DNW

* Time laps

Current trends and developments



Thank you for the attention, and…