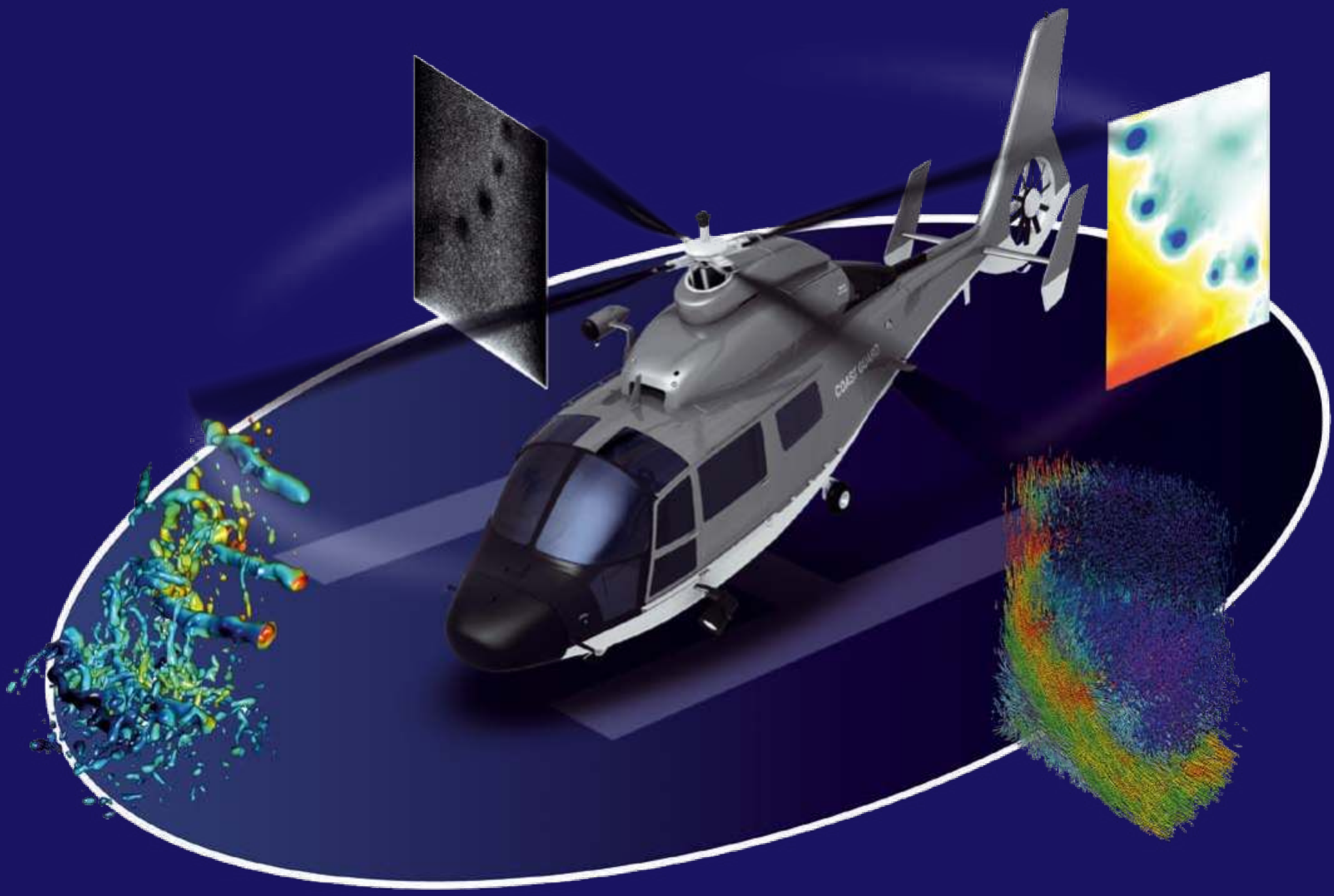


Shake-the-Box

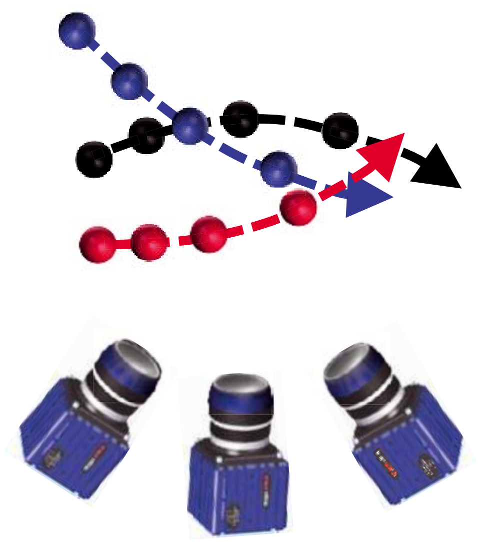
Volumetric Particle Tracking at
Highest Seeding Density

LAVISION
FOCUS ON IMAGING

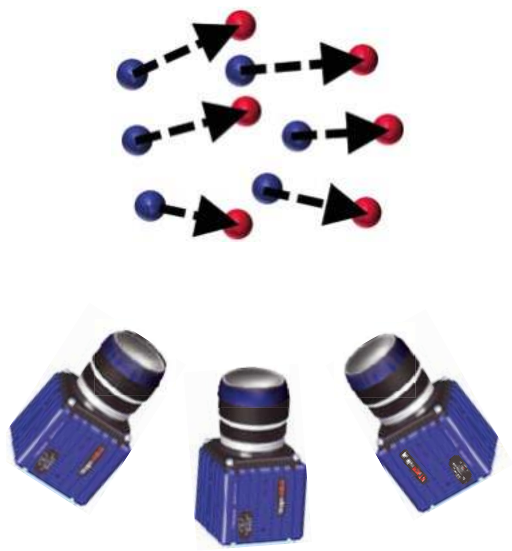
Time-resolved Shake-the-Box: Particle Tracking at Highest Seeding Density

Shake-the-Box[1,2] is the most advanced particle tracking method available today. Its most distinct feature is the accurate tracking of tracer particles at highest possible seeding density so far. The high number of tracked particles is directly related to the highest possible spatial resolution for non-intrusive velocity, vorticity, acceleration and pressure measurement.

The principles of the original **time-resolved Shake-the-Box** have been adopted for **2-pulse** and **4-pulse Shake-the-Box**[3,4] available in LaVision's DaVis 10 software. Now, for the first time, dense particle tracking is possible using standard double-frame PIV cameras with one or two light pulses in each frame. Consequently, the maximum measurable velocity is vastly increased, compared to time-resolved systems.



Time-resolved particle tracking

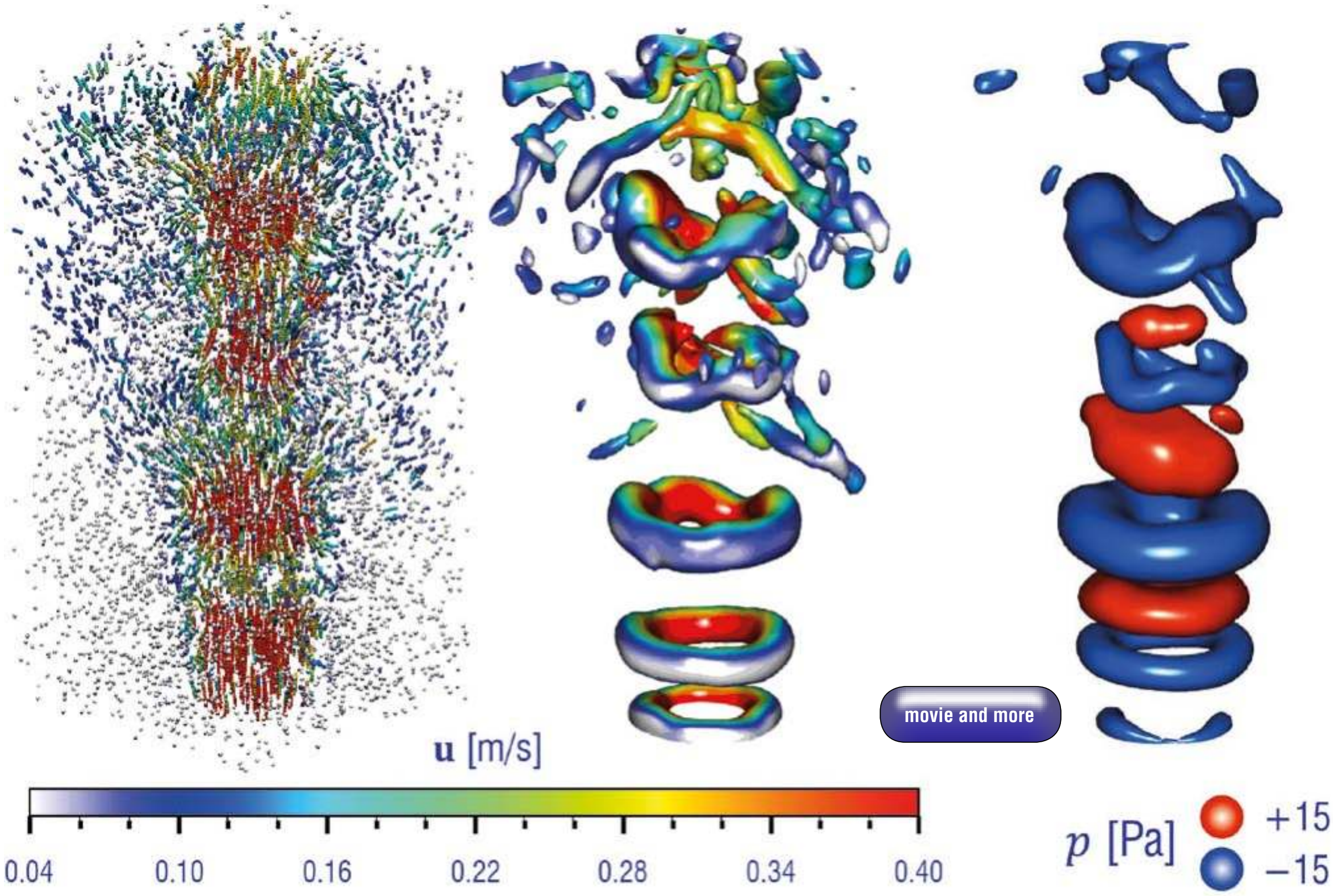


2-pulse particle tracking

Shake-the-Box experiment: helicopter in ground effect (courtesy DLR)

References:
[1] Patent: DE102013105648B3
[2] Schanz et al., „Shake-The-Box: Lagrangian particle tracking at high particle image densities", Exp. Fluids (2016) 57:70
[3] Jahn et al., „2-pulse STB: 3D particle tracking at high particle image densities", ISPIV 2017
[4] Novara et al., „Multi-exposed recordings for 3D Lagrangian particle tracking with Multi-Pulse Shake-The-Box", Exp. Fluids (2019) 60:44

Shake-the-Box Particle Tracks | **Flow Structure** Swirl strength $\lambda_2 = -2000\ s^{-2}$ | **Pressure Structure** $p - p_{avg.} = \pm 15$ Pa



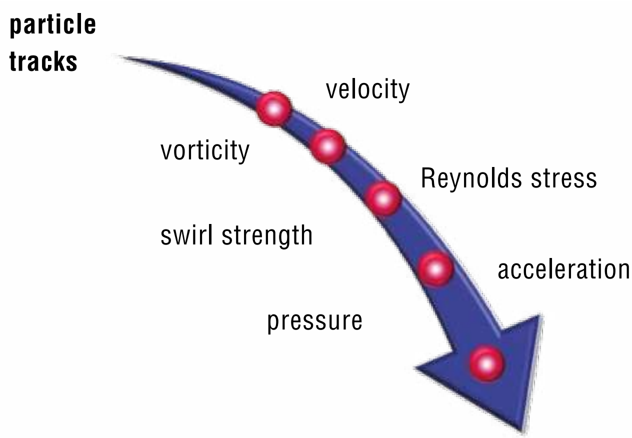
Shake-the-Box experiment: jet in water (courtesy TU Delft)

Shake-the-Box Features:

- award winning tracking method[5]
- highly accurate particle positions from iterative particle reconstruction[6]
- low computational cost – short analysis time

NEW in DaVis 10

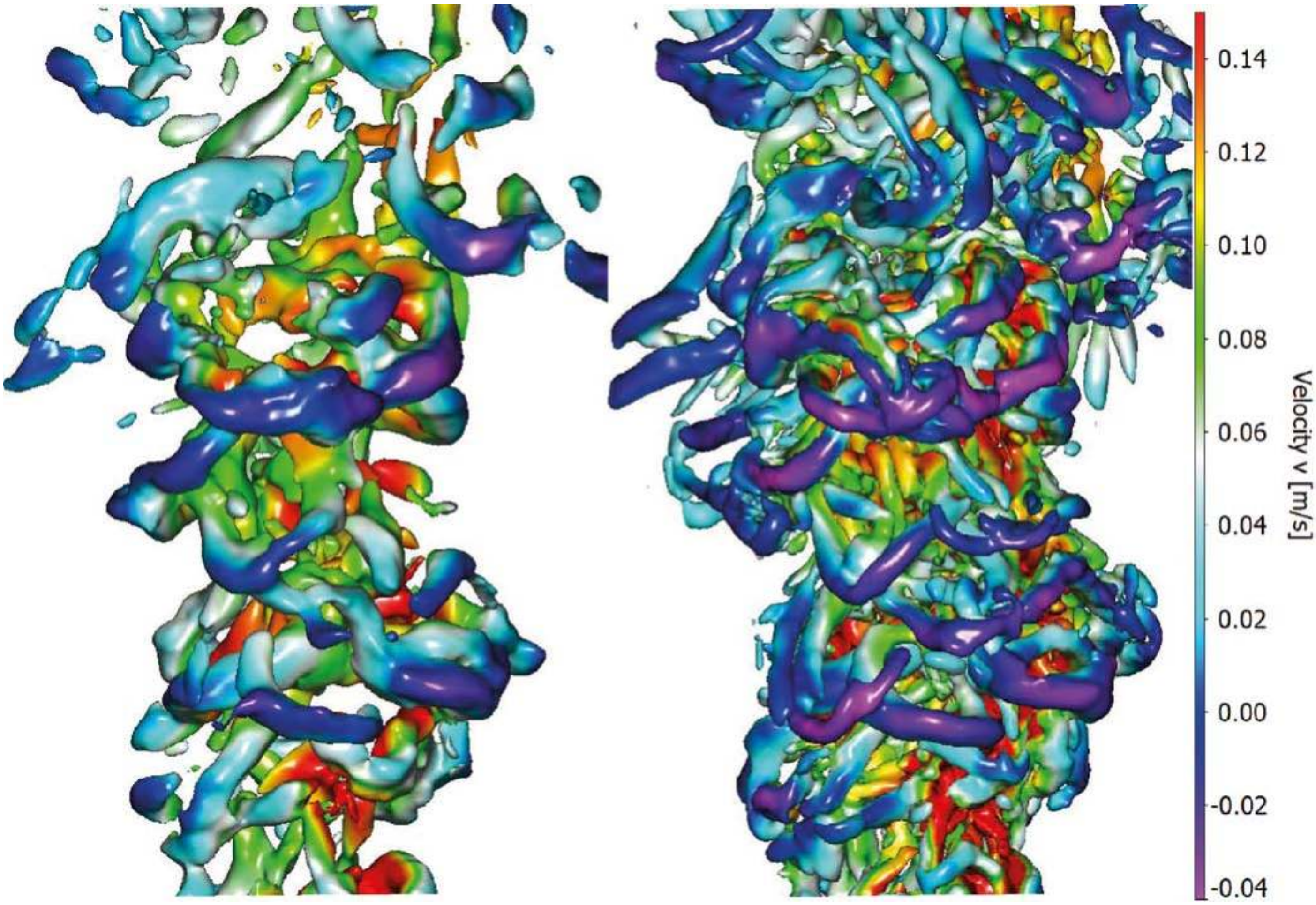
- extension of the application range with complementation of **time-resolved Shake-the-Box** with **multi-pulse Shake-the-Box**
- conversion of particle tracks to a vector grid either by data binning or by Fine Scale Reconstruction (VIC#)[7] for highest spatial resolution
- non-intrusive measurement of pressure fields with pressure from PIV[8]



References:

[5] Kähler et al., „Main results of the 4th International PIV Challenge“, Exp. Fluids (2016) 57:97
[6] Wieneke, „Iterative reconstruction of volumetric particle distribution“, Meas. Sci. Technol. (2013)
[7] Jeon et al., „4D flow field reconstruction from particle tracks by VIC# with additional constraints and multigrid approximation“, ISFV 2018
[8] van Oudheusden, „PIV-based pressure measurement“, Meas. Sc. Technol. (2013) 24

Binning | **Fine Scale Reconstruction**



Conversion of identical Shake-the-Box tracks to a regular grid with Gaussian binning (left) and with Fine Scale Reconstruction (right). The comparison shows the strength of Fine Scale Reconstruction to reveal finest flow features.

Displayed are swirling strength isosurfaces with λ_2 = -1.0 1/s², color coded by the vertical velocity component. Data taken from a large-scale thermal plume experiment[9] (recordings courtesy DLR).

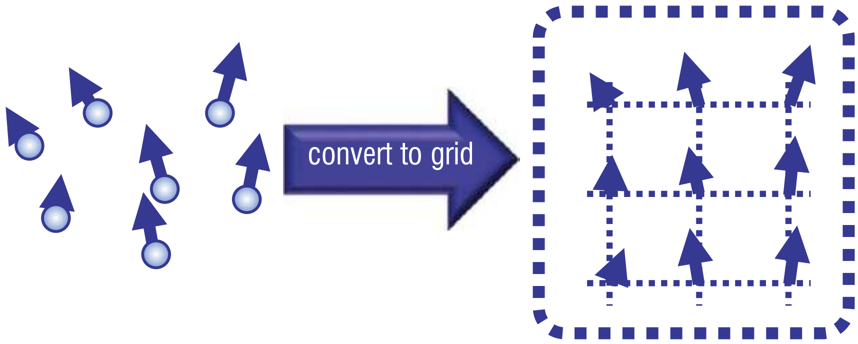
DaVis 10

Fine Scale Reconstruction is a new software feature available for **Shake-the-Box** in DaVis 10

References:

[9] Huhn et al., „Large-scale volumetric flow measurement in a pure thermal plume by dense tracking of helium-filled soap bubbles“, Exp. Fluids (2017) 58:116

Convert Particle Tracks to Data on a Regular Grid



Fine Scale Reconstruction by **data assimilation** using laws of fluid dynamics

Navier-Stokes equation:

$$\nabla p = -\rho \frac{D\mathbf{u}}{Dt} + \mu \nabla^2 \mathbf{u}$$

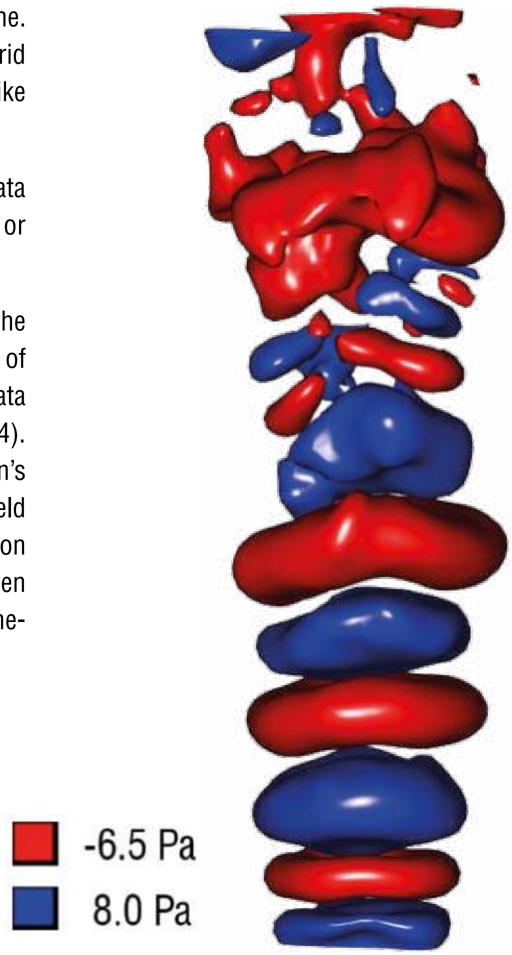
Vorticity transport equation:

$$\frac{\partial \boldsymbol{\omega}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\boldsymbol{\omega} = (\boldsymbol{\omega} \cdot \nabla)\boldsymbol{u}$$

The result of **Shake-the-Box** are particle tracks: series of particle positions over time. Polynomial fits yield velocity and acceleration data. Often, however, data on a regular grid are preferred for visualization, interpretation and the calculation of derived quantities like vorticity, pressure, spatial frequencies and many others.

The traditional technique for converting particle tracks to a regular grid is binning. Here, data at a grid point is calculated from the closest adjacent particles by Gaussian averaging or polynomial regression. Both methods are implemented in LaVision's DaVis software.

Binning has been state of the art for many years. Meanwhile LaVision has driven the development and application of far more powerful techniques. Now, two sources of information, theory in form of physical laws and experimental data, are exploited: data assimilation increases data quality and spatial resolution significantly (see figure on page 4). The combination of measured track data with the laws of fluid dynamics leads to LaVision's new **Fine Scale Reconstruction**. It converts particles tracks from **Shake-the-Box** to flow field data on a grid with an unsurpassed quality and spatial resolution. Fine Scale Reconstruction utilizes the advanced Vortex In Cell (VIC#)[7] approach. Additionally, for the first time it even enables instantaneous pressure calculation from **2-pulse Shake-the-Box** data, where time-resolved data was required before.



Pressure from 2-pulse Shake-the-Box using Fine Scale Reconstruction (recordings courtesy TU Delft)

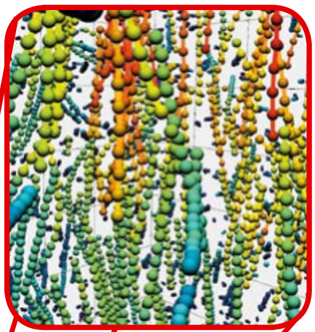
Fine Scale Reconstruction

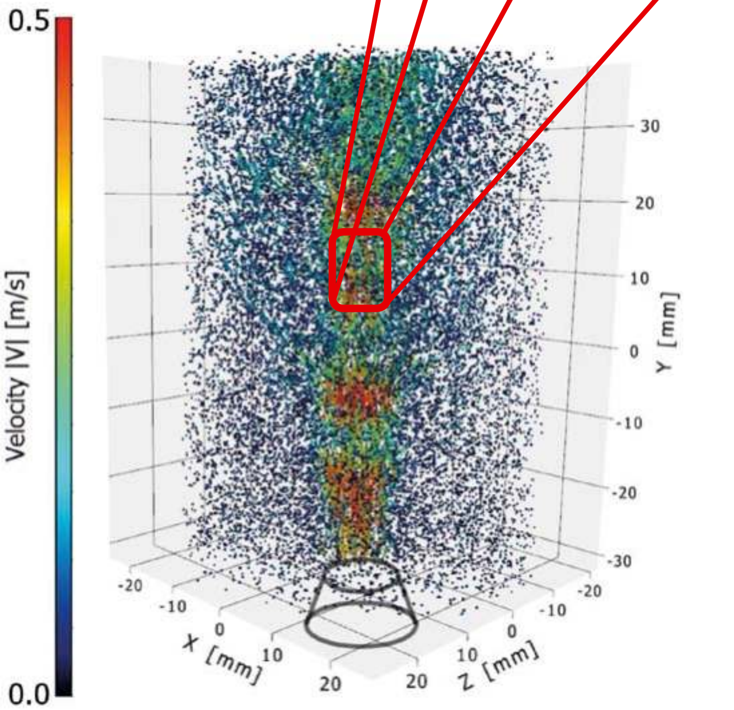
- convert **Shake-the-Box** data to Eulerian grid
- provide unsurpassed quality and spatial resolution
- use laws of fluid dynamics (Navier-Stokes equation, vorticity transport equation, incompressibility constraint) for data assimilation
- calculate pressure along with velocity and acceleration
- instantaneous pressure from **2-pulse Shake-the-Box** data (see figure on the right)

The method of choice for Lagrangian particle tracking in 3D is time-resolved **Shake-the-Box**[2]. Individual particles are tracked over multiple equidistant time steps revealing velocity and acceleration. Exploiting the temporal information, **time-resolved Shake-the-Box** ensures a minimum noise level even on acceleration data.

Derived quantities like vorticity, Reynolds stress and swirl strength are directly accessible after data conversion to a regular grid. With the new pressure from PIV package, even instantaneous and average pressure fields are available.

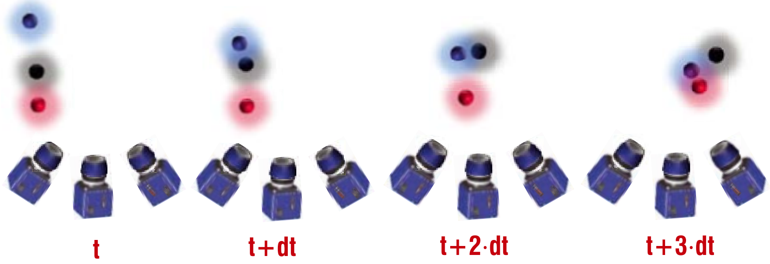
The required hardware is identical to the hardware for time-resolved Tomographic-PIV, usually including four high repetition rate cameras and a high repetition rate laser. Still, nowadays the MiniShaker in combination with the LED-Flashlight 300 is a quick and easy to use alternative for many cases.



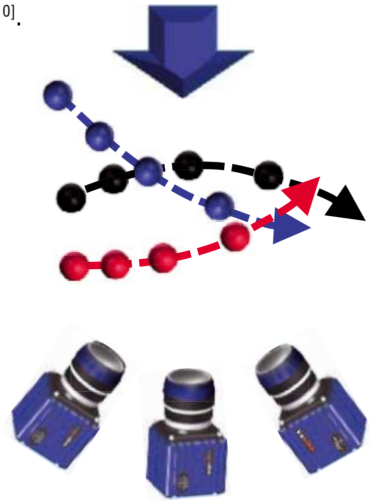


Time-resolved STB particle tracks in a water jet from a circular nozzle, particle tracks of 15 time-steps, recordings courtesy D. Violato, TU Delft

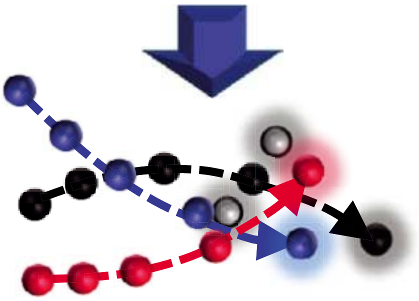
Working Principle: Time-resolved Shake-the-Box



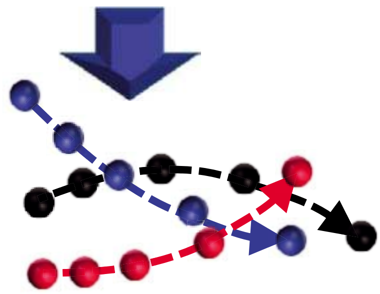
Triangulate particles from particle images in each frame of a time-resolved recording and "shake" these time-efficient into place using the optical transfer function[10].



Track the detected particles over multiple time steps and predict the particle position in the next time step.

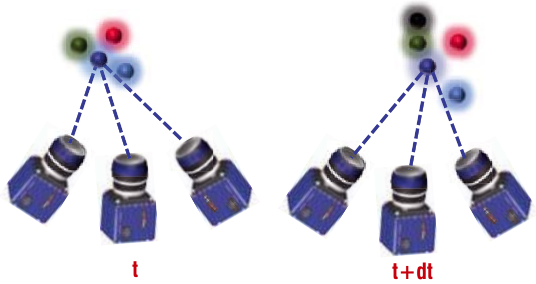


Search for the next particle position in the predicted region and "shake" the particle into place. Then, find new particles entering the region of interest on residual images after subtracting already detected particles.

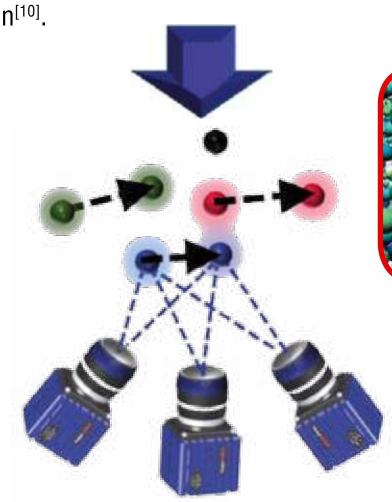


Add particles detected and tracked for at least four time steps to the final particle flow field.

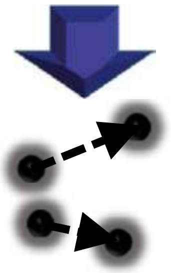
Working Principle: 2-pulse Shake-the-Box



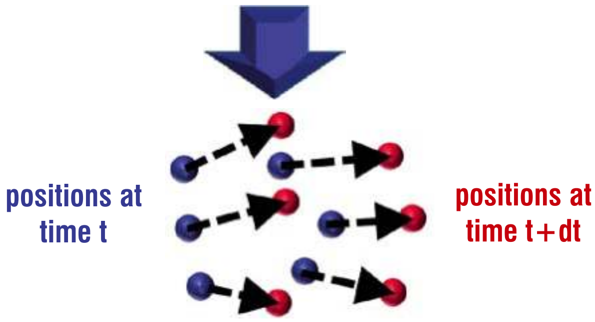
Triangulate particles from the particle images in each frame of a double-frame recording and "shake" these into place using the optical transfer function[10].



Track all matches in the double-frame images and again "shake" all particles which have a partner in the other frame into place[5].



Subtract the images of all detected particles from the camera images to find previously hidden particles by triangulation. Shake and track them. Repeat these steps on the residual camera images where the images of the particles detected so far have been subtracted.



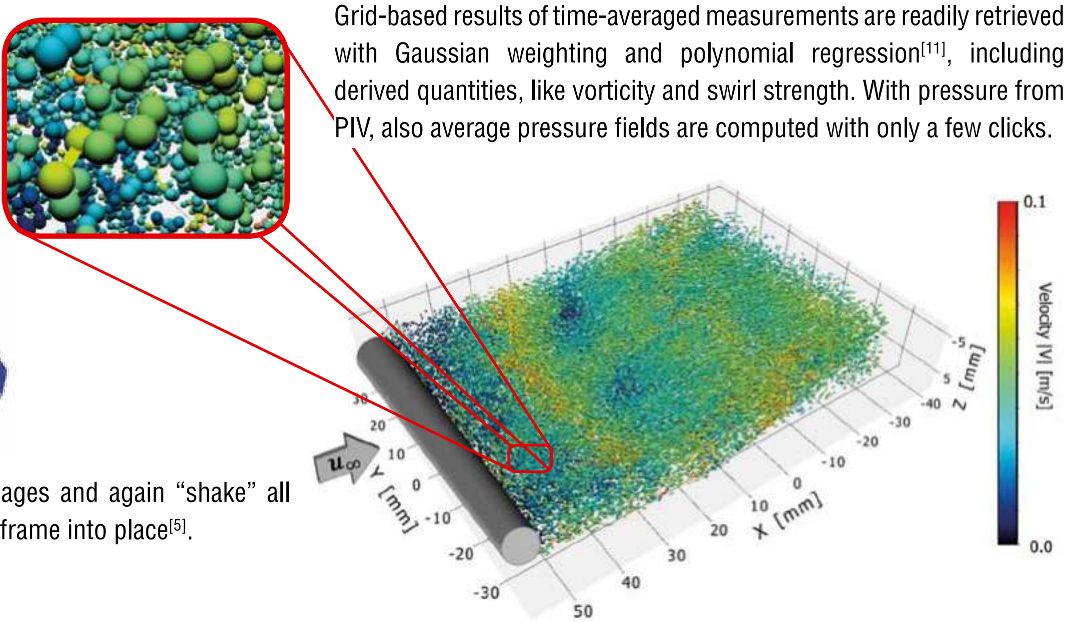
Add all particles detected and tracked in all iterations to the final particle flow field result.

The **Shake-the-Box** package is now extended with options for double-frame cameras: **multi-pulse Shake-the-Box**[3]. Here, the main objects of interest are flows containing high velocities, which can only be resolved with short pulse separations (dt) of a double-pulse laser and the short interframe-time of double-frame cameras.

The standard multi-pulse option is **2-pulse Shake-the-Box**. Here, each of the two camera frames is illuminated once and the result are tracks over the two time steps.

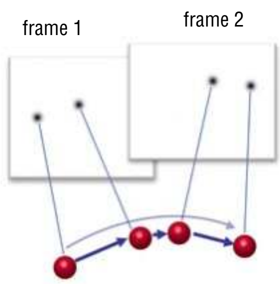
Instantaneous velocity results are directly available in the track data from **2-pulse Shake-the-Box**. Instantaneous acceleration and pressure are calculated with Fine Scale Reconstruction.

Grid-based results of time-averaged measurements are readily retrieved with Gaussian weighting and polynomial regression[11], including derived quantities, like vorticity and swirl strength. With pressure from PIV, also average pressure fields are computed with only a few clicks.



Shake-the-Box result of a double-frame particle image from a cylinder wake experiment, recordings courtesy F. Scarano, TU Delft

Also **4-pulse Shake-the-Box**[4] is now available in DaVis. Here, each camera frame is illuminated twice. Two positions of the particle in the 1st frame are matched with the two positions of the same particle in the 2nd frame. The result is a multi-pulse track containing four positions for each particle, leading to increased velocity precision and direct access to instantaneous acceleration.



Multi-pulse Shake-the-Box principle using four pulses

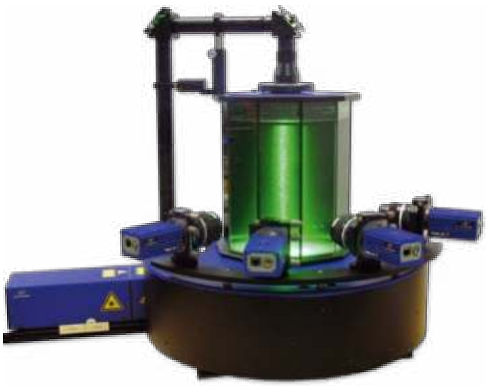
4-pulse Shake-the-Box requires the same hardware as the 2-pulse version and a second double-pulse laser. Timing and synchronization of all pulses and the camera exposures are conveniently controlled by LaVision's Programmable Timing Unit via DaVis.

References:

[10] Schanz et al. „Non-uniform optical transfer functions in particle imaging: calibration and application to tomographic reconstruction" Meas. Sci. Technol. 24 (2013) 024009

[11] Jiménez et al., „On the performance of particle tracking", J. Fluid Mech. (1987) 185:447-468

Shake-the-Box Imaging System



Modular and Upgradable Shake-the-Box Solutions

LaVision provides a complete range of flexible and modular **Shake-the-Box** systems and components for an integrated “easy to use” solution for your application. The modular system enables a straightforward upgrade from all LaVision PIV, Stereo-PIV and Tomographic PIV systems to a **Shake-the-Box** system.

From Flow Illumination to Volumetric Flow Field Data

Laser

- same standard laser used in traditional PIV systems
- low repetition rate: larger volumes, smaller seeding particles
- high repetition rate: time-resolved 4D flow field imaging

Volume Illumination Optics for Laser

- collimated illumination up to 50 x 100 mm²
- adjustable divergent optics for larger volumes
- higher illumination levels with multi-pass arrangements

LED Illumination

- volumetric illumination for water applications and Helium-filled soap bubbles
- up to 20 kHz illumination rate
- high power overdrive mode
- no laser safety requirements
- white and blue version available, blue is optimal for fluorescent tracer particles in water applications avoiding background reflections in camera images

Cameras

- all LaVision PIV camera models are supported
- Imager sCMOS for high resolution and highest sensitivity
- 2 - 8 camera imaging systems possible
- straightforward upgrade from 2 up to 8 cameras
- increased scope of application with DaVis 10: **Shake-the-Box** is even available for double-frame cameras and double-pulse lasers
- MiniShaker camera series optimized for **Shake-the-Box** measurements: easy-to-use, wide application range ensured by multiple models

FlowMaster Shake-the-Box Main Performance Features:

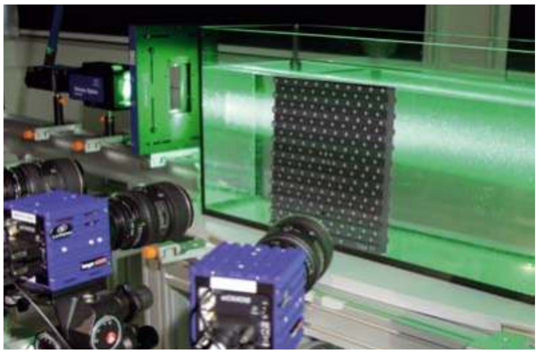
- 3D imaging system with highest spatial resolution powered by advanced iterative particle reconstruction and volume self-calibration
- suitable for measurements in low and high-speed flows and for time-resolved recordings for 4D flow analysis
- upgradable and versatile multi camera imaging concept

Camera Scheimpflug Adapters for Oblique Viewing

- independent adjustment for Scheimpflug angle and optical axis
- motorized and software controlled models
- rigid construction supporting sub-pixel imaging without jiggling

3D Calibration Targets

- highly accurate double-sided calibration targets
- single view calibration, **no scanning required**
- calibration active on both sides
- one target position sufficient for volume calibration



Synchronizer and Timing Unit

- multi-channel **P**rogrammable **T**iming **U**nit (**PTU X**)
- versatile combination of low- and high-speed lasers and multiple cameras
- precise synchronization even for varying external triggers
- designed for demanding experiments with complex trigger schemes
- fully integrated device trigger generation in **DaVis**
- software controlled PIV-dt and phase scans

DaVis Shake-the-Box Software Package

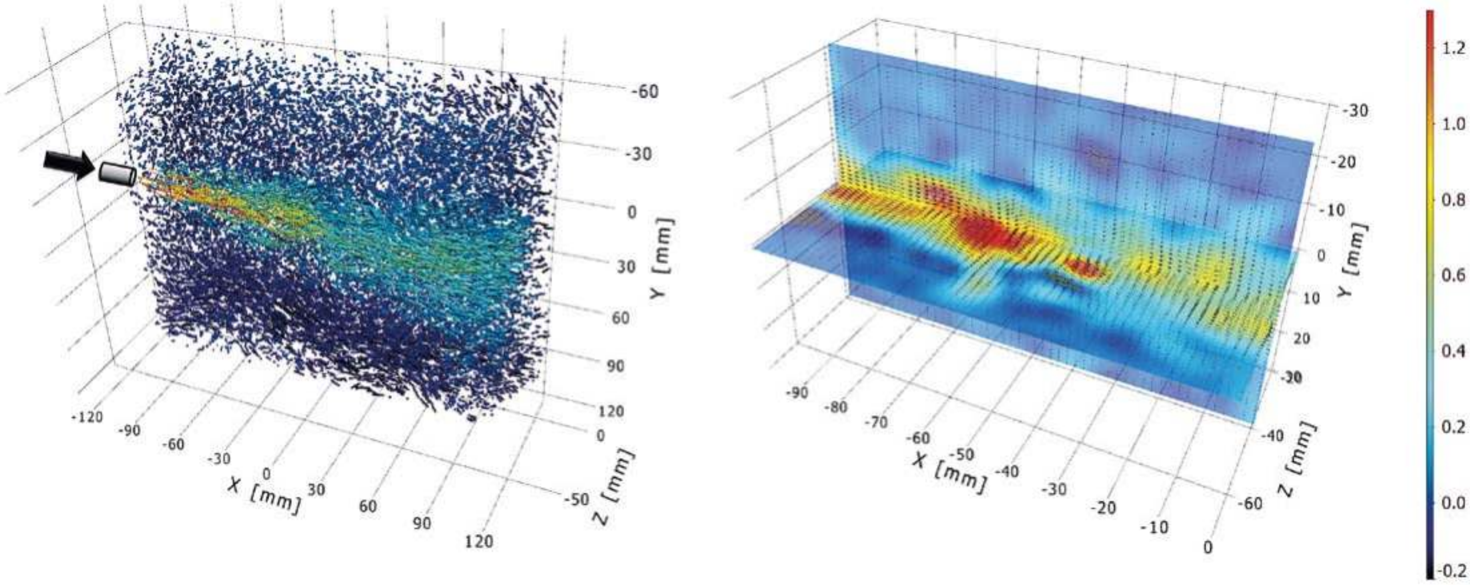
- award winning **Shake-the-Box** particle tracking of highest quality
- time-resolved, 2-pulse and 4-pulse options
- lowest calibration errors with patented **volume self-calibration**
- massive parallel processing: support of multi-processor PCs
- **Fine Scale Reconstruction** (conversion to grid) for outstanding precision and spatial resolution
- powerful post-processing and 3D display features incl. avi-movies
- upgradable from the universal DaVis FlowMaster PIV package
- Matlab® and TecPlot® Add-on for customized analysis and outstanding 3D visualization
- **pressure** field computation from **Shake-the-Box** data (optional)

MiniShaker and LED Illumination

The 3D camera MiniShaker is designed for **time-resolved Shake-the-Box** measurements up to 5 m/s and **double-frame Shake-the-Box** up to 50 m/s. Compared to a system with discrete cameras, the setup requires only a fraction of time.

Combined with the high-power LED-Flashlight 300, flow fields of 50 x 30 x 15cm³ and more can easily be measured time-resolved at 500 Hz. Without regulations imposed by laser safety making it not only a valuable probe but also an easy to use and instructive system for education purposes.

The MiniShaker paves the way to readily-obtainable 3D measurements. Four sensors are aligned in a compact housing and fully integrated into LaVision's DaVis software. To avoid complicated cabling both power supply and data transfer employ USB 3.0 interfaces.

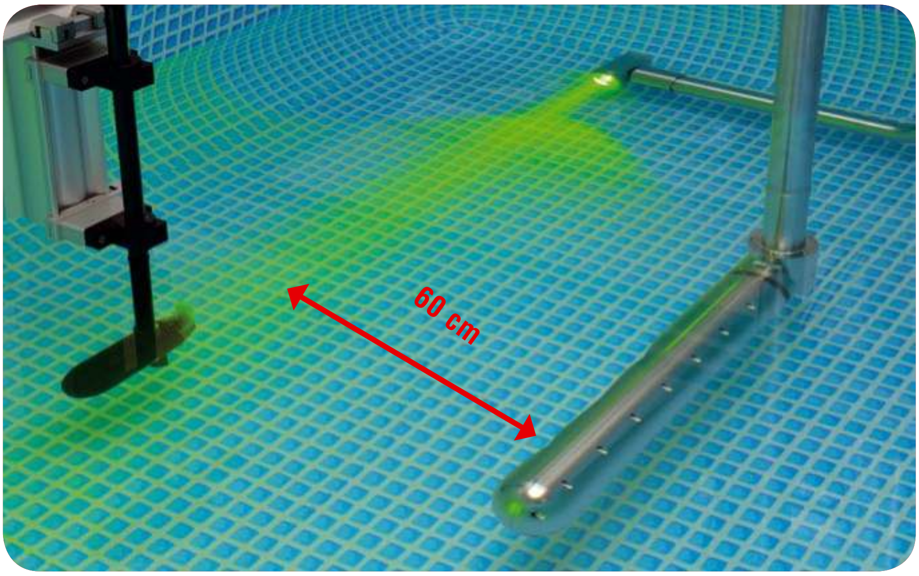


Water jet in a fish tank measured with MiniShaker TR and LED-Flashlight 300, left: particle tracks over +/- 10 time steps clipped to the jet position, right: instantaneous data at the nozzle exit retrieved with Fine Scale Reconstruction on a grid with 1 mm resolution, horizontally only every 2nd velocity vector is displayed.

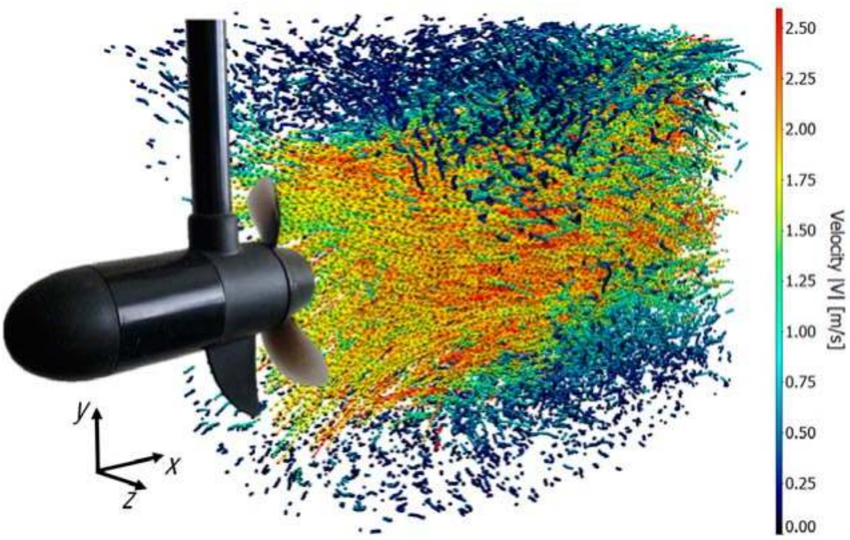
MiniShaker TR

LED-Flashlight 300

movie and more

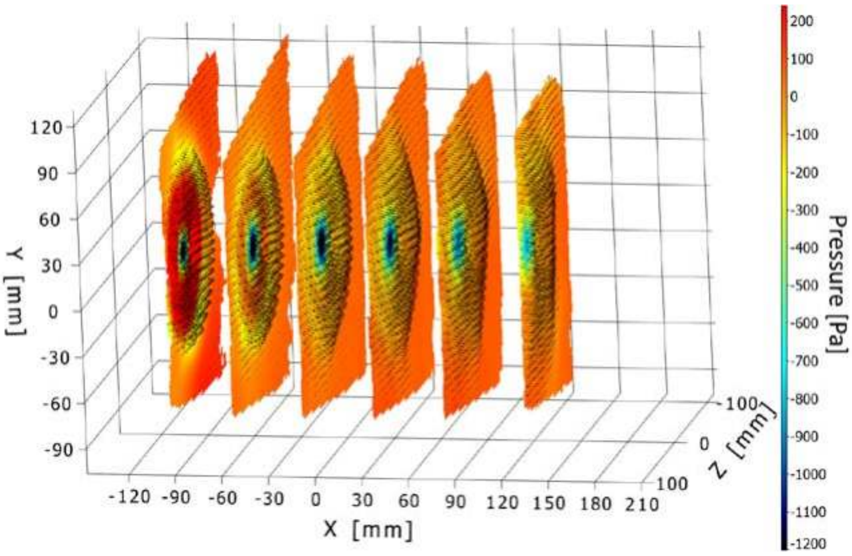


The 4-camera system MiniShaker Underwater with Underwater Volume Optics measuring a propeller wake.



Shake-the-Box Underwater

A completely modular system design enables a wide variety of options for using **Shake-the-Box** in underwater applications like in towing tanks or cavitation tunnels. Either modules with remote control of camera lenses and Scheimpflug adapters can be used or the MiniShaker Underwater with a fixed working distance and maintenance free optics. Thanks to volume self-calibration, reliable measurements are retrieved even in these vibration intense environments.



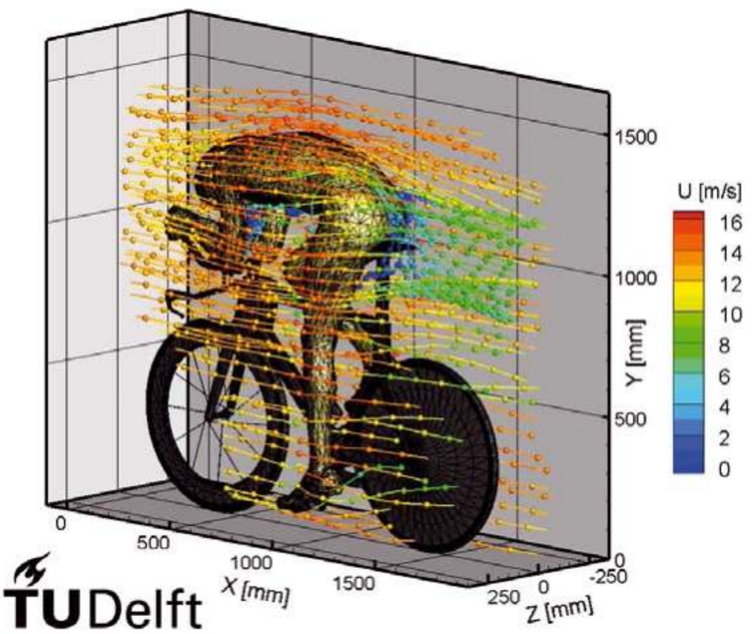
Particle tracks over 15 time steps (top) and instantaneous pressure data based on Fine Scale Reconstruction (bottom) of the flow behind a propeller measured with the MiniShaker Underwater

MiniShaker Aero Robotic

The aerodynamically optimized MiniShaker Aero mounted on a robotic arm combined with LaVision's volume self-calibration and **Shake-the-Box** software is a system for easy installation and calibration. Full-scale flow fields around large objects are recorded in a short period of time.

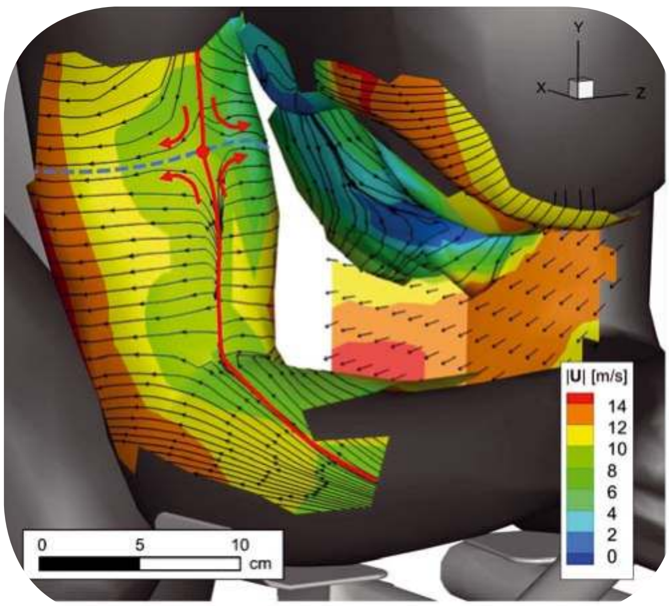
The MiniShaker with 4 cameras enclosed in a rigid housing makes a single calibration sufficient for measurements at multiple positions. At each position of the robotic arm, volumetric data are acquired, which is then stitched together to a single large-scale flow field. Coaxial illumination delivered by a laser fiber with its exit in the MiniShaker head enables measurements even in occluded areas.

MiniShaker Aero on a robotic arm



Streamlines measured with Shake-the-Box around a full-sized cyclist, courtesy TU Delft[12]

movie and more



Near-surface streamlines, close-up at elbow[13]

References:
[12] Jux et al., „Robotic volumetric PIV of a full-scale cyclist", Exp. Fluids (2018) 59:74
[13] Schneiders et al., „Coaxial volumetric velocimetry", Meas. Sci. Technol. (2019)

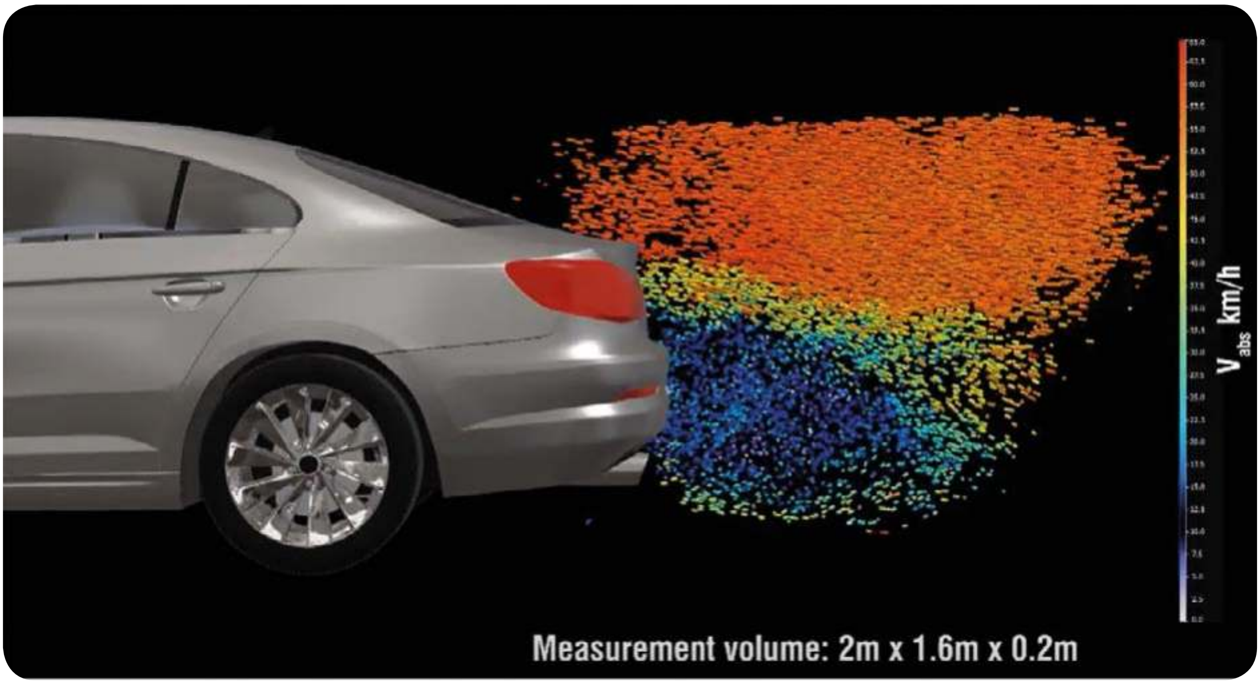
Accessing Large Scales with Helium-filled Soap Bubbles

Compared to common air-flow seeding with oil aerosol of 1 µm diameter, Helium-filled soap bubbles (HFSB) increase the scattering signal by a factor of more than 10000[14]. Now, **time-resolved** or **multi-pulse Shake-the-Box** and Tomographic PIV measurements become possible for measurement volumes even larger than 1 m³.

- typically 4 cameras
- high-speed laser or high-power LED illumination for time-resolved measurement
- double pulse laser for **2-pulse Shake-the-Box**
- for large fields of view and deep volumes
- Fluid Supply Unit with remote seeding control

Fluid Supply Unit with remote control


Aerodynamically optimized linear nozzle array for HFSB seeding



Measurement in the wake of a full-scale Volkswagen Sedan (courtesy VW)

movie and more

References:

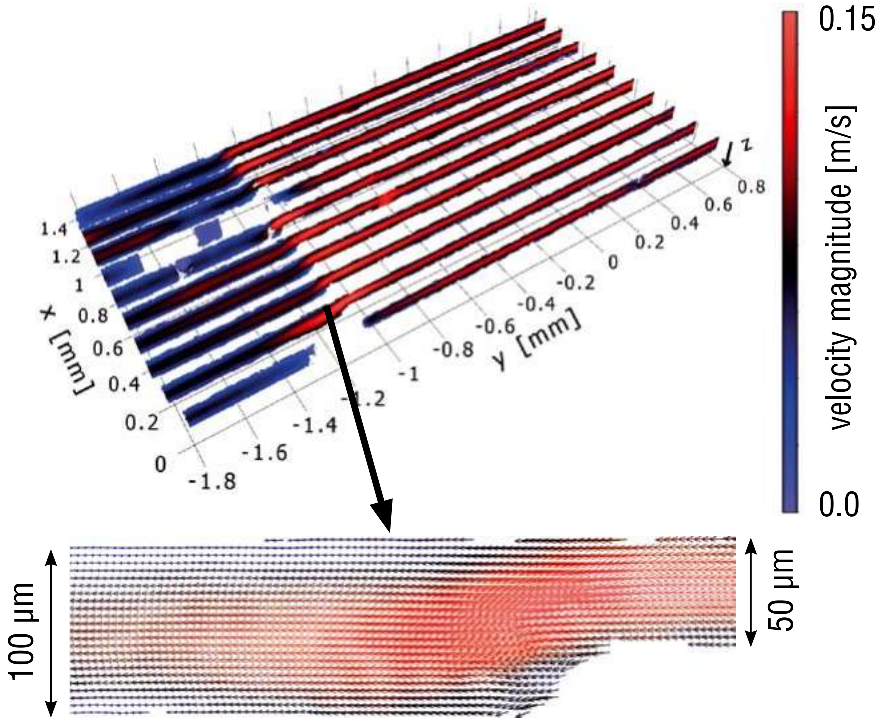
[14] Caridi, PhD Thesis, TU Delft (2018)

Shake-the-Box: Volumetric Measurements at Microscopic Scale

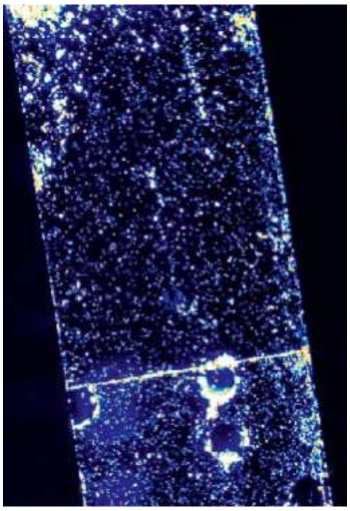
Shake-the-Box has unique strengths for microscopic measurements in 3D. Especially for flows with strong shear stress, as commonly present in microchannels, **Shake-the-Box** ensures the best measurement quality by tracking individual particles[15].

- xyz-motorization of microscope
- easy planning and repetition of measurement positions
- light delivered to the microscope via an optical fiber
- readily exchangeable filter cubes for different excitation and emission wavelengths for the use of fluorescent tracers

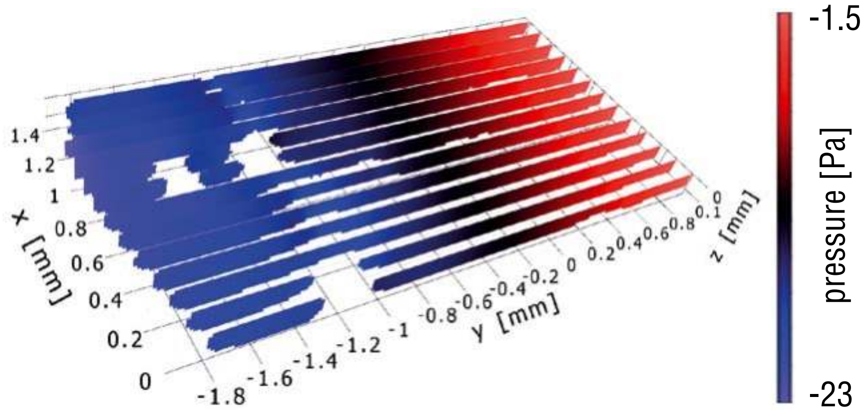
Setup for Micro-Shake-the-Box



Backward facing step: Shake-the-Box measurement converted to a grid



Particle image:
backward-facing step with three major and numerous smaller air bubbles in the channel



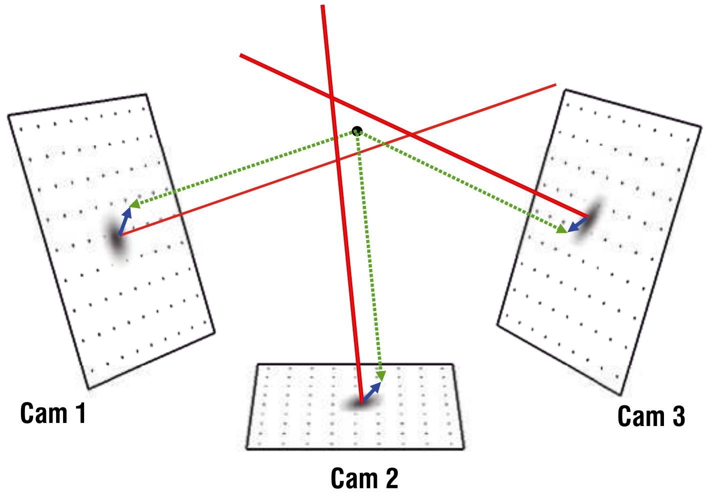
Time-averaged pressure field

References:

[15] Hesseling et al., „Volumetric Microscopic Flow Measurement with a Stereoscopic Micro-PIV System“, ISPIV 2019

High Precision Camera Calibration for 3D Reconstruction

A precise volumetric calibration based on a calibration target is required for 3D particle tracking and tomographic imaging applications. For **Shake-the-Box** and Tomographic-PIV the calibration accuracy needs to be better than 0.1 pixel throughout the measurement volume[2,5].



Challenge

Camera mounts or other mechanical parts are never 100% stiff. Temperature-changes cause extension or contraction of mechanical parts, wind loads or other vibration sources affect the camera adjustment. Unnoticed, in many experiments, the initial volume calibration will have become inaccurate at the time of measurement.

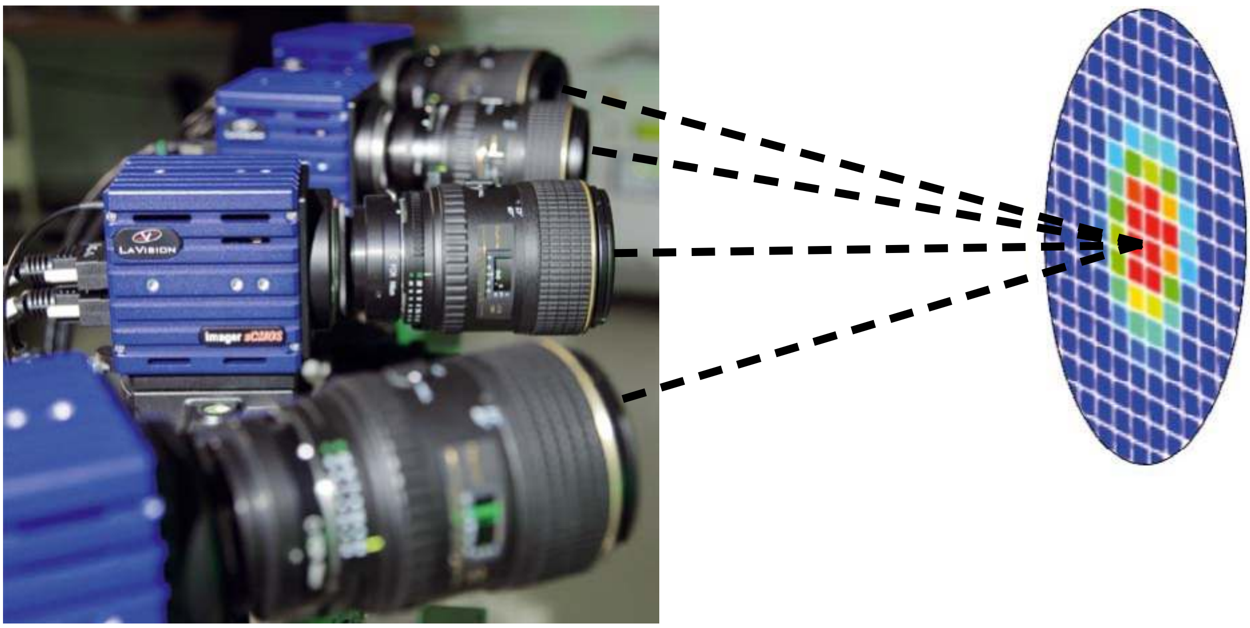
Solution

LaVision's patented[16] **volume self-calibration**[17] allows the detection and correction of calibration inaccuracies using the tracer particle recordings themselves. Misalignments are corrected and the required calibration accuracy is recovered.

Volume Self-Calibration

Due to inaccuracies in the calibration function, particles in the volume are imaged at slightly offset positions in the camera images. Averaging these differences for many particles in a local subvolume, 3D disparity maps are generated and the calibration function is corrected accordingly.

This widely accepted volume self-calibration procedure provides a check for and a remedy of possible calibration problems and is an **indispensable pre-processing step for Shake-the-Box and Tomographic PIV.**



References:
[16] Patents: EP 1 926 049, US 8,120,755
[17] Wieneke, „Volume self-calibration for 3D particle image velocimetry", Exp. Fluids (2008) 45:549

Volumetric Flow Analysis Techniques

Particle images	Processing 1	Processing 2	Processing 3	Result	Velocity	Vorticity	Acceleration	Instant. pressure
Time-resolved	Tomo-PIV (SMTE)			Grid	✓	✓	✗	✗
Time-resolved	Shake-the-Box			Tracks	✓	✗	✓	✗
Time-resolved	Tomo-PIV (SMTE)	Pressure from PIV		Grid	✓	✓	✓	✓
Time-resolved	Shake-the-Box	Binning		Grid	✓	✓	✓	✗
Time-resolved	Shake-the-Box	Binning	Pressure from PIV	Grid	✓	✓	✓	✓
Time-resolved	Shake-the-Box	Fine Scale Reconst. VIC#		Grid	✓	✓	✓	✓
2-pulse	Tomo-PIV (MTE)			Grid	✓	✓	✗	✗
2-/4-pulse	Shake-the-Box			Tracks	✓ / ✓	✗ / ✗	✗ / ✓	✗ / ✗
2-/4-pulse	Shake-the-Box	Binning		Grid	✓ / ✓	✓ / ✓	✗ / ✓	✗ / ✗
2-/4-pulse	Shake-the-Box	Fine Scale Reconst. VIC#		Grid	✓ / ✓	✓ / ✓	✓ / ✓	✓ / ✓

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LaVisionUK Ltd
2 Minton Place / Victoria Road
Bicester / Oxon / OX26 6QB / United Kingdom
E-Mail: sales@lavisionuk.com
www.lavisionUK.com
Phone: +44-(0)-870-997-6532
Fax: +44-(0)-870-762-6252

LaVision GmbH
Anna-Vandenhoeck-Ring 19
D-37081 Göttingen / Germany
E-Mail: info@lavision.com
www.lavision.com
Tel.: +49-(0)5 51-9004-0
Fax: +49-(0)551-9004-100

LaVision Inc.
211 W. Michigan Ave. / Suite 100
Ypsilanti, MI 48197 / USA
E-Mail: sales@lavisioninc.com
www.lavision.com
Phone: (734) 485 - 0913
Fax: (240) 465 - 4306