8. Principles of Phase Doppler Anemometry

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http://www.dantecmt.com

General features of PDA

- Extension of the LDA principle
- Simultaneous measurement of velocity (up to 3 components) and size of spherical particles as well as mass flux, concentration etc.
- First publication by Durst and Zaré in 1975
- First commercial instrument in 1984
- Non-intrusive measurement (optical technique), on-line and in-situ
- Absolute measurement technique (no calibration required)
- Very high accuracy
- Very high spatial resolution (small measurement volume)

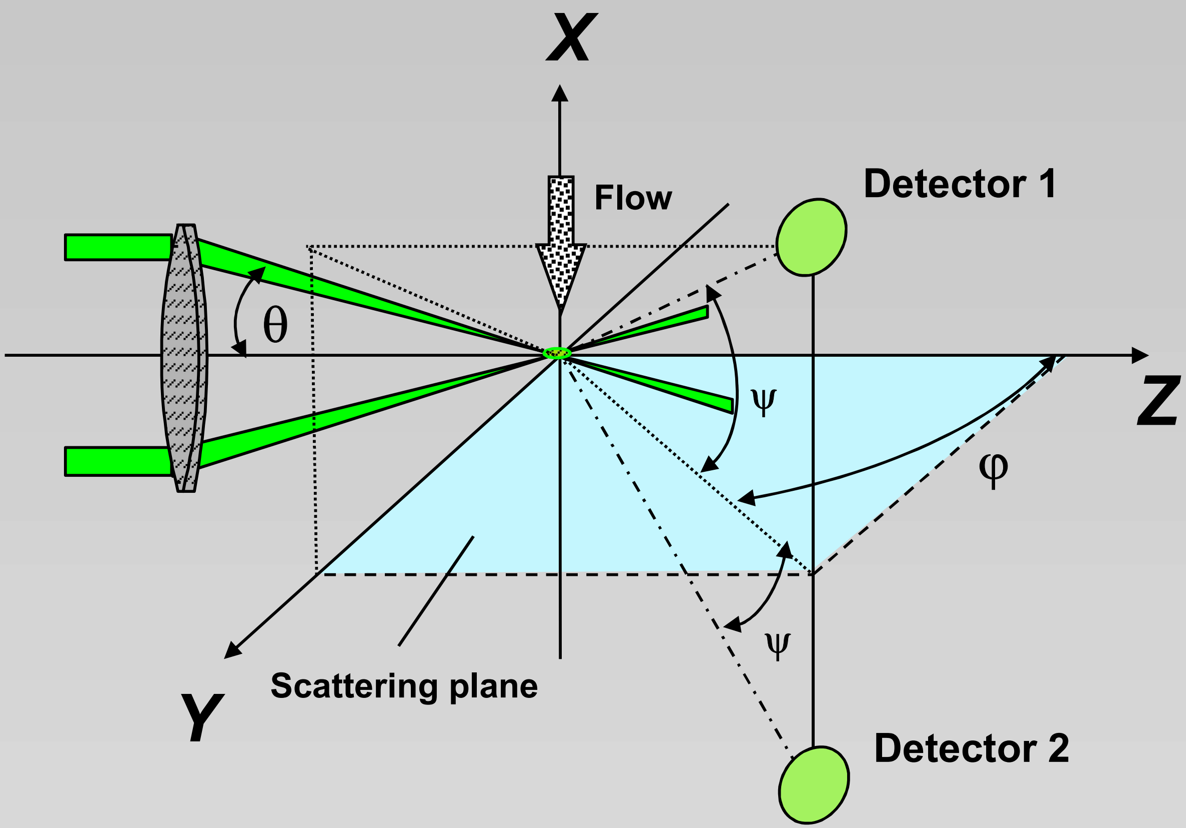
Preconditions for the application of PDA

- Optical access to the measurement area (usually from two directions)
- Sphericity of particles (droplets, bubbles, solids)
- Homogeneity of particle medium
  (slight inhomogeneities may be tolerated if the concentration of the inhomogeneities is low and if the size of the inhomogeneities is much smaller than the wavelength used)
- Refractive indices of the particle and the continuous medium must usually be known
- Particle size between ca. 0.5 µm and several millimeters
- Max. particle number concentration is limited

Principle setup of PDA

Optical parameters of a PDA setup:

- Beam intersection angle θ
- Scattering angle φ
- Elevation angle ψ
- Polarization
  (parallel or perpendicular to scattering plane)
- Shape and size of detector aperture



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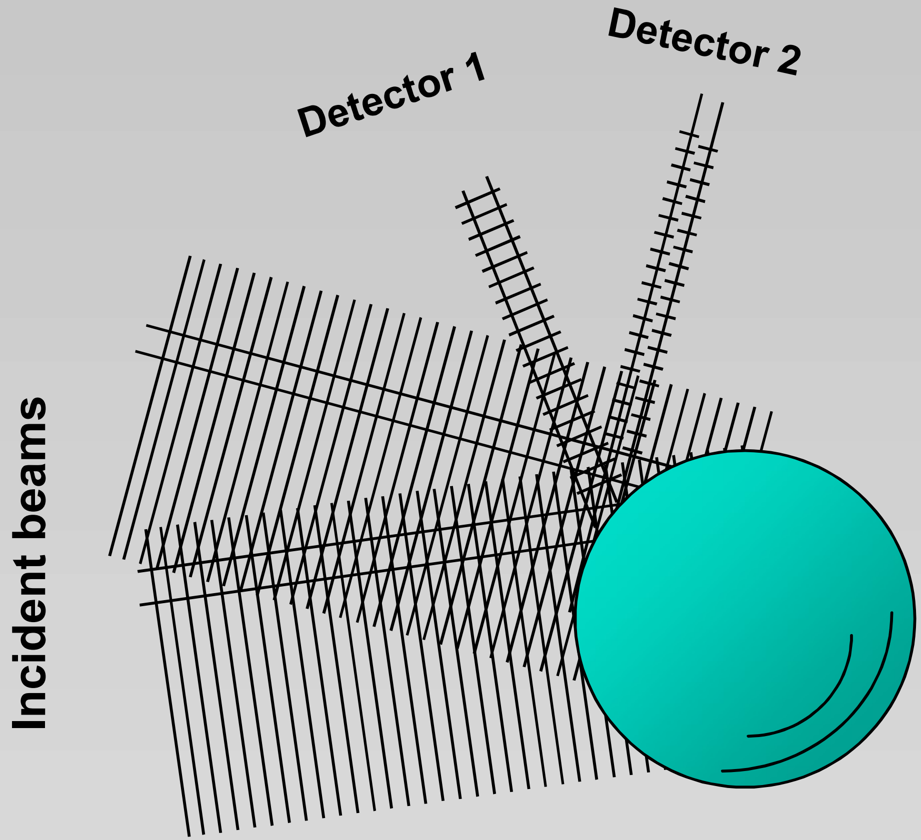
Optical principle of PDA

- A particle scatters light from two incident laser beams
- Both scattered waves interfere in space and create a beat signal with a frequency which is proportional to the velocity of the particle
- Two detectors receive this signal with different phases
- The phase shift between these two signals is proportional to the diameter of the particle



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Light scattering principles

The principle of the PDA technique is the scattering of plane lightwaves by spherical particles.

A lightwave is fully described by:

- wavelength
- intensity
- polarization
- phase

Scattering is composed of:

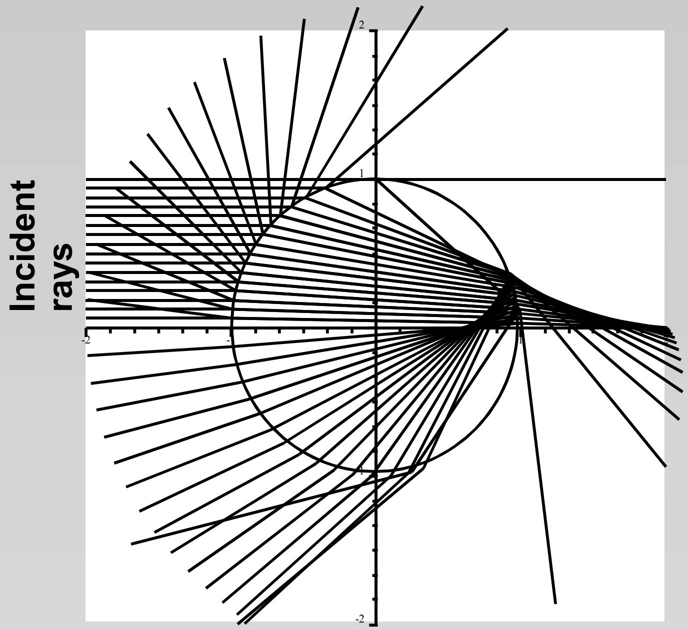
- diffraction
- reflection
- refraction
- absorption

An exact description of the scattering of light by a homogeneous sphere is given by the full solution of Maxwell´s equations formulated by Mie in 1908.

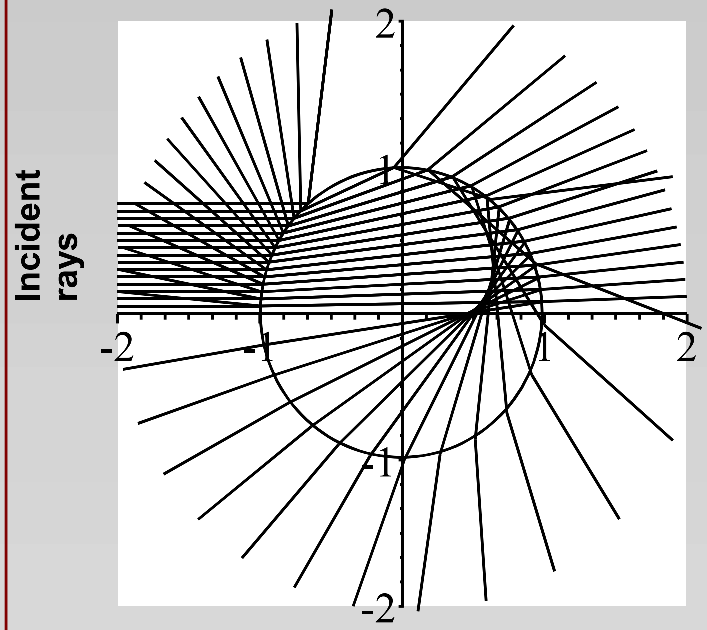
Geometric optics (Snell´s law) is a simplified way to describe light scattering.

Light scattering by droplets and bubbles

Water droplet in air



Air bubble in water



Phase relationships

The phase shift between two detectors is:

For reflection:

$$\Phi = \frac{2\pi d_p}{\lambda} \frac{\sin\theta \sin\psi}{\sqrt{2(1-\cos\theta \cos\psi \cos\phi)}}$$

For 1st order refraction:

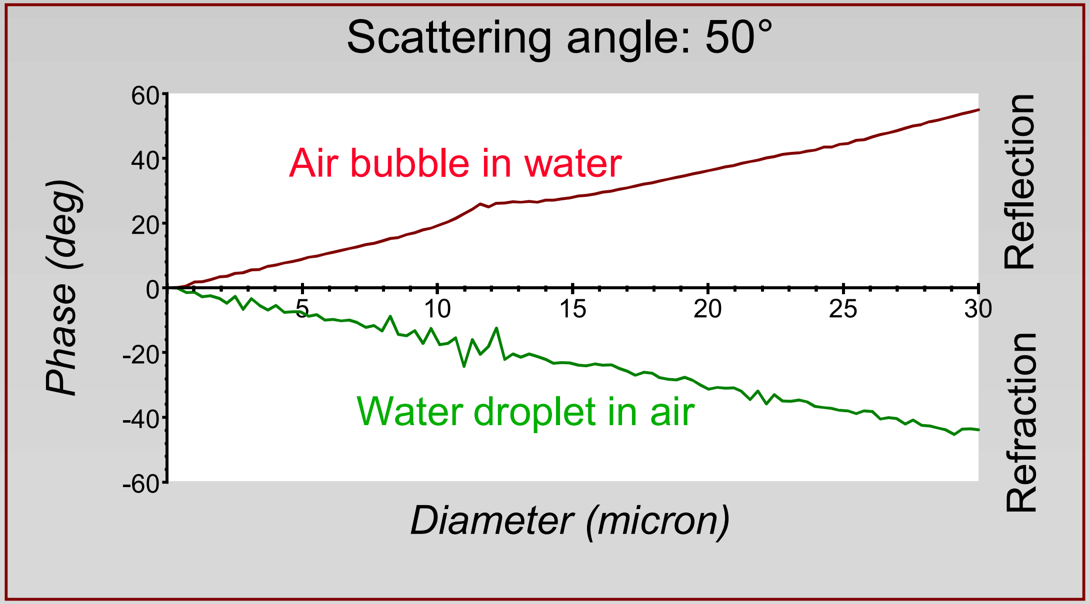
$$\Phi = \frac{-2\pi d_p}{\lambda} \frac{n_{rel} \sin\theta \sin\psi}{\sqrt{2(1+\cos\theta \cos\psi \cos\phi)(1+n_{rel}^2 - n_{rel}\sqrt{2(1+\cos\theta \cos\psi \cos\phi)})}}$$

No calibration constant is contained in these equations.

Phase - diameter linearity

- A linear relationship between measured phase difference and particle diameter only exists, if the detector is positioned such that one light scattering mode dominates.

- Simultaneous detection of different scattering modes of comparable intensity leads to non-linearities in the phase-diameter relationship.



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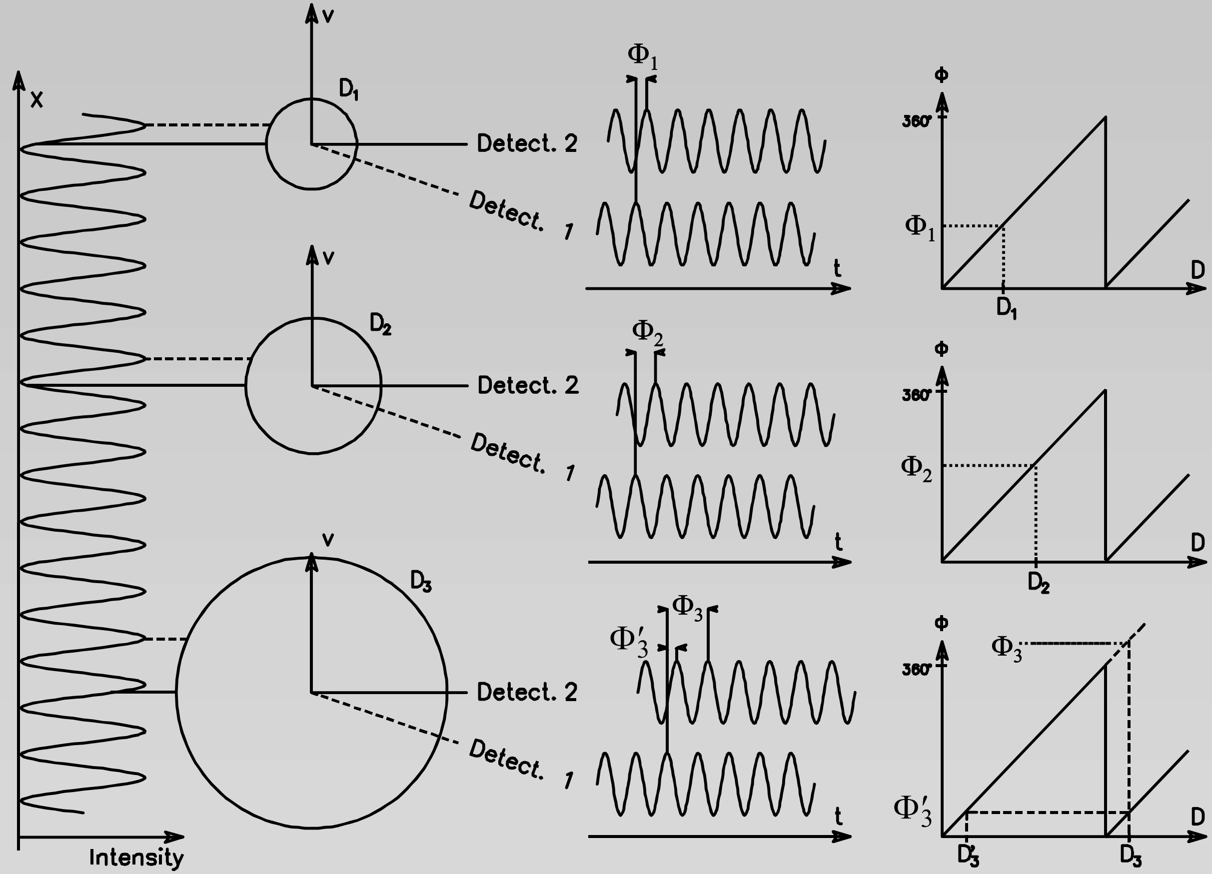
2π ambiguity in a two-detector system

- The phase difference increases with increasing particle size.
- Since phase is a modulo 2π function, it cannot exceed 2π, i.e. 360°.
- Therefore, if a particle has a size that causes the phase to go beyond a 2π jump, a two-detector PDA cannot discriminate between this size and a much smaller particle.



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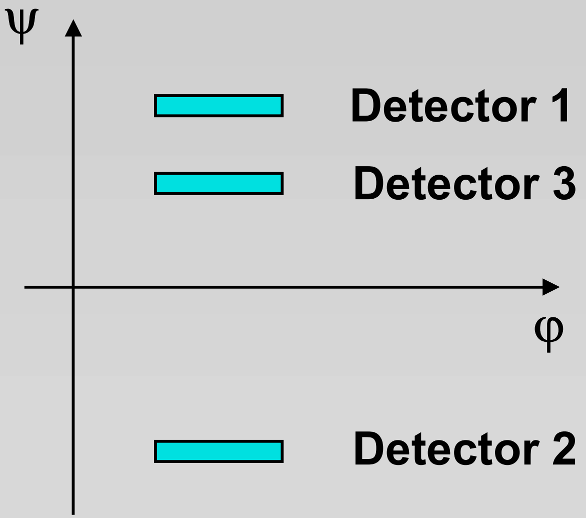
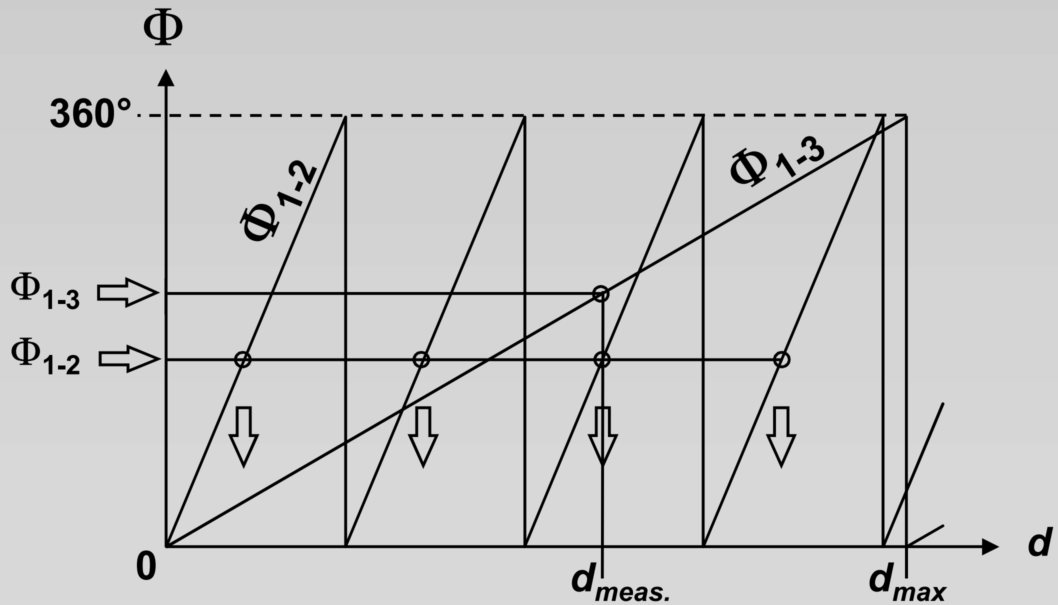
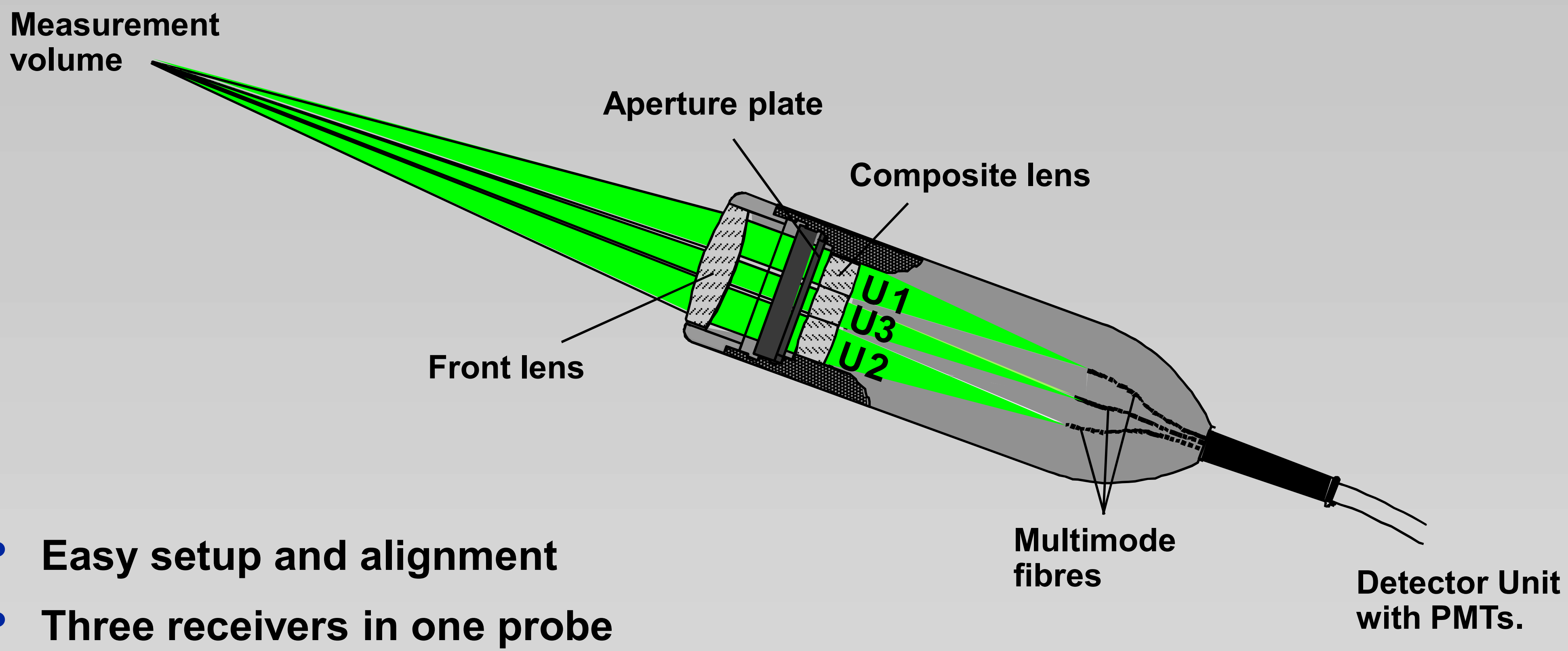
3-detector setup

- Overcoming the 2π ambiguity
- Increasing the measurable size range
- Maintaining a high measurement resolution





Dantec 57X40 FiberPDA



- Easy setup and alignment
- Three receivers in one probe
- Exchangeable aperture masks
- Up to three velocity components

Applications

- Sprays and liquid atomization processes
  - Water sprays
  - Fuel-, diesel injection
  - Paint coating
  - Agricultural sprays
  - Medical, pharmaceutical sprays
  - Cosmetic sprays
- Powder production
  - Spray drying
  - Liquid metal atomization
- Bubble dynamics
  - Cavitation
  - Aeration
  - Multiphase mass transfer

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Automotive Fuel Injection

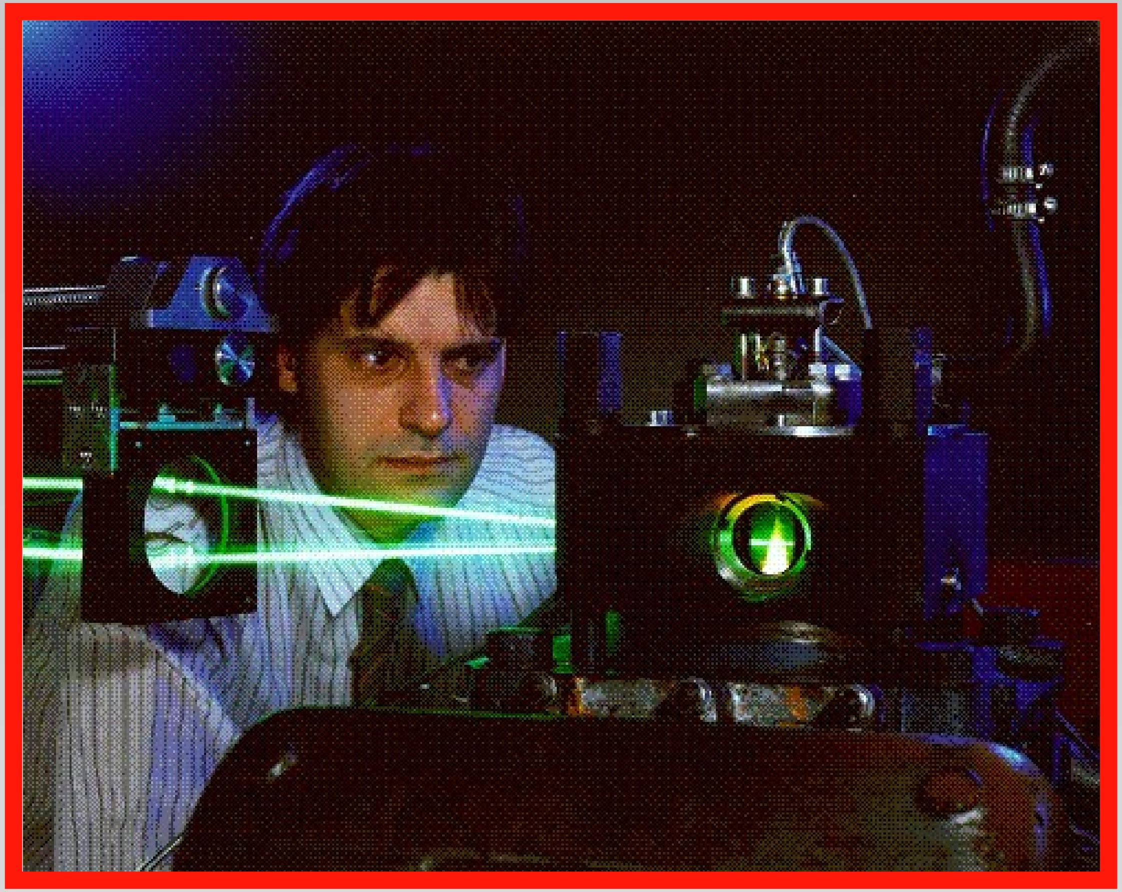

Photo: AVL, Graz, Austria

Nozzle Design

Photo: Gustav Schlick GmbH & Co., Untersiemau, Germany

Aircraft Engine Fuel Injection

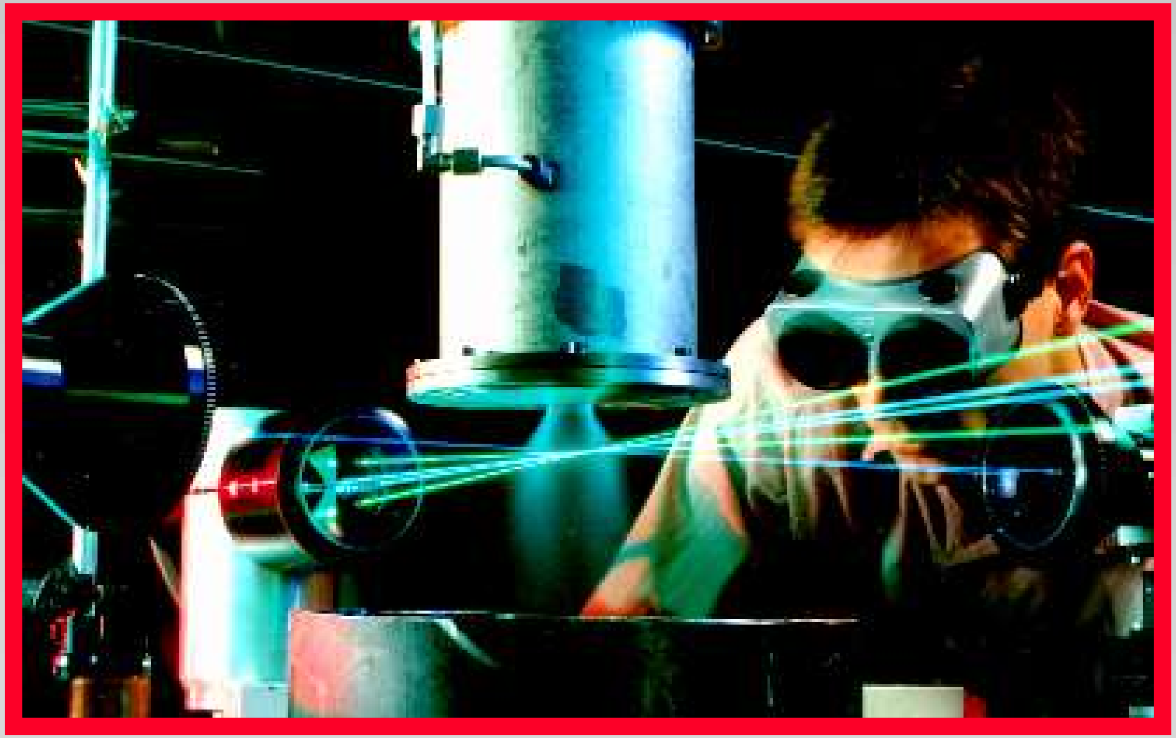

Photo: DLR, Institut für Antriebstechnik, Köln, Germany

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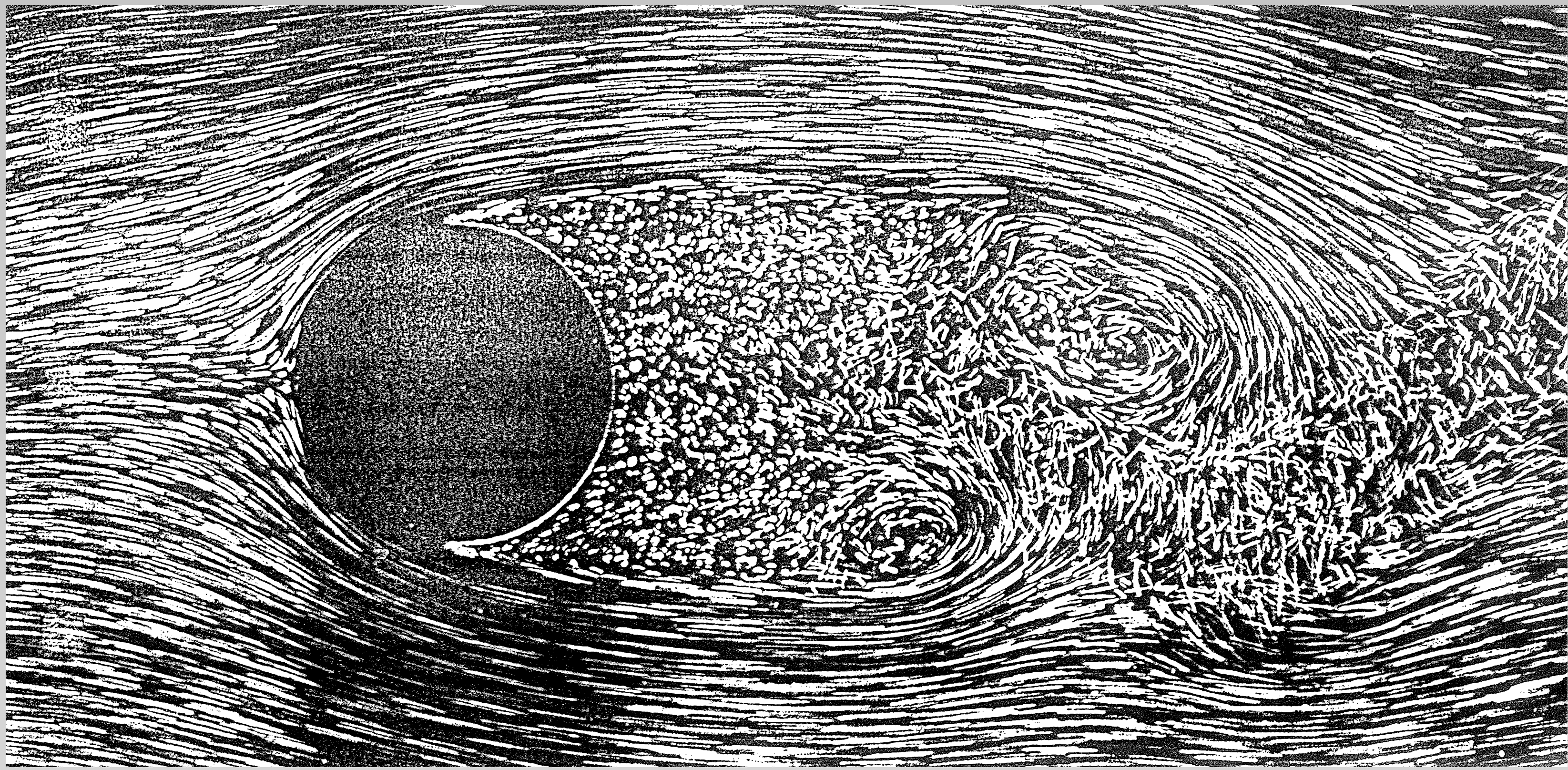
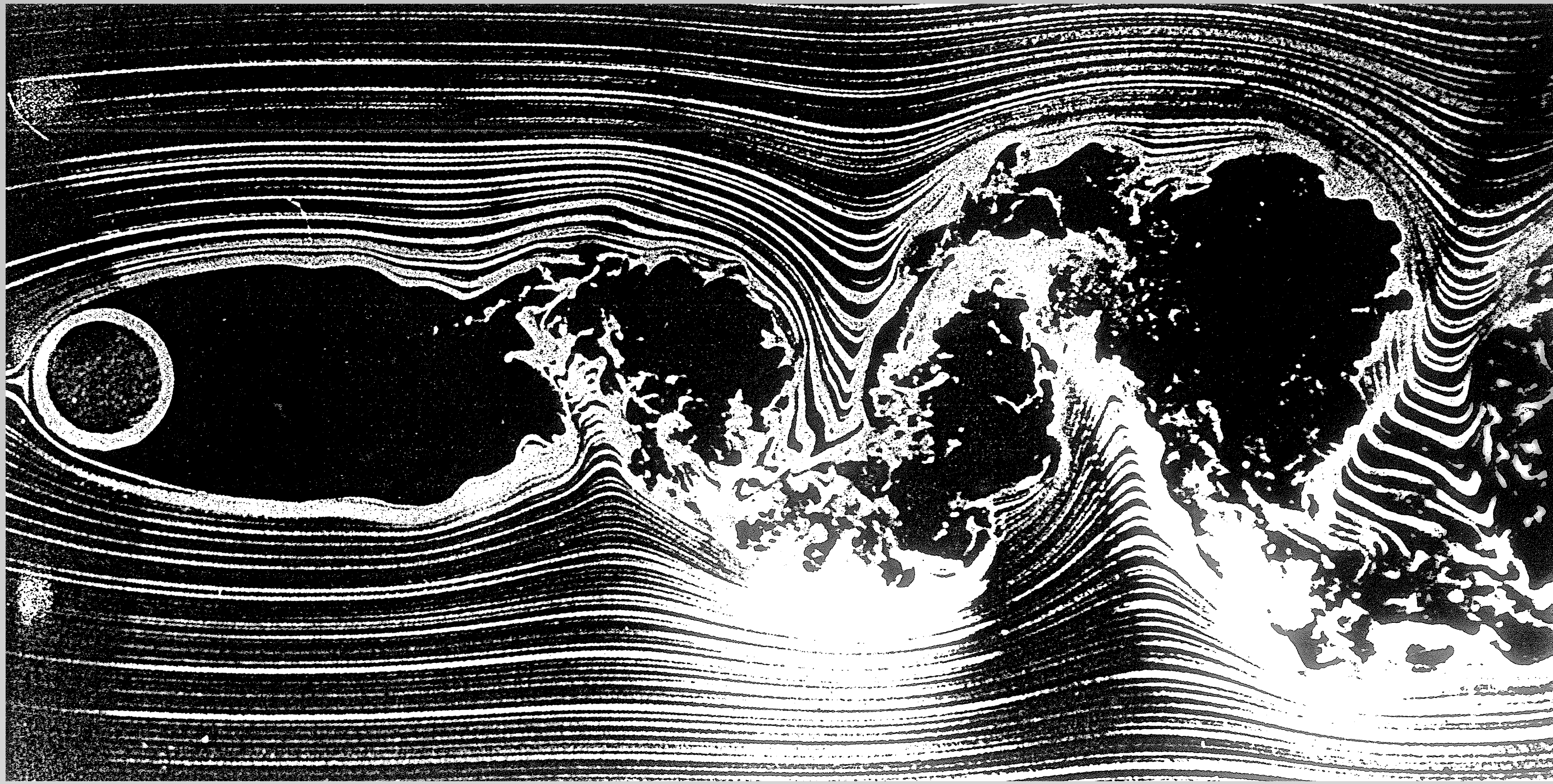
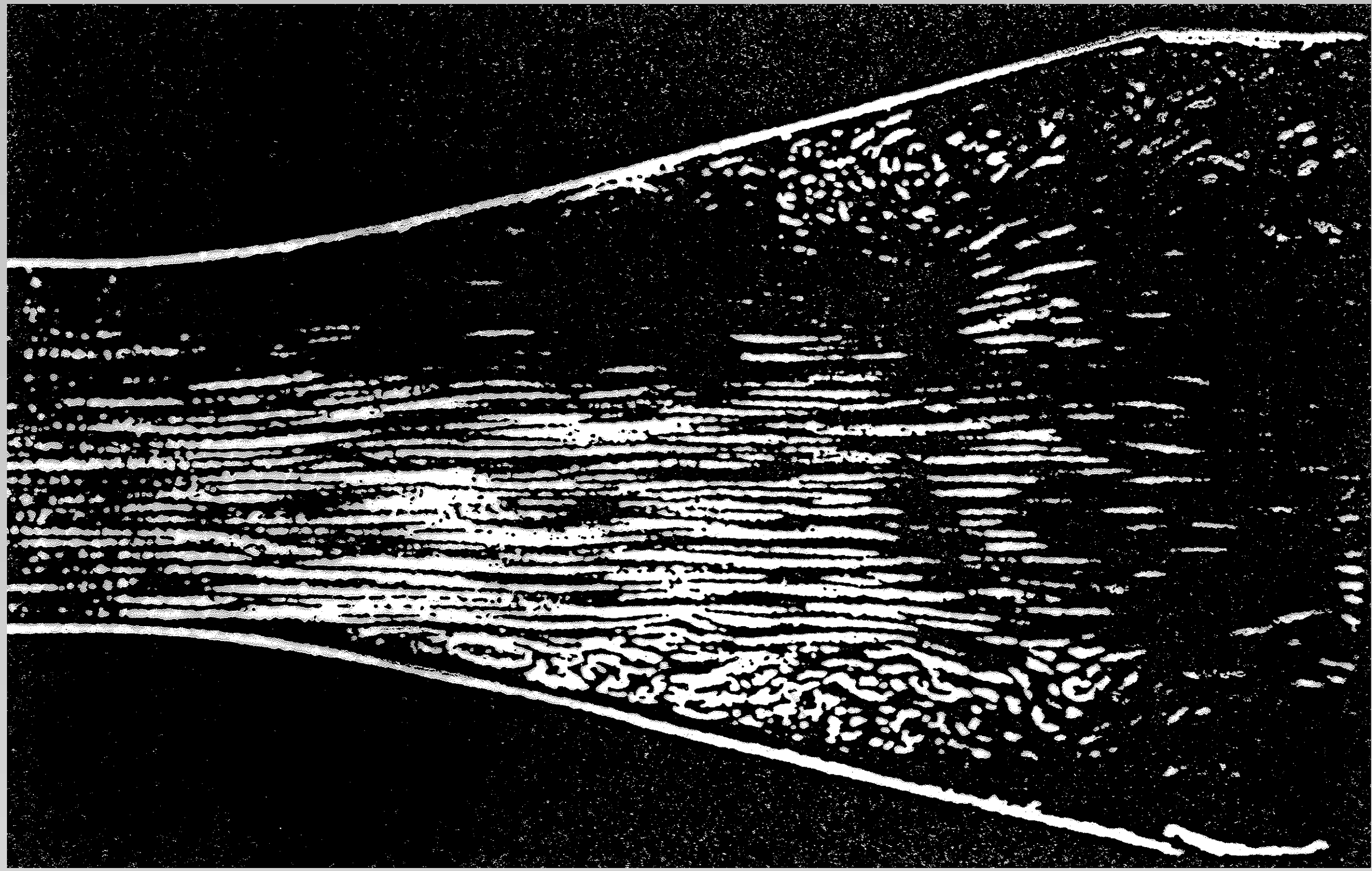
9. Light sheet flow visualisation



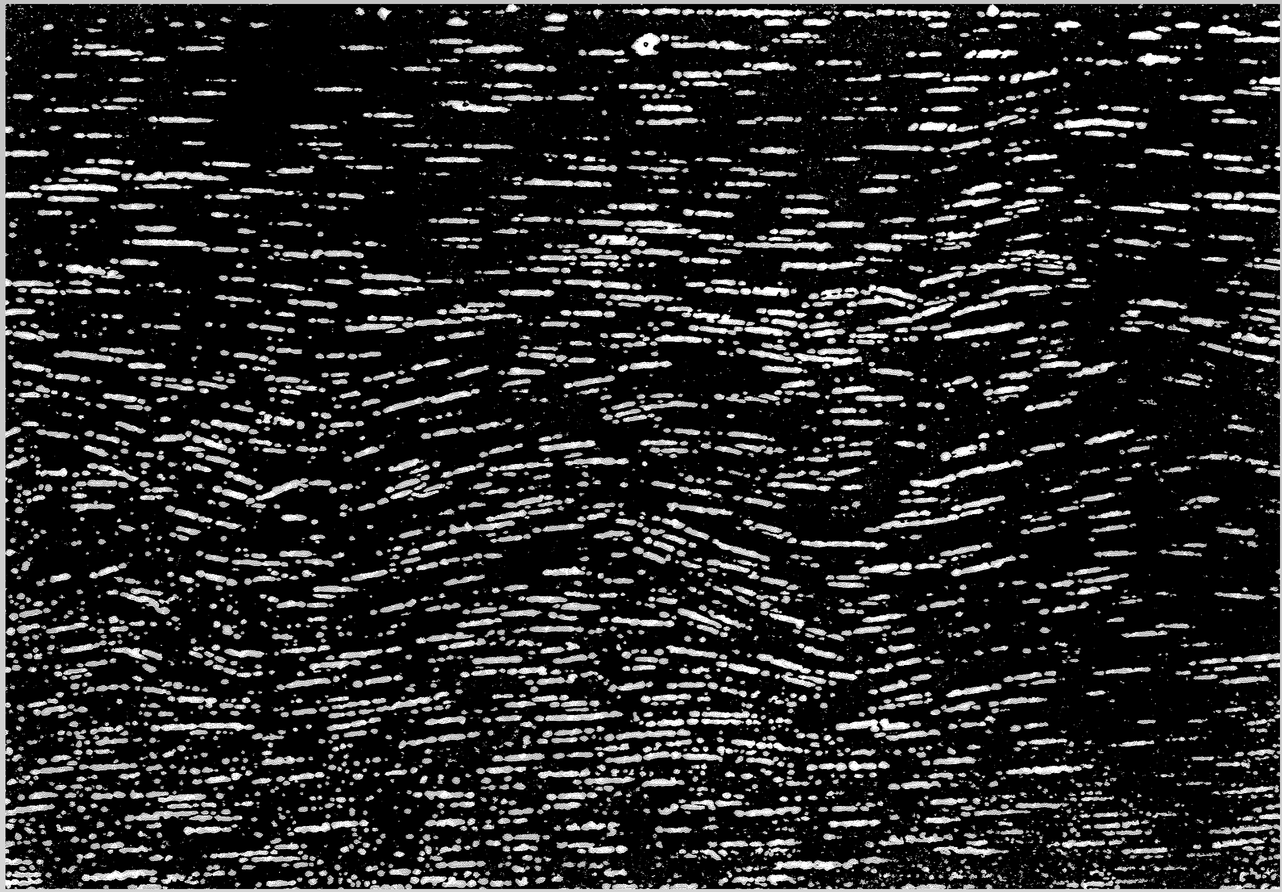
Flow visualised in the vicinity of a cylinder. Re = 2 000. Air bubbles in water. (Van Dyke: An Album of Fluid Motion, Parabolic Press, stanford, California, 1982)



Flow visualised in the vicinity of a cylinder. Re = 10 000. Hydrogene bubbles in water. (Van Dyke: An Album of Fluid Motion, Parabolic Press, stanford, California, 1982)



Flow visualised in a diffuser. Air bubbles in water. (Kaufmann, W.: Technische Hydro- und Aeromechanik, Springer Verlag, 1963)



Particle Tracking Velocimetry. Flow downstream of a cylinder. (Agui, J. C. A., Jimenez, J.: On the Performance of Particle Tracking. J Fluid Mechanics, pp. 447 – 468, 1987)

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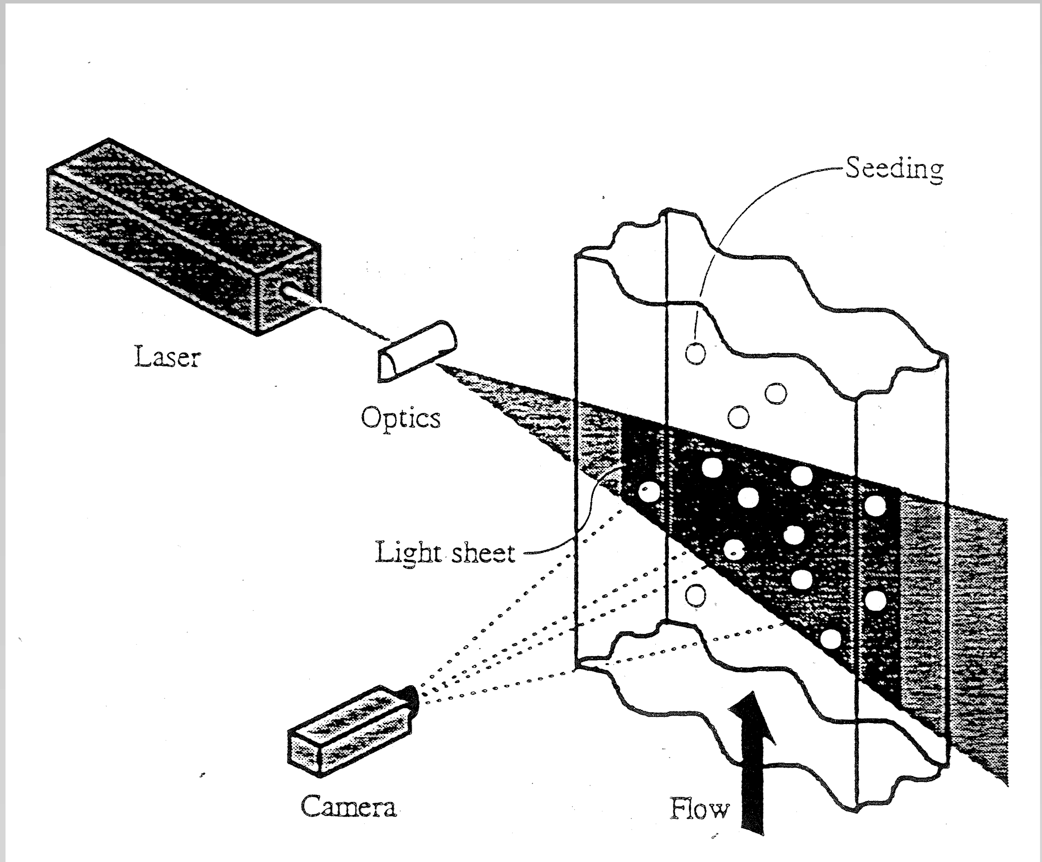
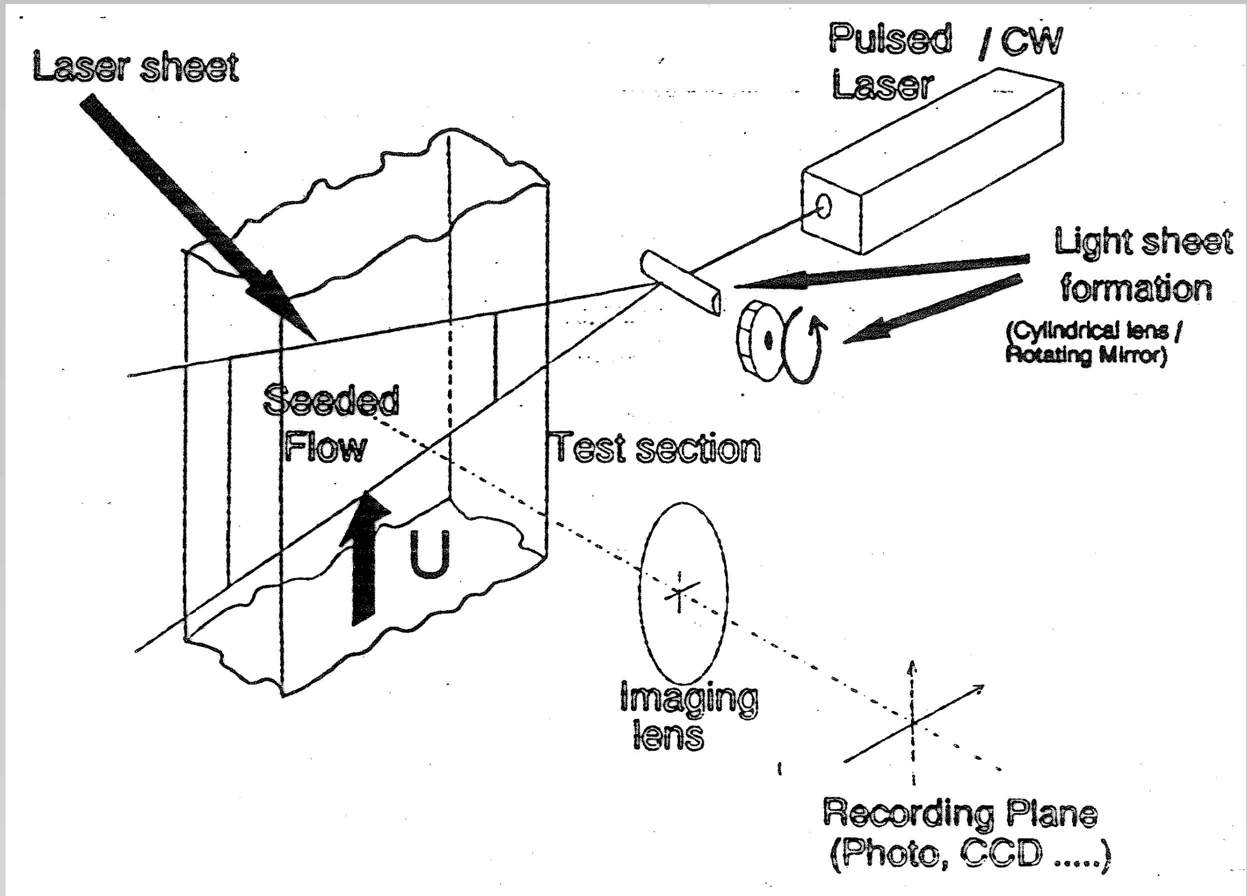
10. Particle Image Velocimetry (PIV)



Principle of PIV (Lecture note by Pap, E., Otto-Von-Guericke Universitaet Magdeburg, Institut für Strömungstechnik und Thermodynamik, Lehrstuhl für Strömungsmaschinen)



PIV arrangement with rotating mirror laser sheet generator (Lecture note by Pap, E., Otto-Von-Guericke Universitaet Magdeburg, Institut für Strömungstechnik und Thermodynamik, Lehrstuhl für Strömungsmaschinen)

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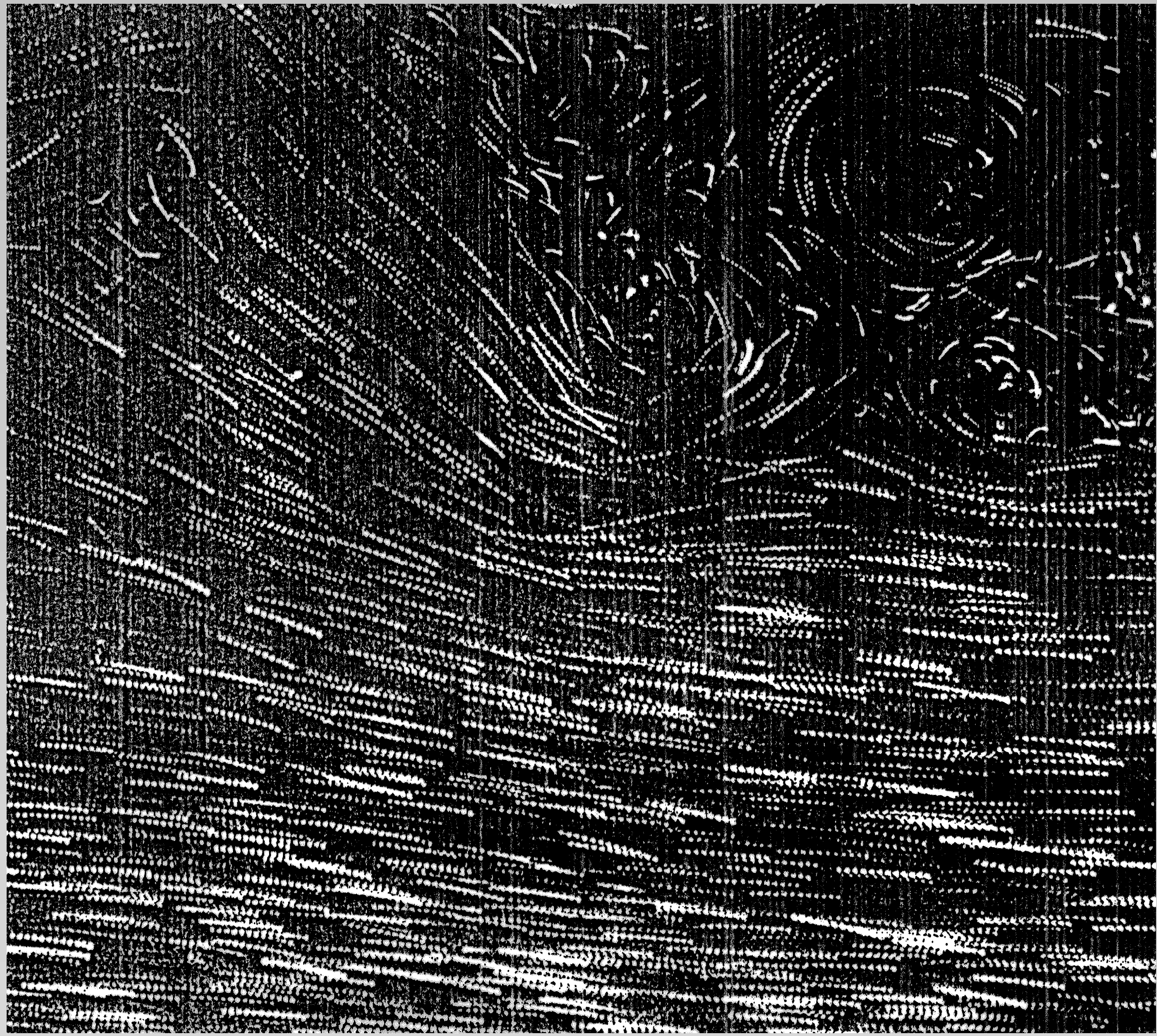
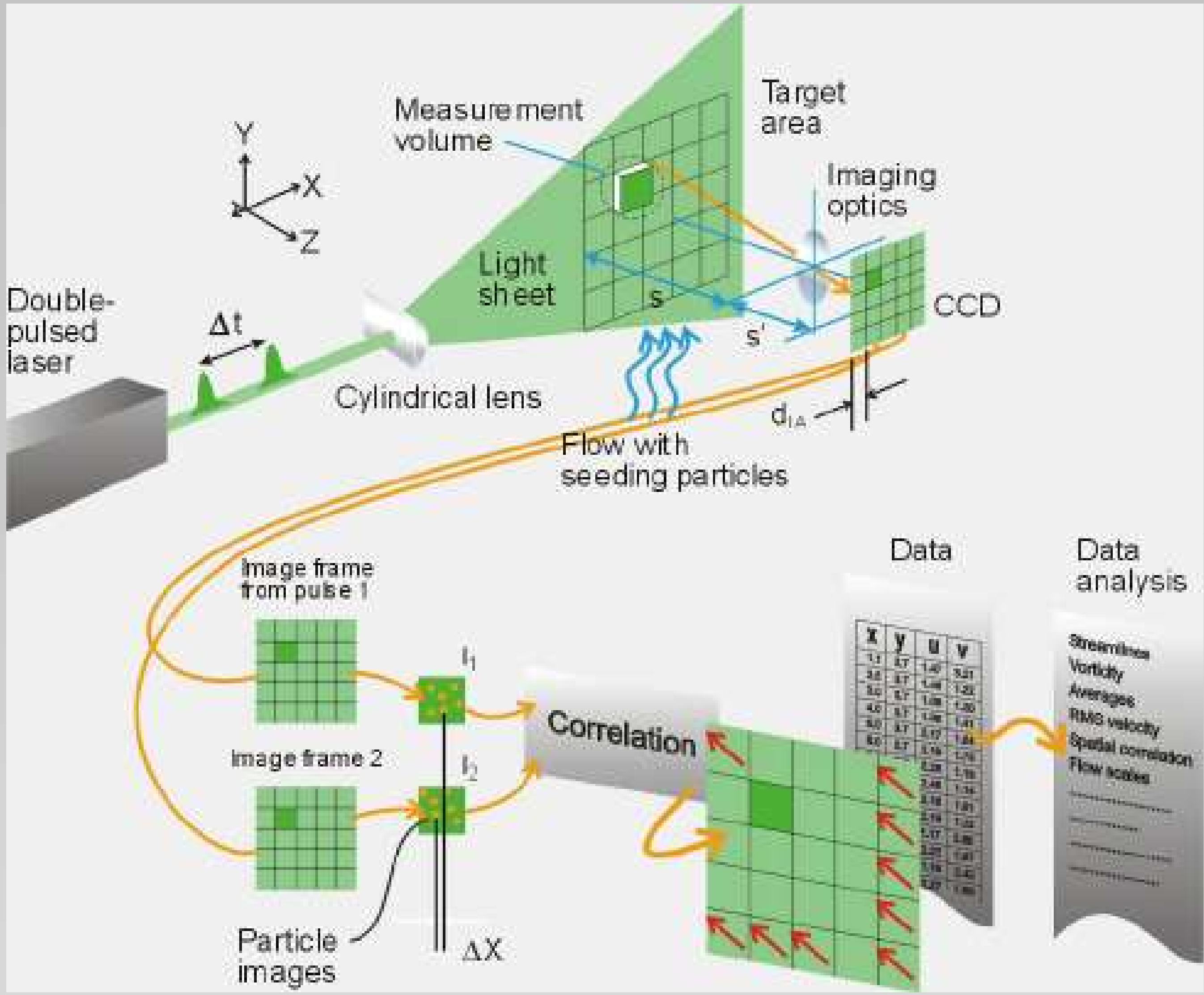


Typical image originated from multipulse illumination



Summary of PIV http://www.dantecdynamics.com/piv/princip/index.html

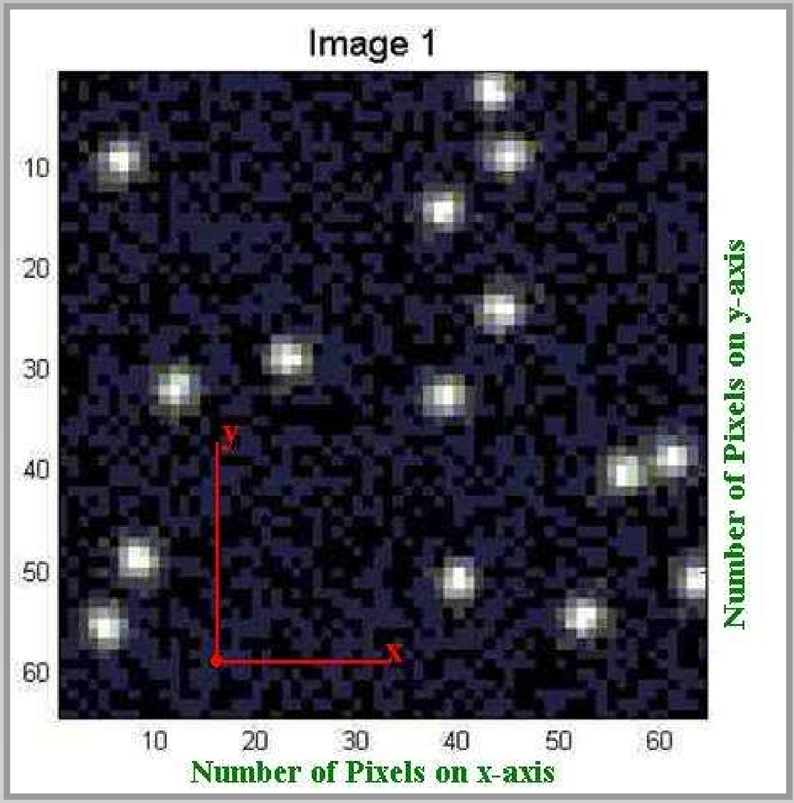


Image 1 at time t1

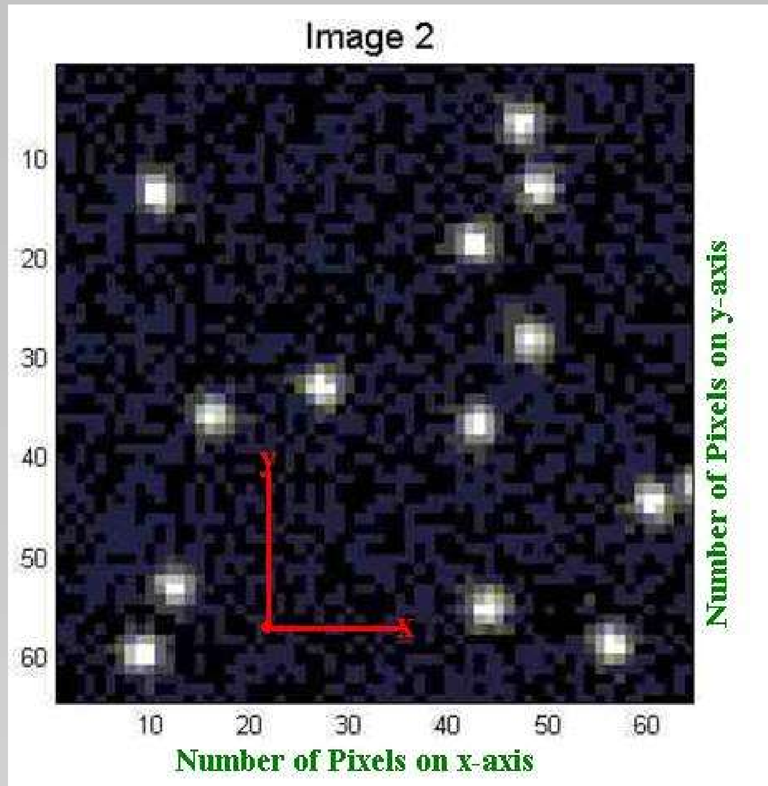
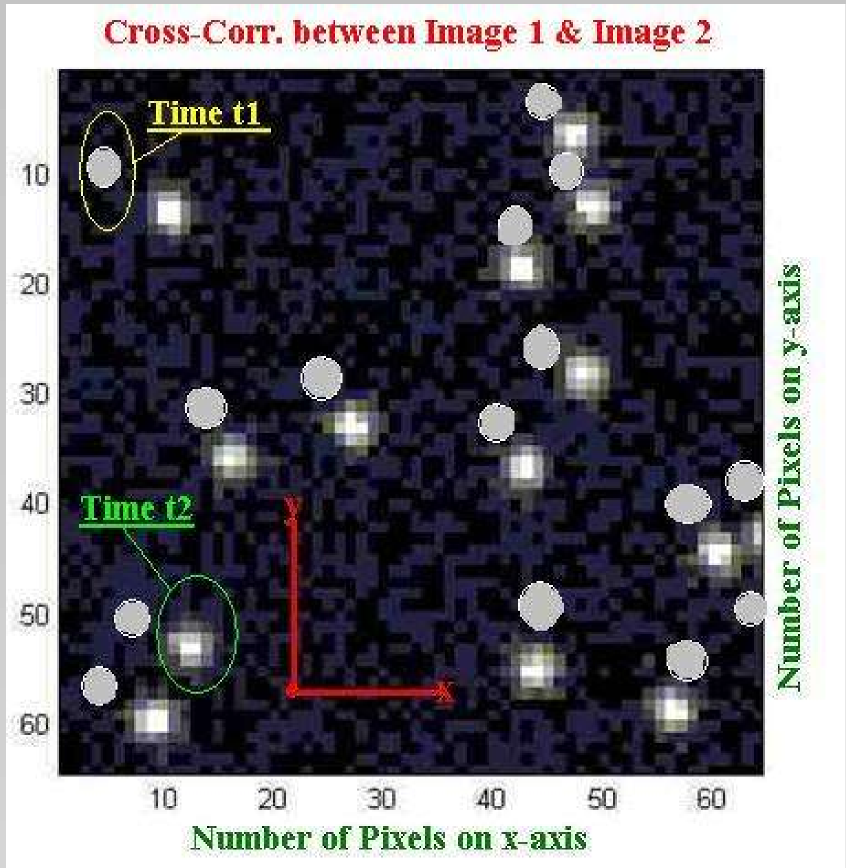


Image 2 at time t2

$$\bar{V} = \frac{\Delta \bar{x}}{\Delta t}$$

$$\Delta \bar{x} = ?$$

PIV Lecture_Notes, “Particle Image Velocimetry”, University of WARWICK, Optical Engineering Laboratory (OEL)



Maximum cross-correlation between Image 1 & Image 2

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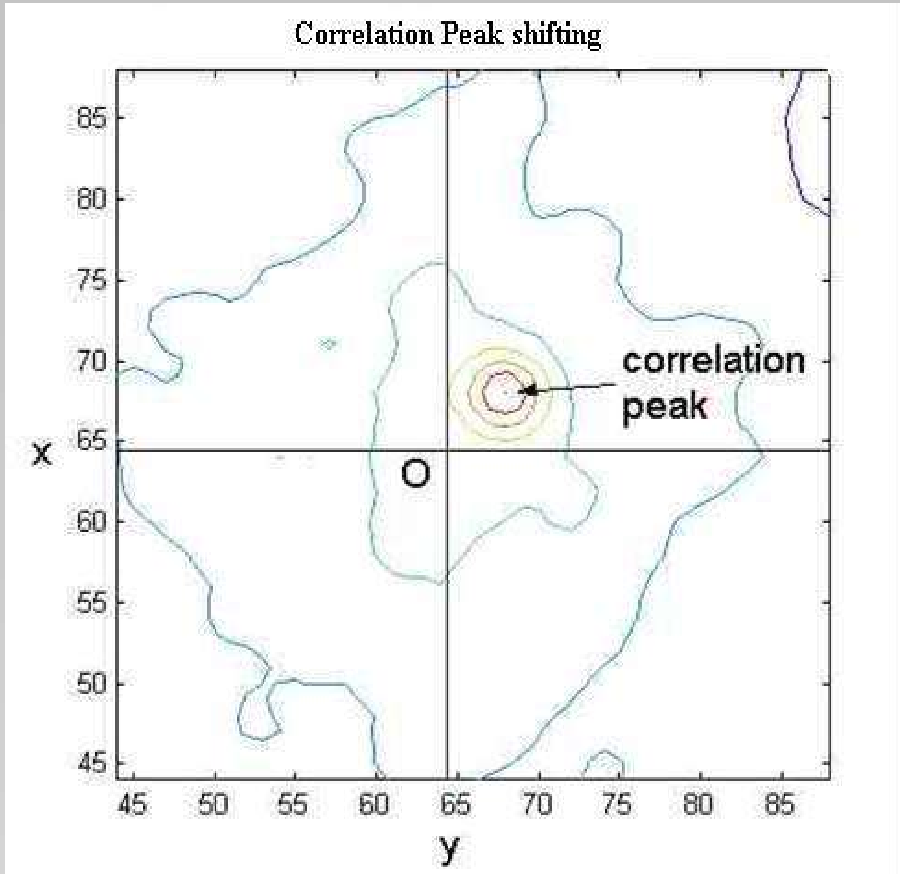
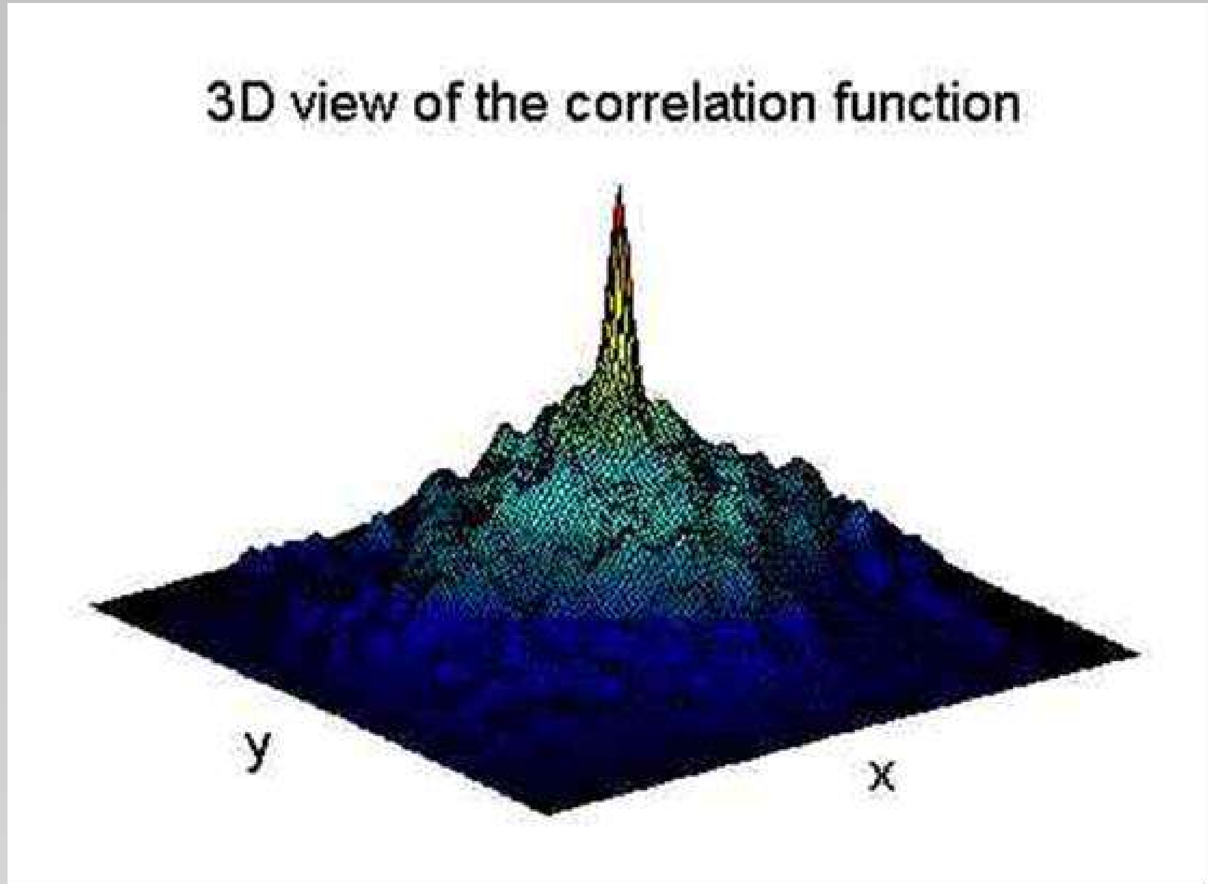
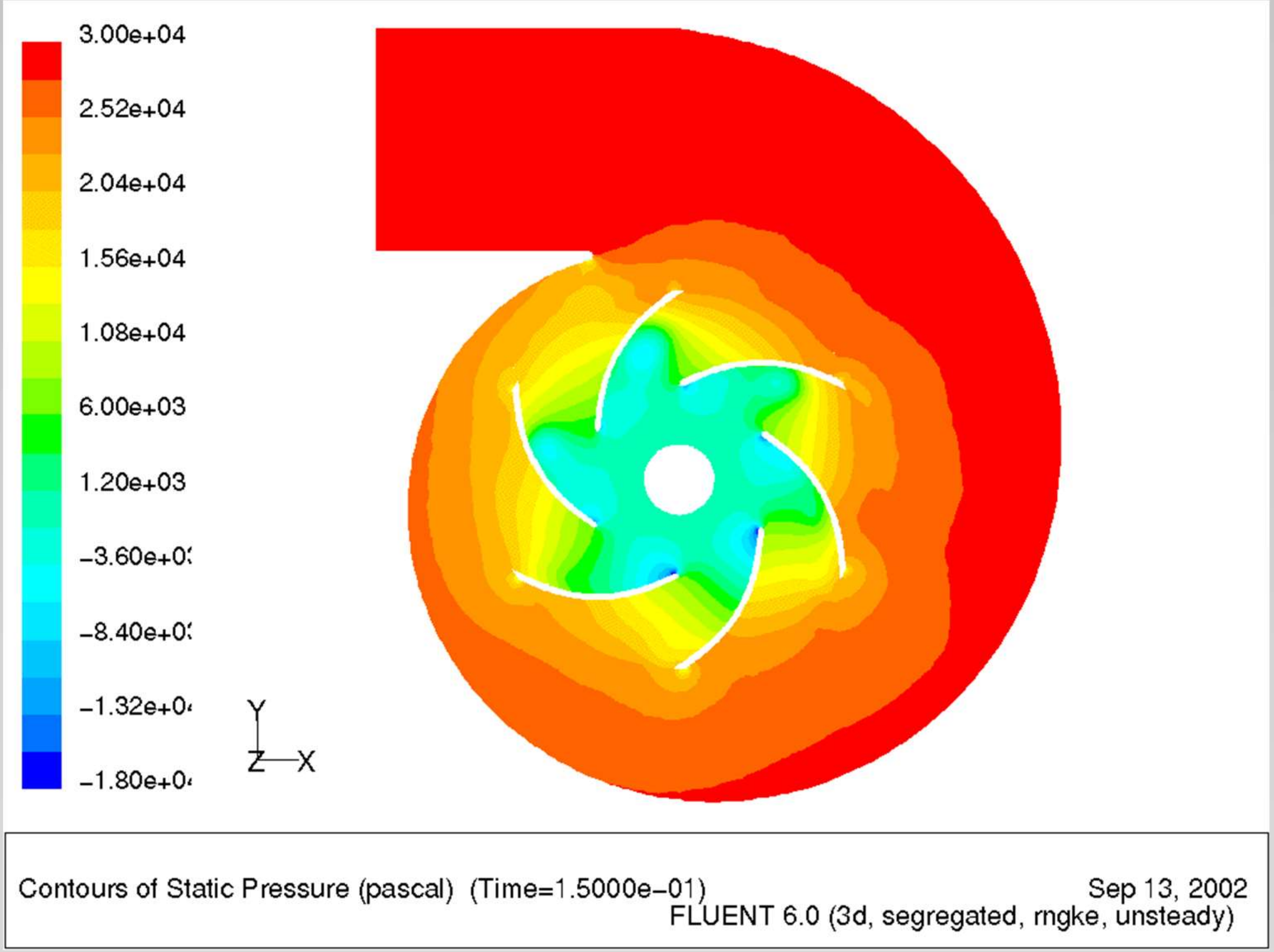




PIV Lecture_Notes, “Particle Image Velocimetry”, University of WARWICK, Optical Engineering Laboratory (OEL)

Radial pump simulation: comparison of simulated flow field and PIV data



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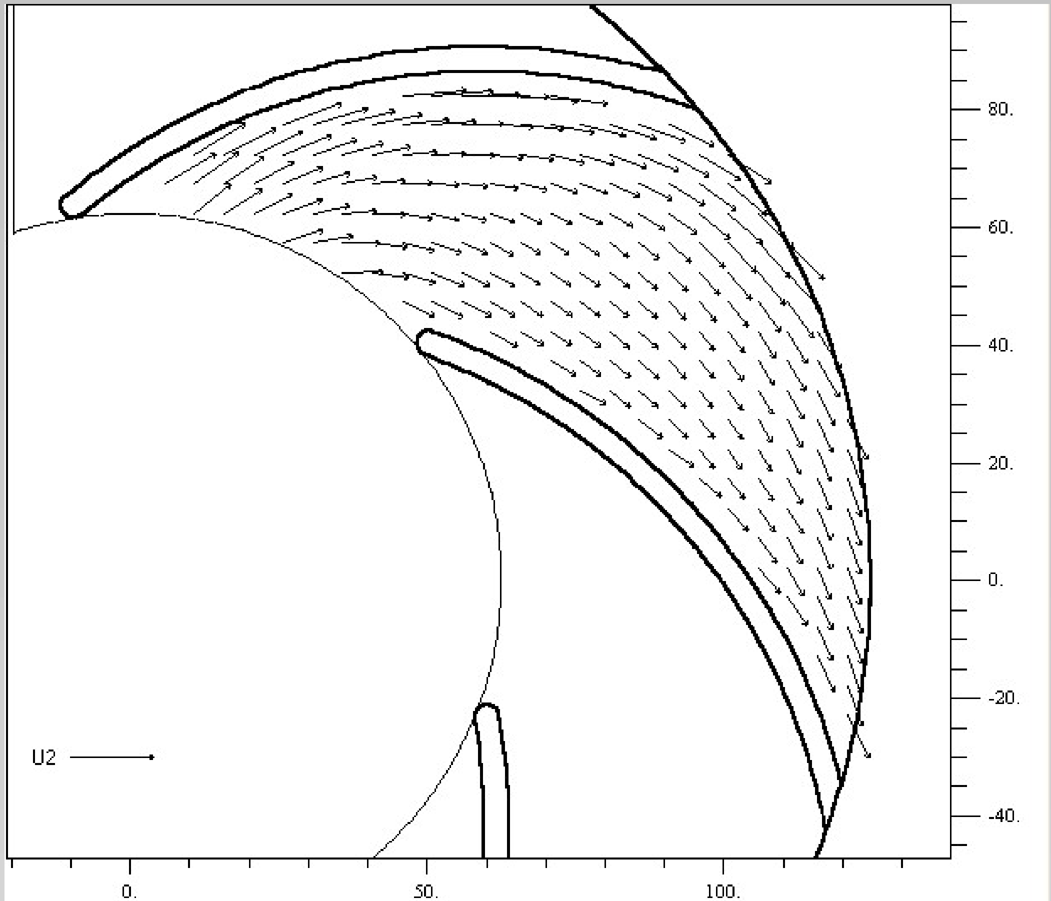

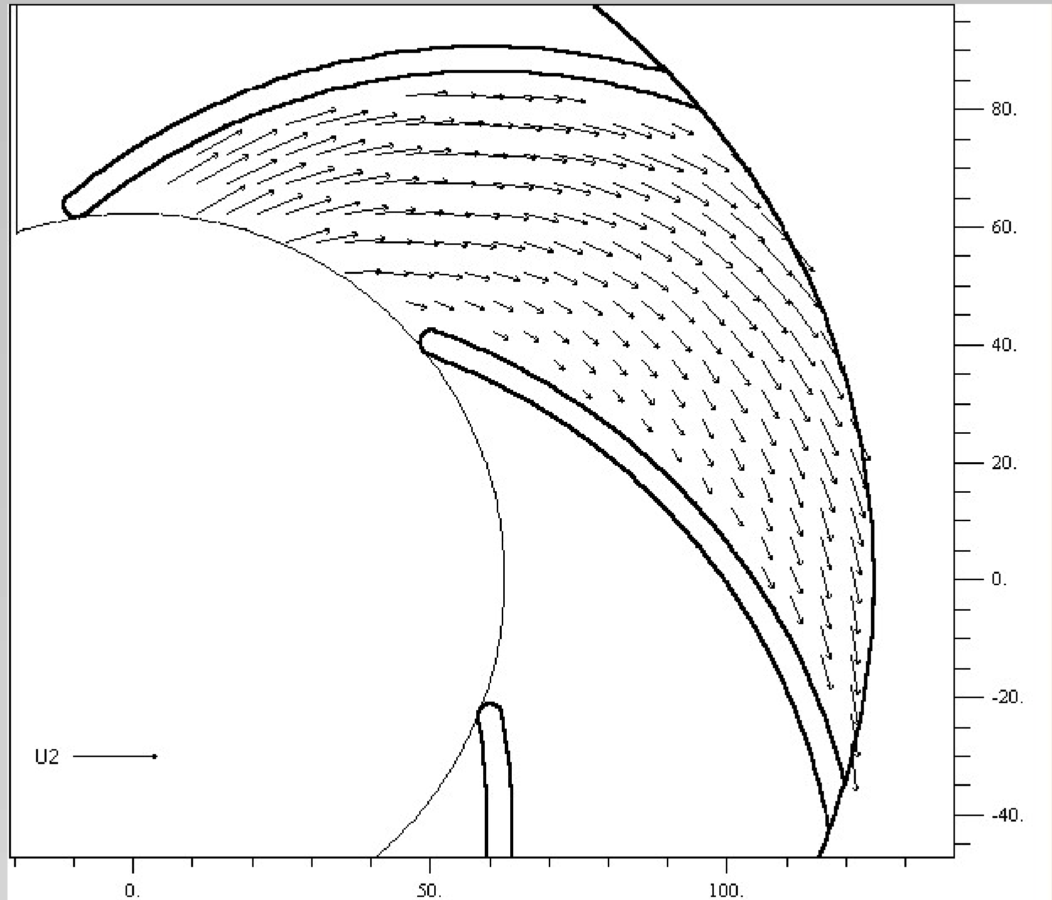

PIV measurement
(Otto-Von-Guericke Universitaet Magdeburg)

FLUENT simulation
(Dept. of Fluid Mechanics, BME)

FlowManager 3D-PIV (Stereo PIV)

- **Theory of stereoscopic PIV**
- **Dantec 3D-PIV software**
- **Application example:**
  3D-PIV in an automotive wind tunnel
  (used as example through the slide show)

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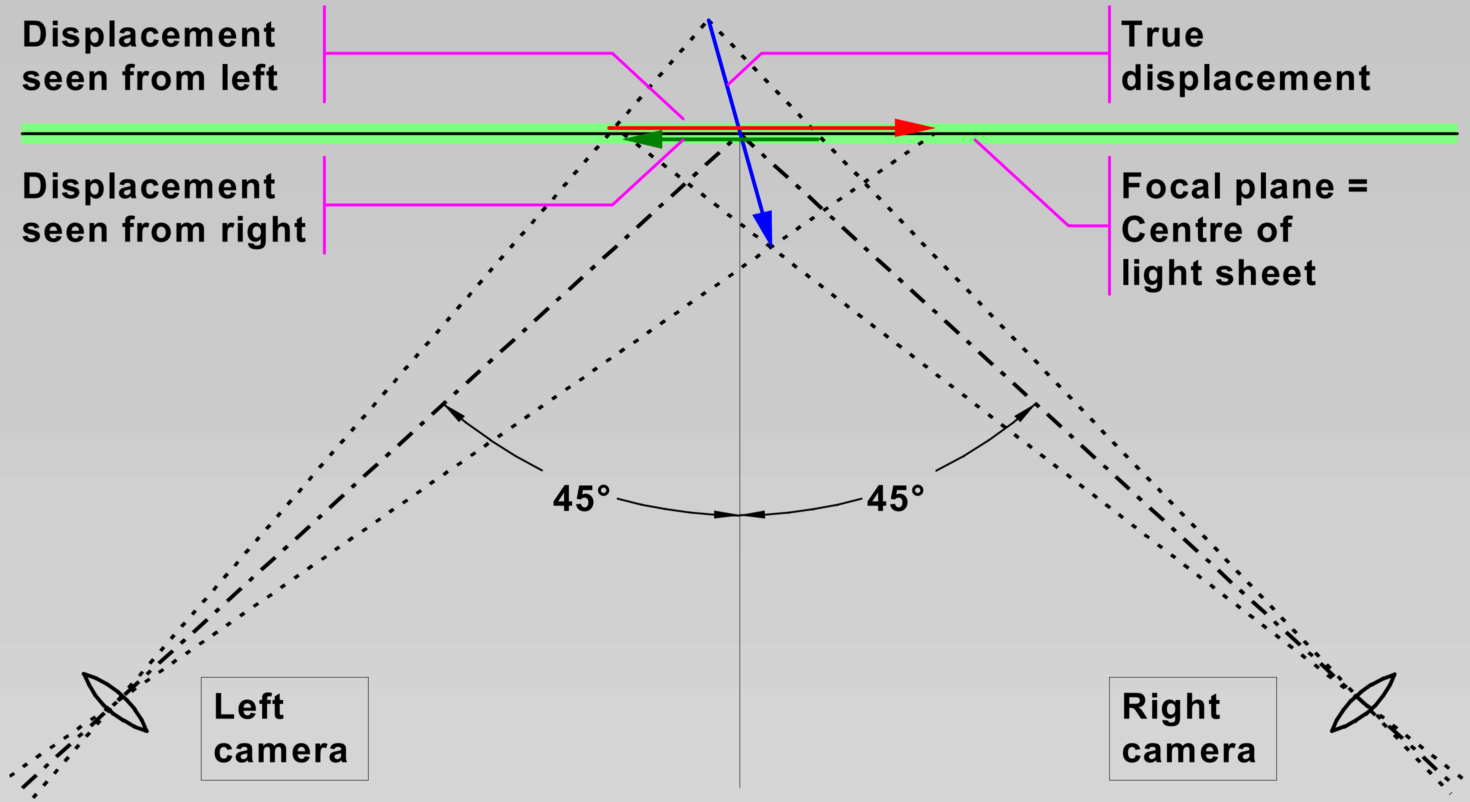
Fundamentals of stereo vision



True 3D displacement (ΔX,ΔY,ΔZ) is estimated from a pair of 2D displacements (Δx,Δy) as seen from left and right camera respectively

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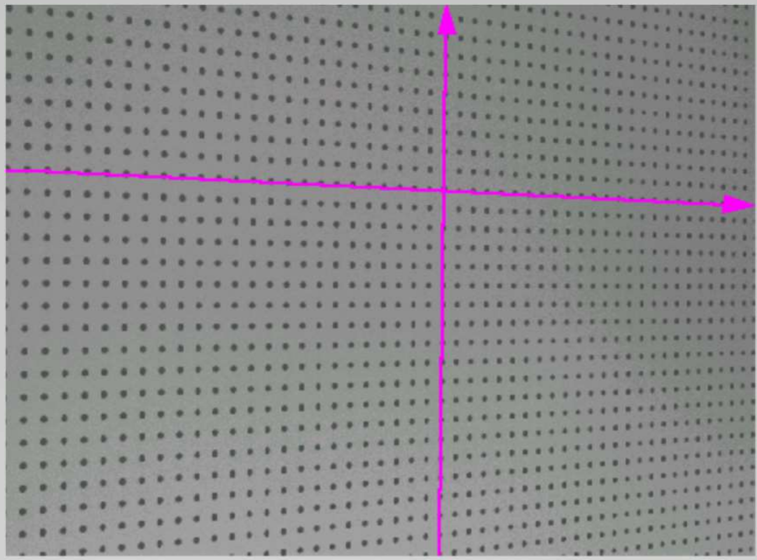
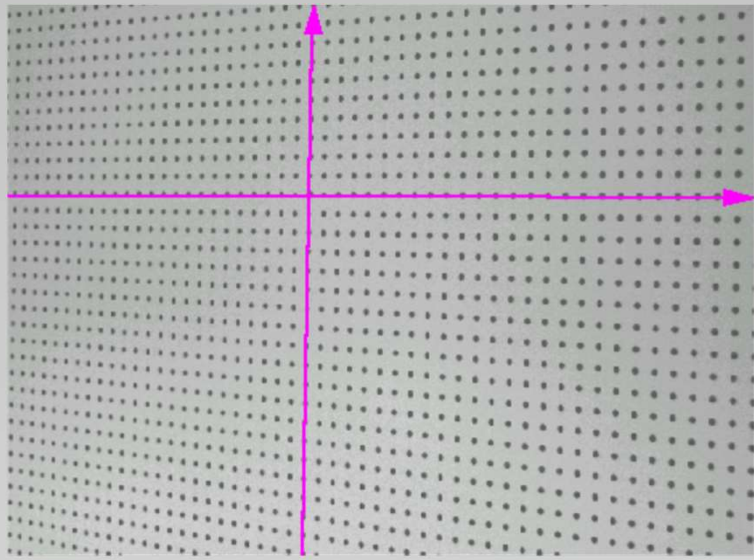
Camera calibration

Images of a calibration target are recorded.

The target contains calibration markers in known positions.

Comparing known marker positions with corresponding marker positions on each camera image, model parameters are adjusted to give the best possible fit.

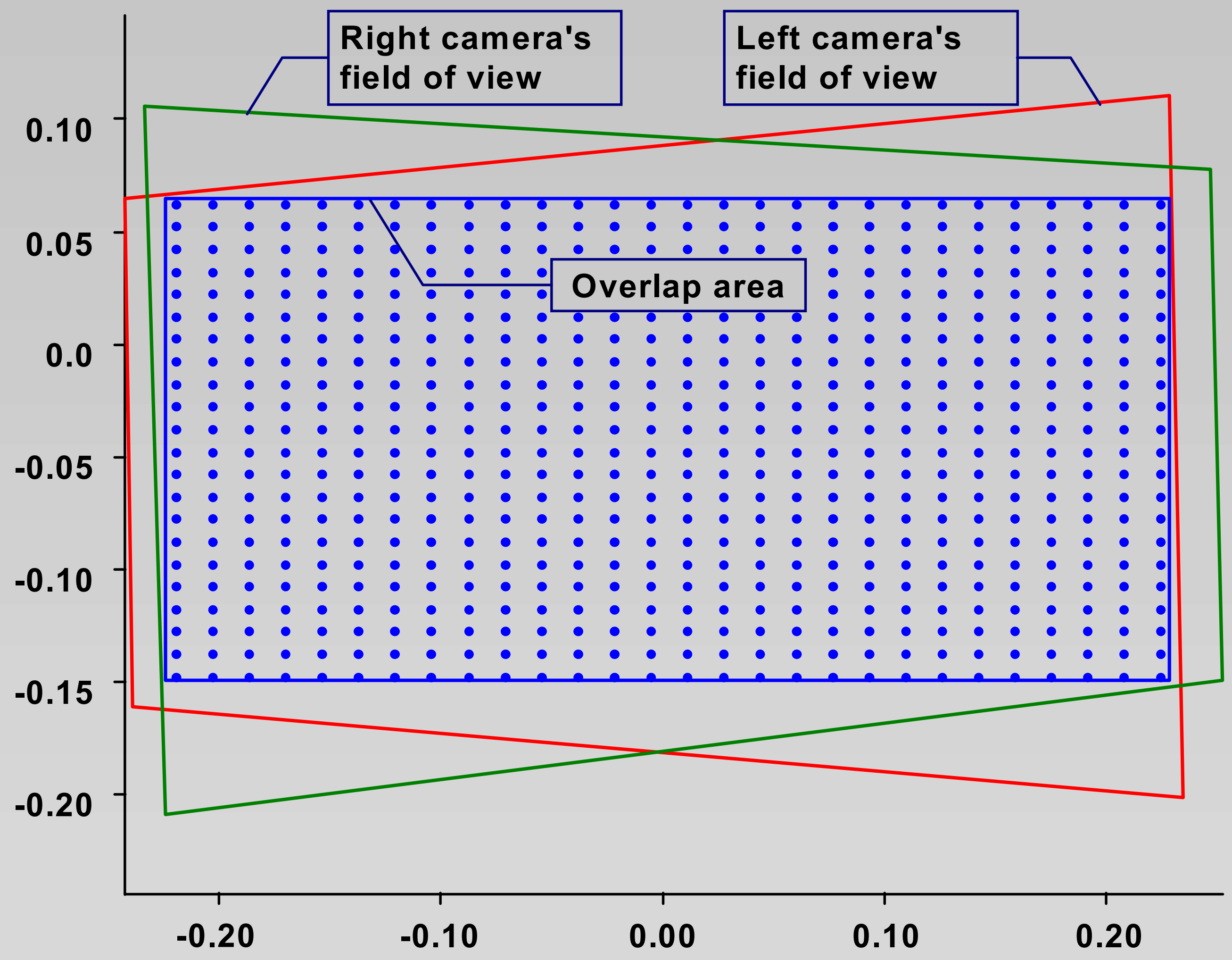
Overlapping fields of view

3D evaluation is possible only within the area covered by both cameras.

Due to perspective distortion each camera covers a trapezoidal region of the light sheet.

Careful alignment is required to maximize the overlap area.

Interrogation grid is chosen to match the spatial resolution.



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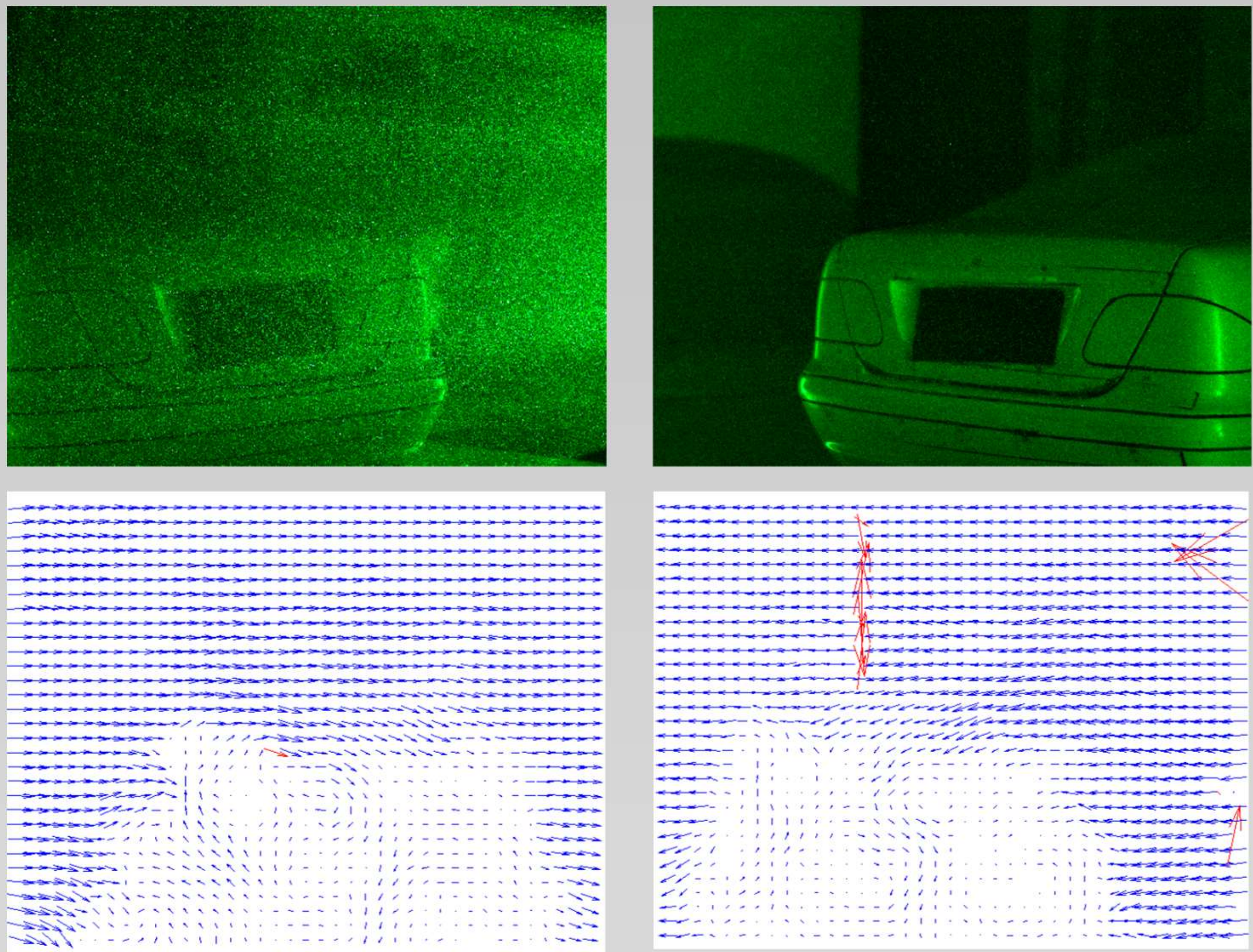
Left / Right 2D vector maps

Left & Right camera images are recorded simultaneously.

Conventional PIV processing produce 2D vector maps representing the flow field as seen from left & right.

The vector maps are re-sampled in points corresponding to the interrogation grid.

Combining left / right results, 3D velocities are estimated.



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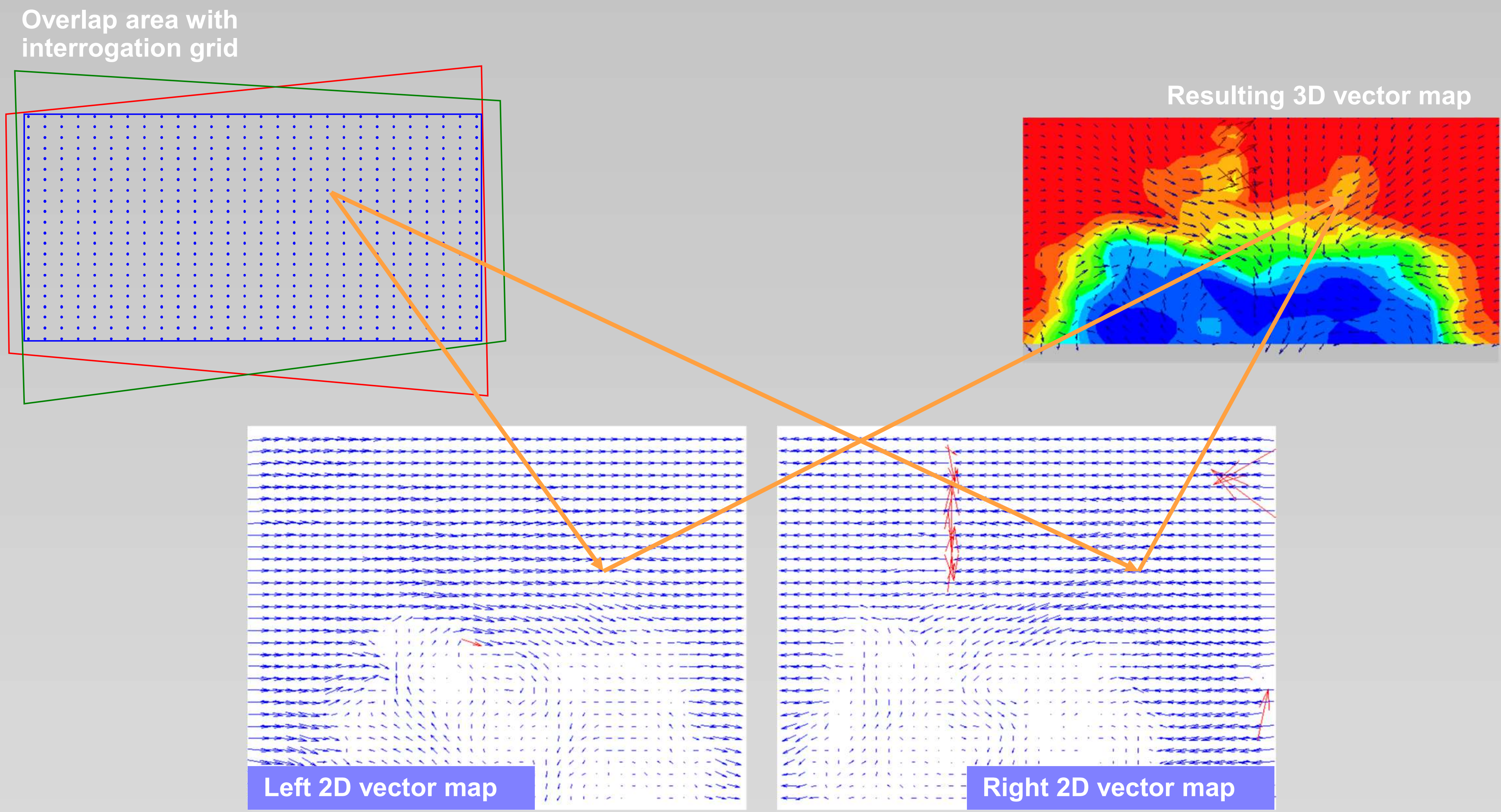
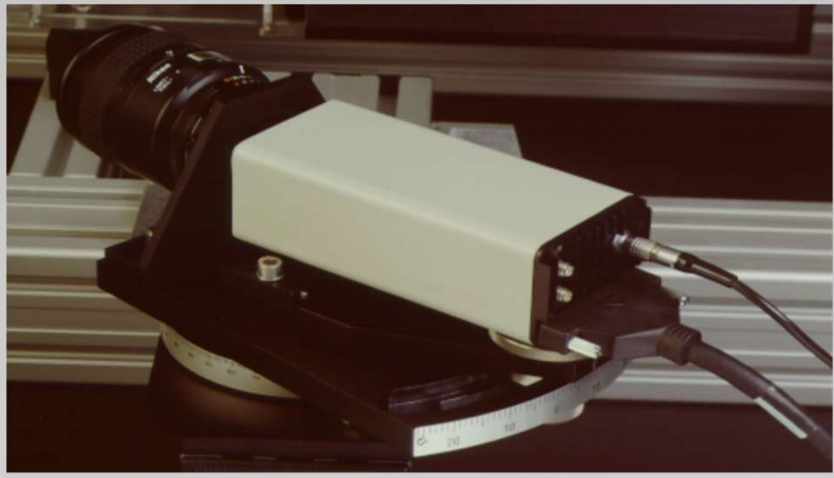
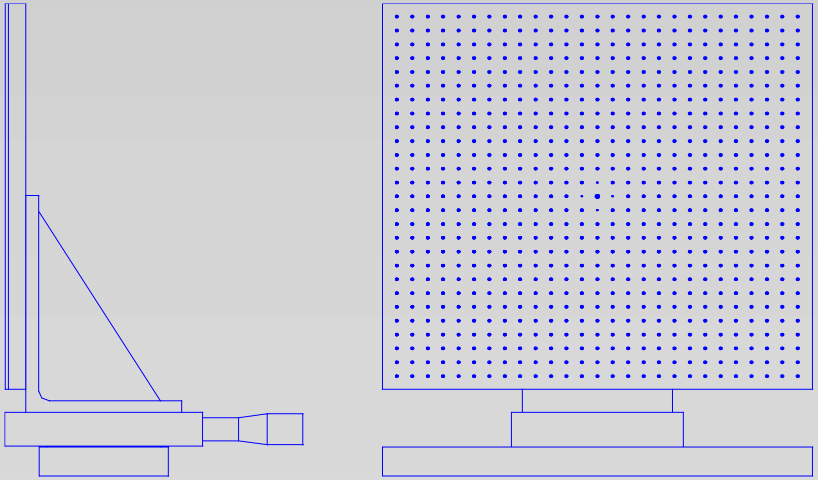
3D reconstruction



Dantec 3D-PIV system components

- Seeding
- PIV-Laser
  (Double-cavity Nd:Yag)
- Light guiding arm &
  Lightsheet optics
- 2 cameras on stereo mounts
- FlowMap PIV-processor with
  two camera input
- Calibration target on a traverse
- FlowManager PIV software
- FlowManager 3D-PIV option





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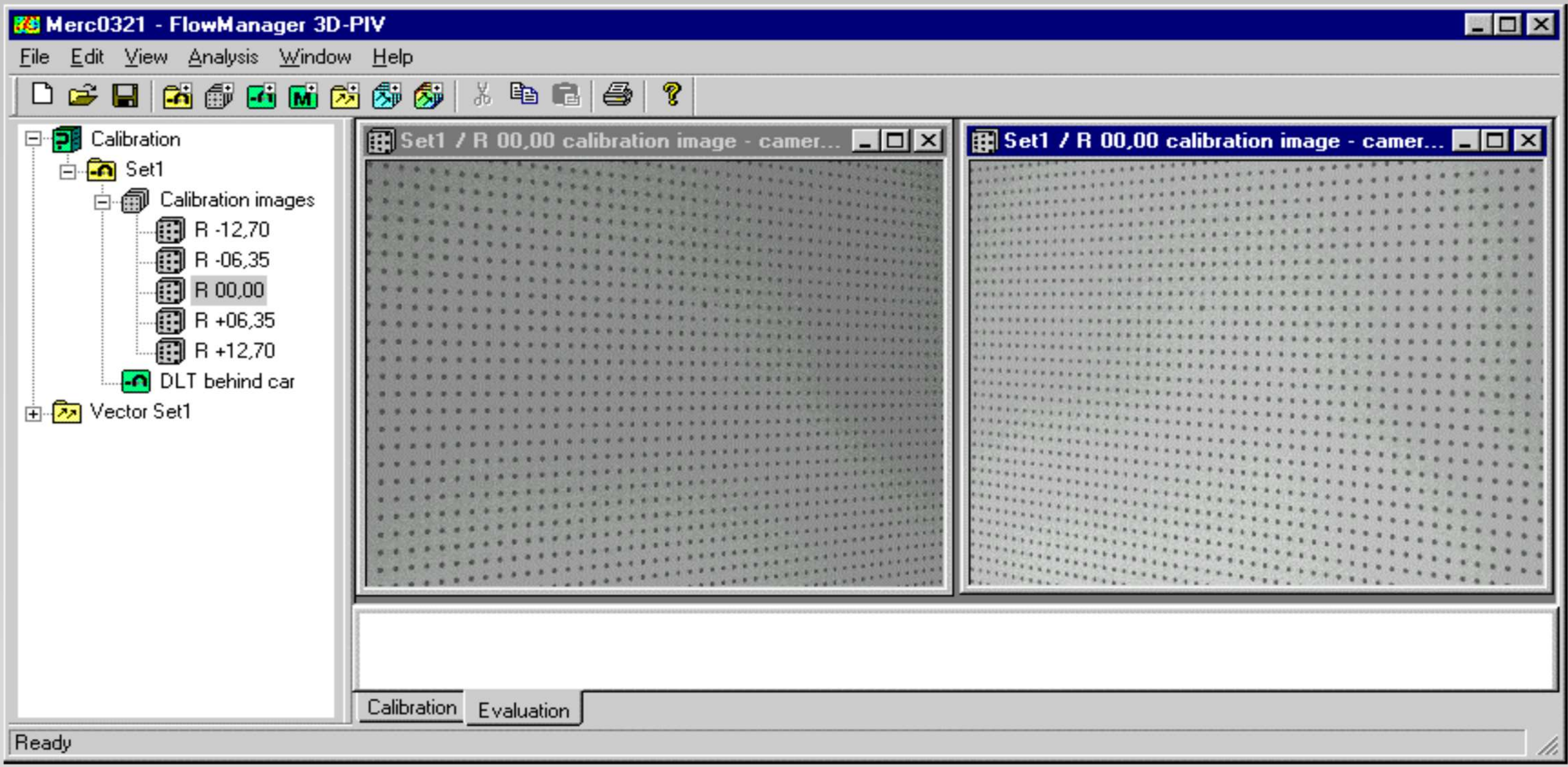
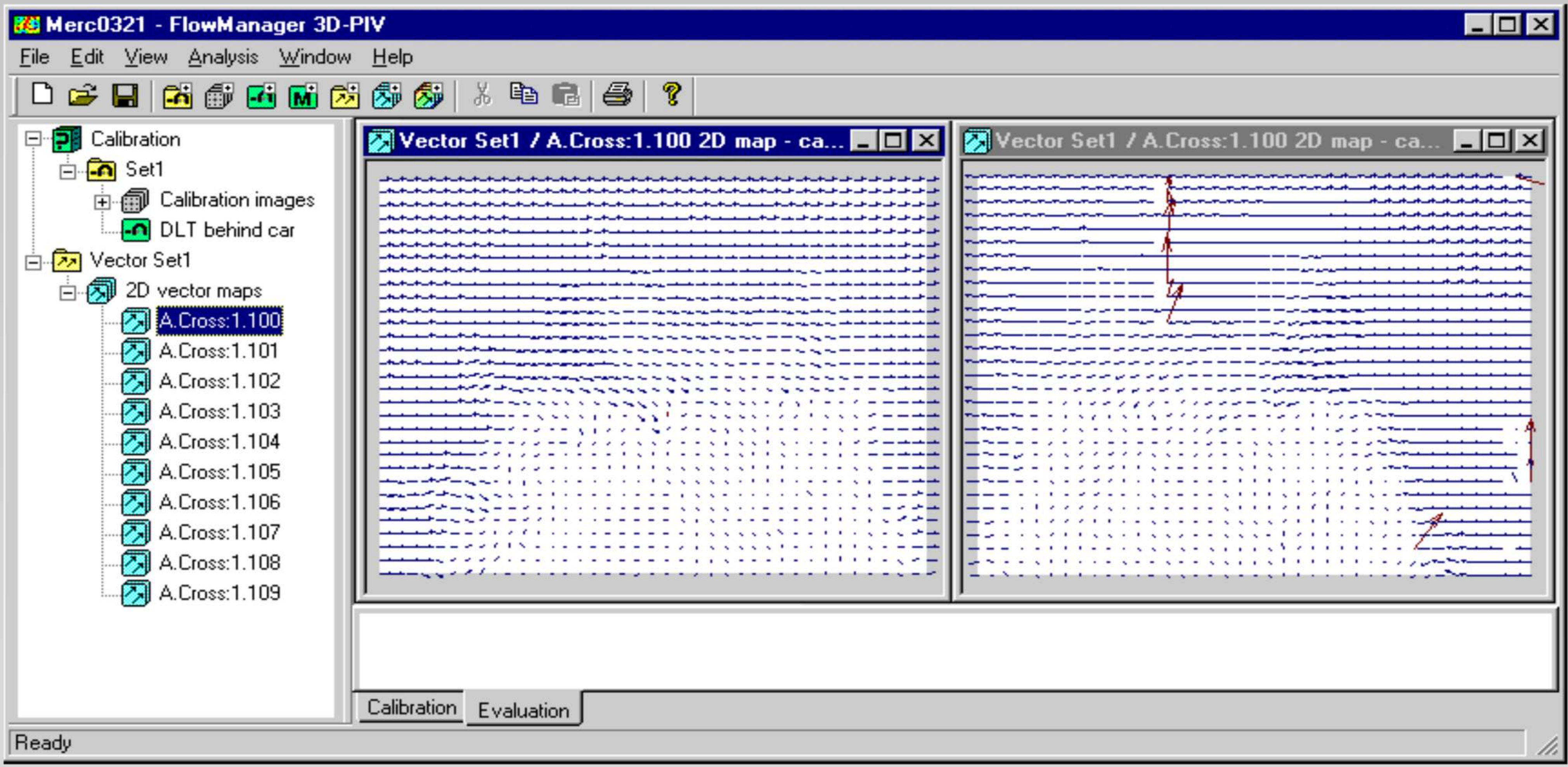
Recipe for a 3D-PIV experiment

- Record calibration images in the desired measuring position (Target and traverse defines the co-ordinate system!)
- Align the lightsheet with the calibration target
- Record calibration images using both cameras
- Record simultaneous 2D-PIV vector maps using both cameras
- Calibration images and vector maps is read into FlowManager
- Perform camera calibration based on the calibration images
- Calculate 3D vectors based on the two 2D PIV vector maps and the camera calibration

Camera calibration



Importing 2D vector maps



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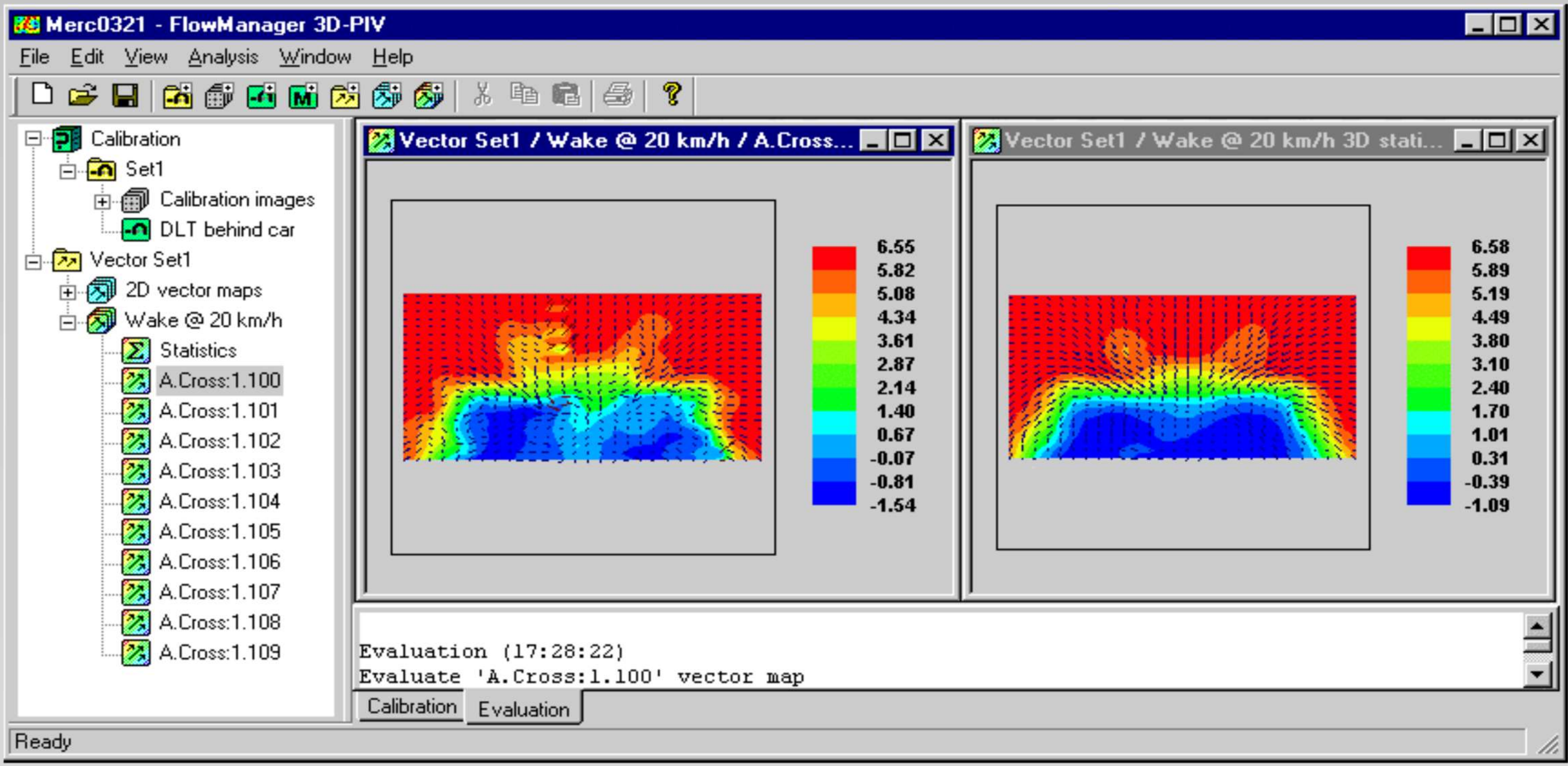
3D evaluation & statistics



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