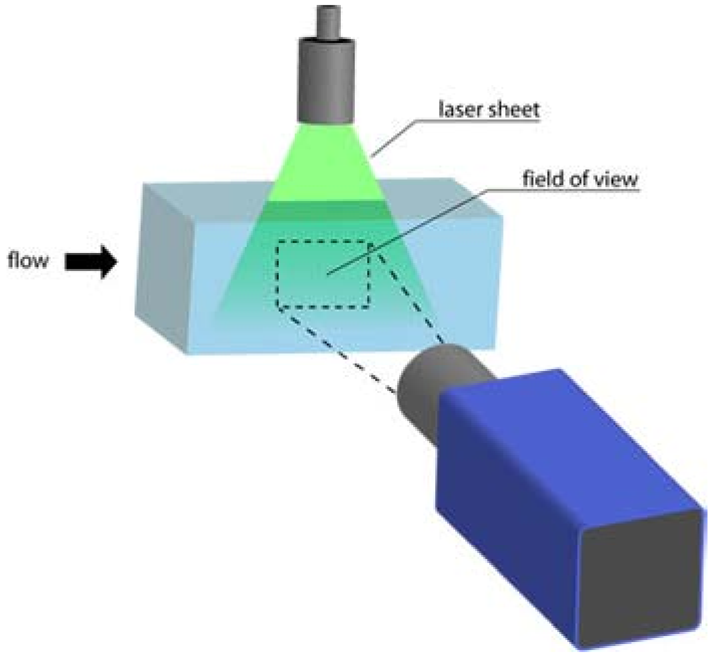
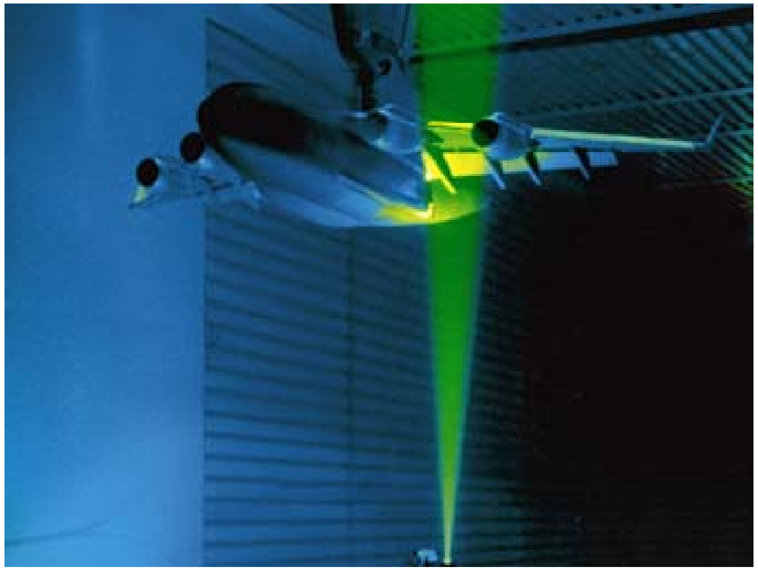
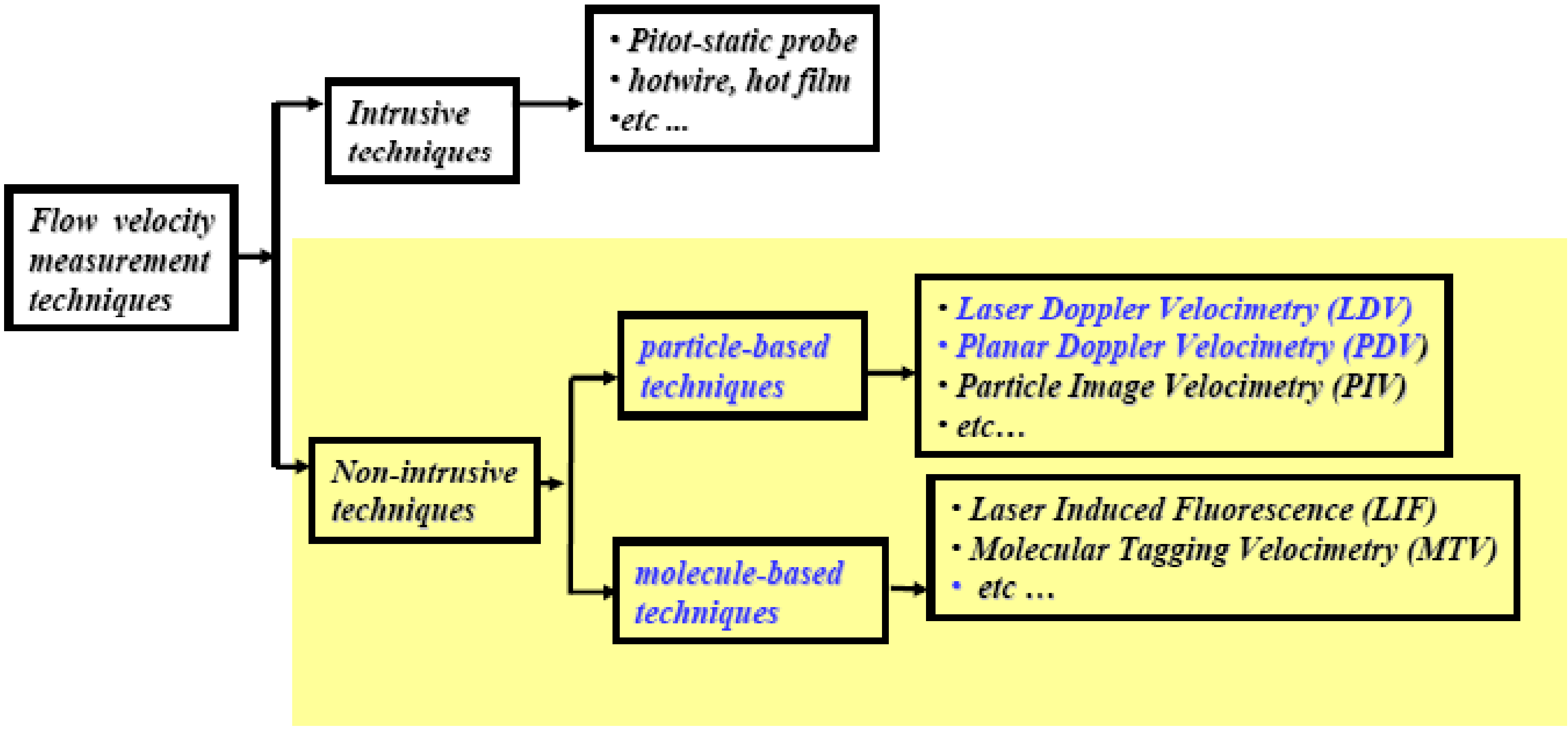


Particle Image Velocimetry (PIV)



Flow Velocity Measurement Techniques



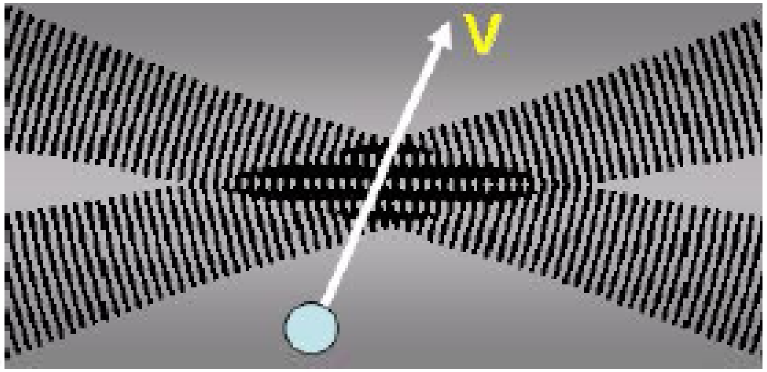
Frequency Shift Based Methods

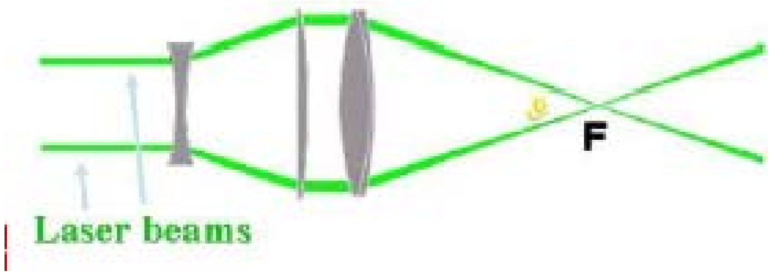
•Based on the Doppler phenomenon, namely the shift of the frequency of waves scattered by moving particles

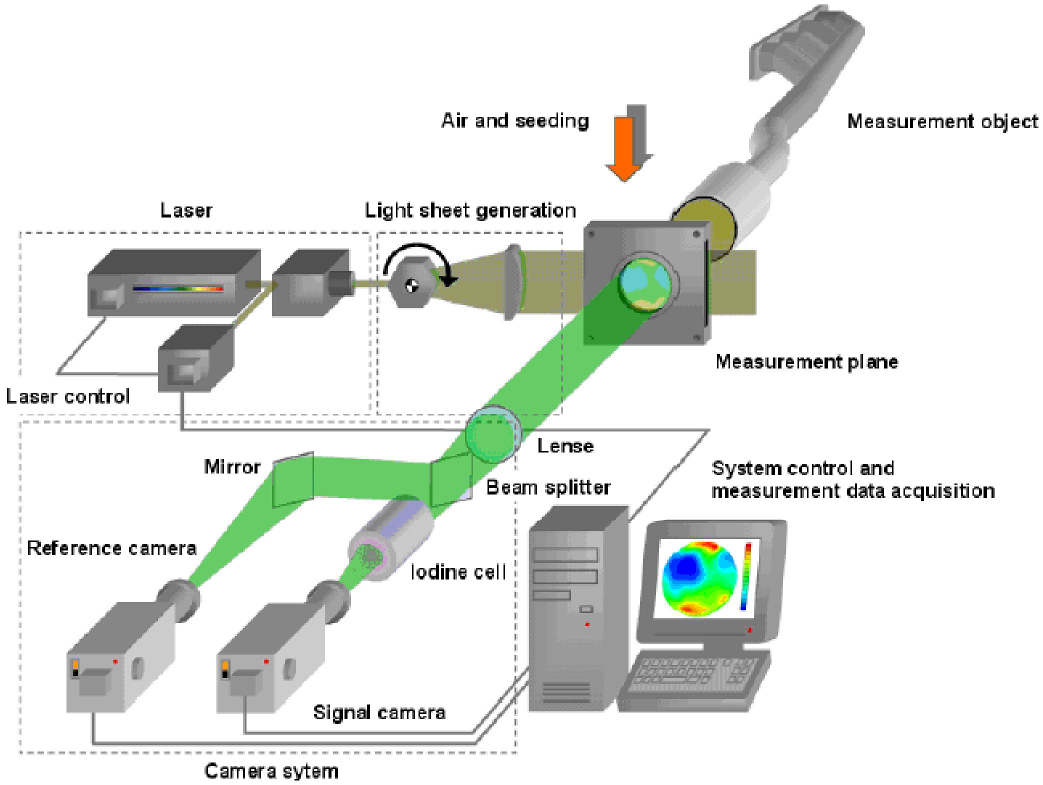
•Laser Doppler Velocimetry (LDV) or Laser Doppler Anemometry (LDA)

•Planar Doppler Velocimetry (PDV) or Planar Doppler Anemometry (PDA)

$$v_{\perp} = \frac{\lambda}{2\sin\frac{\vartheta}{2}} f$$

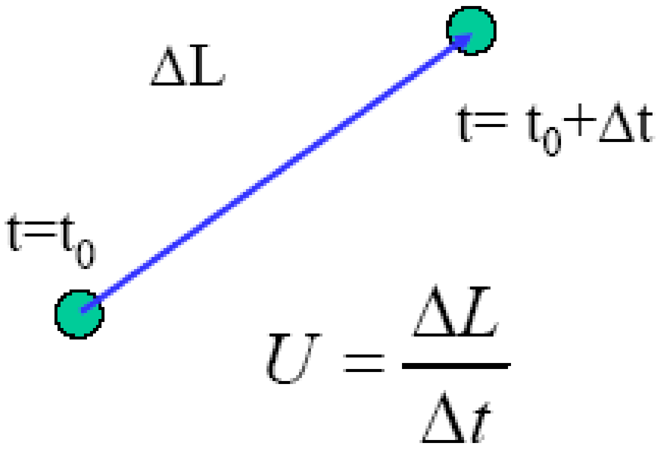


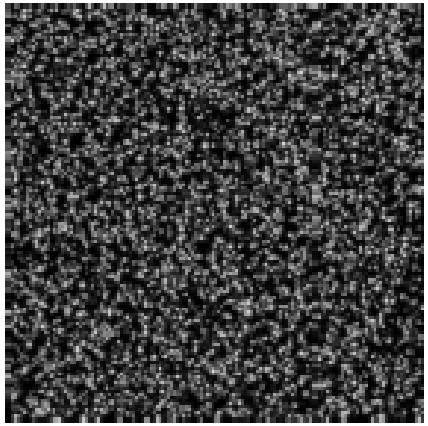


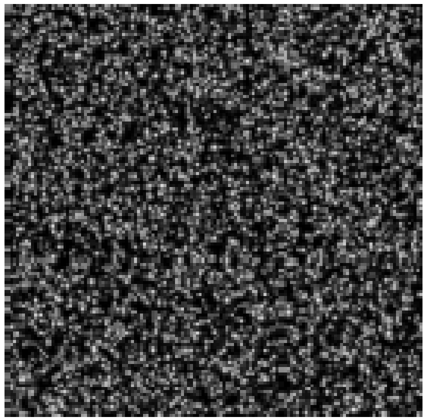


Particle Image Velocimetry Technique

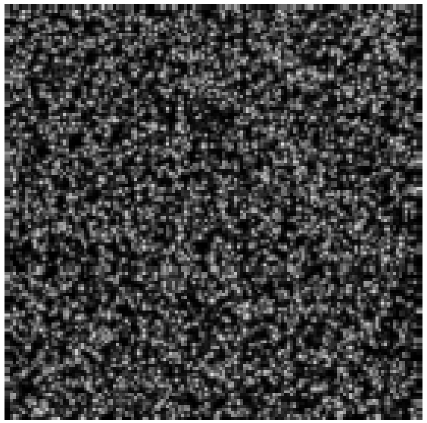
Particle displacement method: to measure the displacements of the tracer particles seeded in the flow in a fixed time interval.



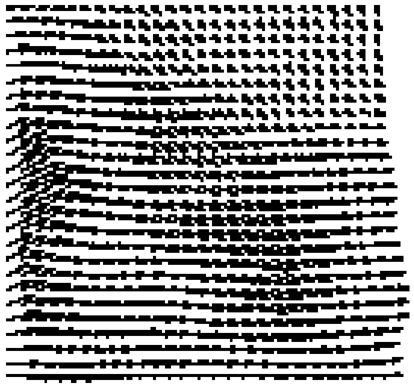




a. T=t0



b. T=t0+4ms



Corresponding Velocity field

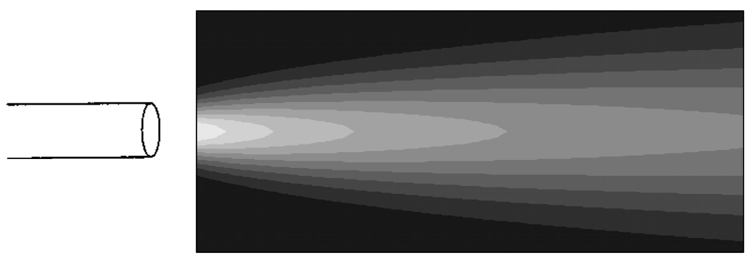
Why use imaging?

Conventional methods **(HWA, LDV)**

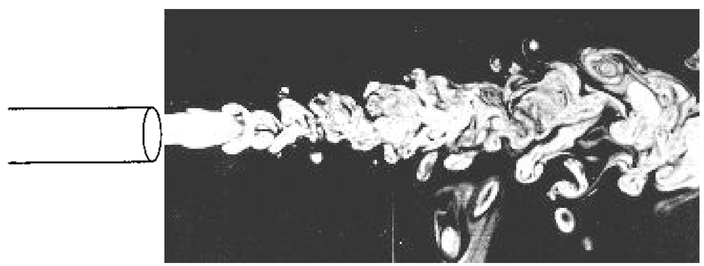
- Single-point measurement
- Traversing of flow domain
- Time consuming
- Only turbulence statistics (e.g. the mean velocity, turbulence intensity and Reynolds stress, but such quantities do not represent the actual flow structure)

Particle image velocimetry

- Whole-field method
- Non-intrusive (seeding)
- Instantaneous flow field



z



Historical development

- Quantitative velocity data from particle streak photographs (1930)
- The technique now called PIV was born as Laser speckle velocimetry; Young’s fringes analysis (Dudderar & Simpkins 1977)

The specific characteristic of scattered laser light that causes the phenomenon called “speckle” was used to allow the measurement of the displacements of the surface of samples subjected to strains.

- Particle image velocimetry
- Interrogation by means of spatial correlation
- ‘Digital’ PIV
- Stereoscopic PIV; holographic PIV

Basic Principle of PIV

•Particle Image Velocimetry is based, like Laser Doppler Velocimetry, on the measurement of the velocity of tracer particles by the fluid.

•However, rather than concentrating light in a small probe volume as in LDV, a complete plane of the flow under investigation is illuminated. This is performed by creating a narrow light sheet which is spread over the region of interest.

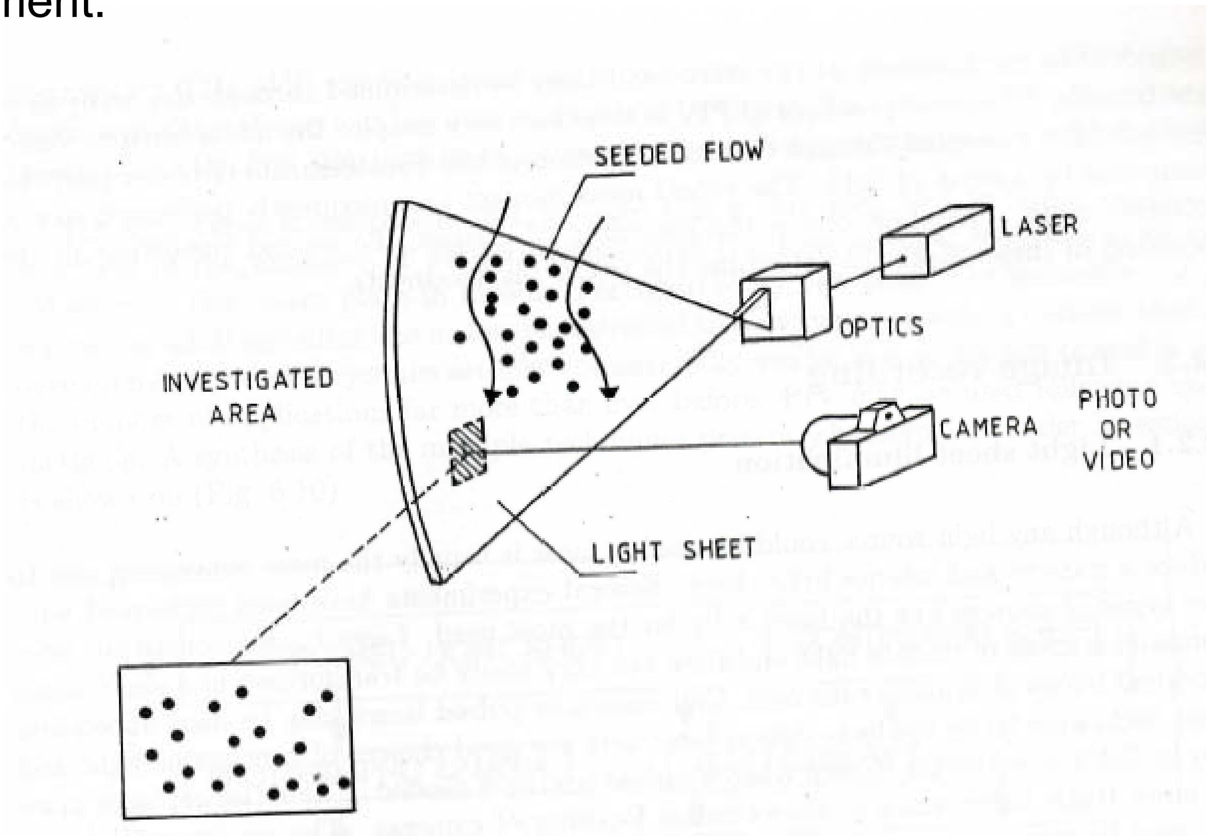
•Tracer particles are therefore made visible and images of the illuminated particles will be recorded.

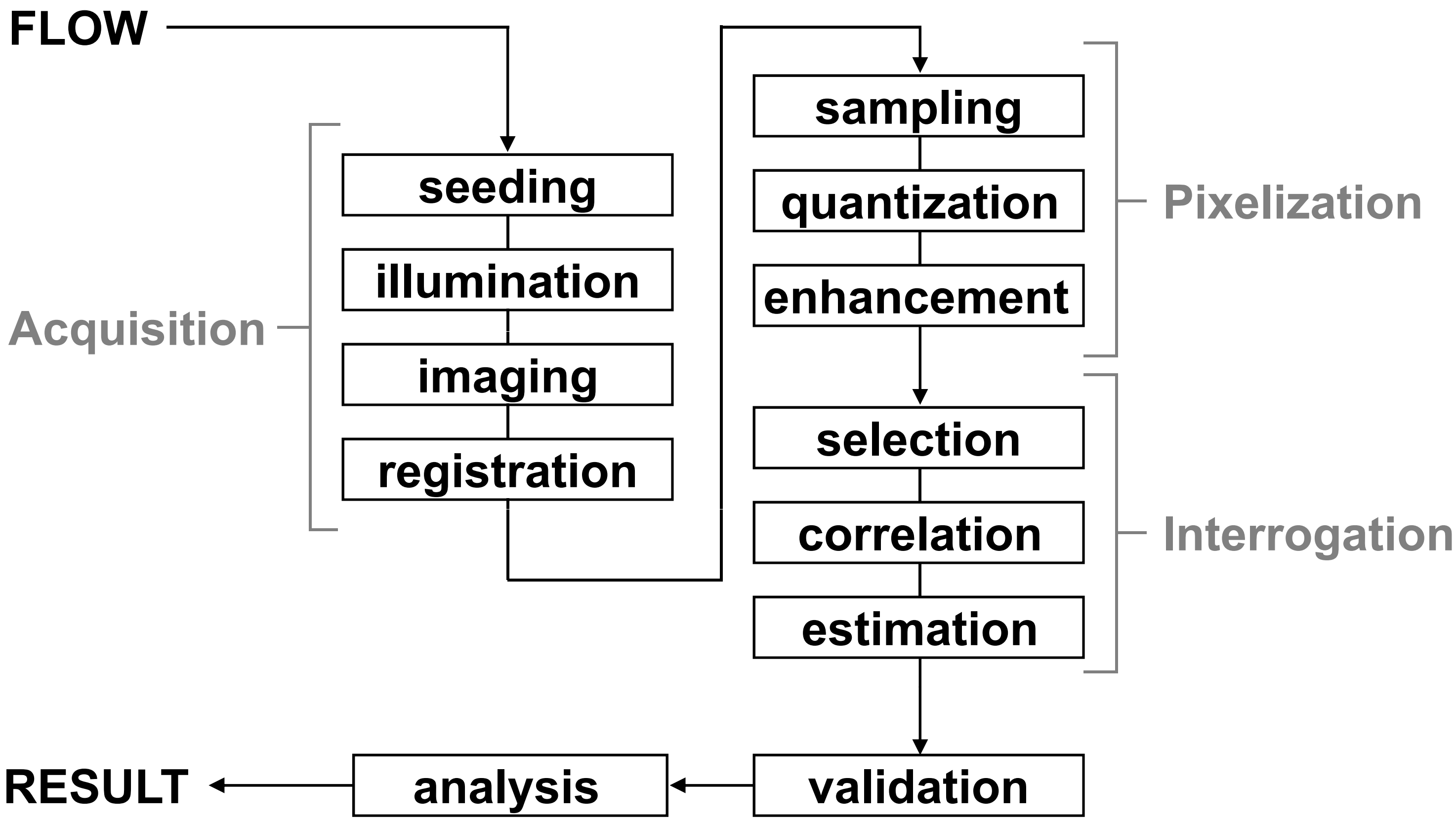
•The instantaneous velocity of a fluid is measured through the determination of the displacements of tracer particles illuminated by a sheet of light.

Basic Principle of PIV

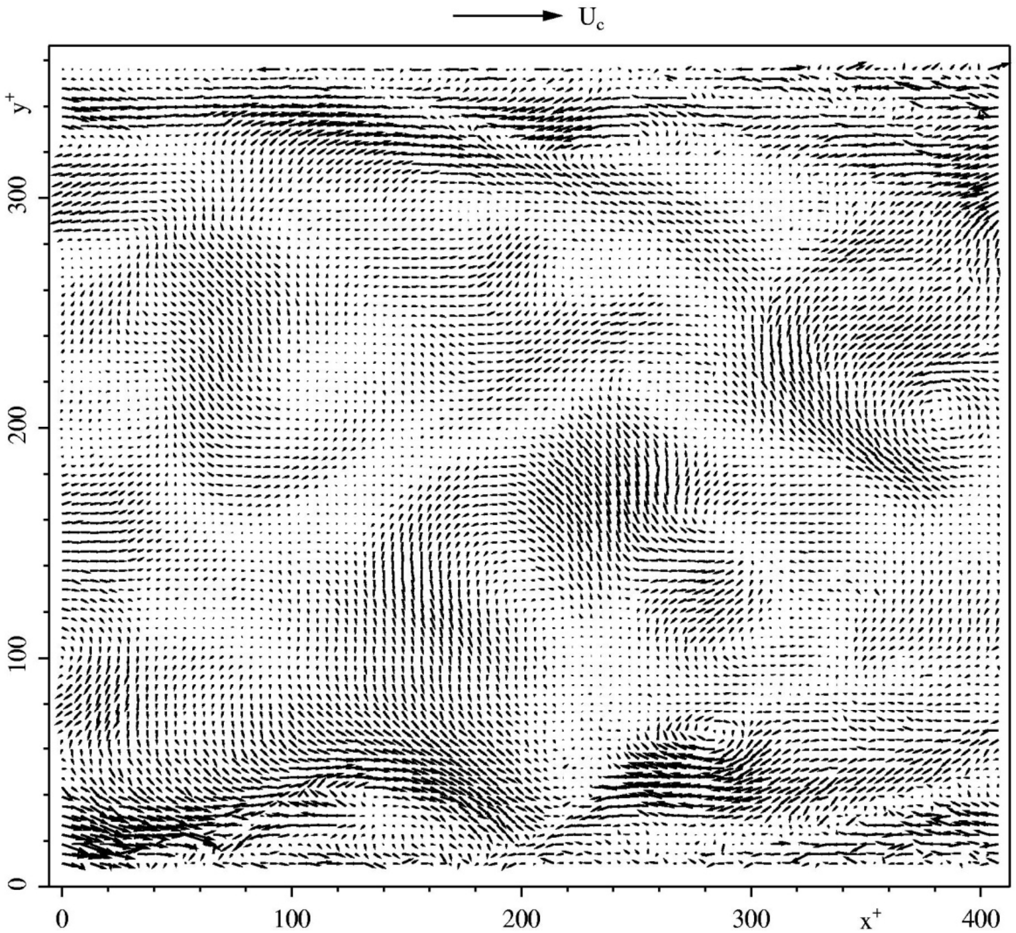
•The actual measurement is consequently performed in two successive steps:

-The fist one is the recording of images
-The second is the processing of these images to determine the tracer displacement.



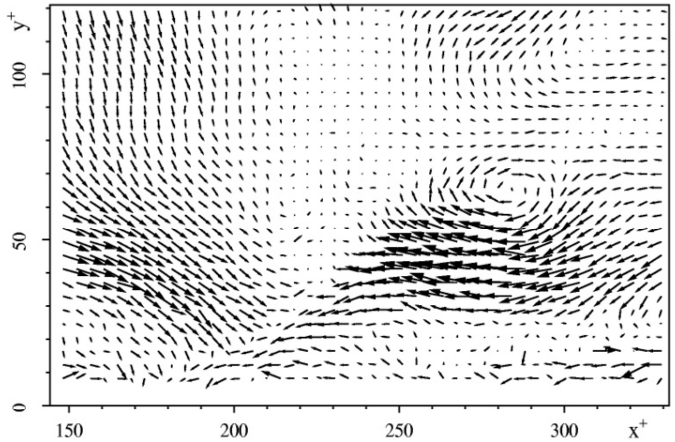

FLOW
seeding
illumination
imaging
registration
Acquisition
sampling
quantization
enhancement
Pixelization
selection
correlation
estimation
Interrogation
validation
analysis
RESULT

PIV result



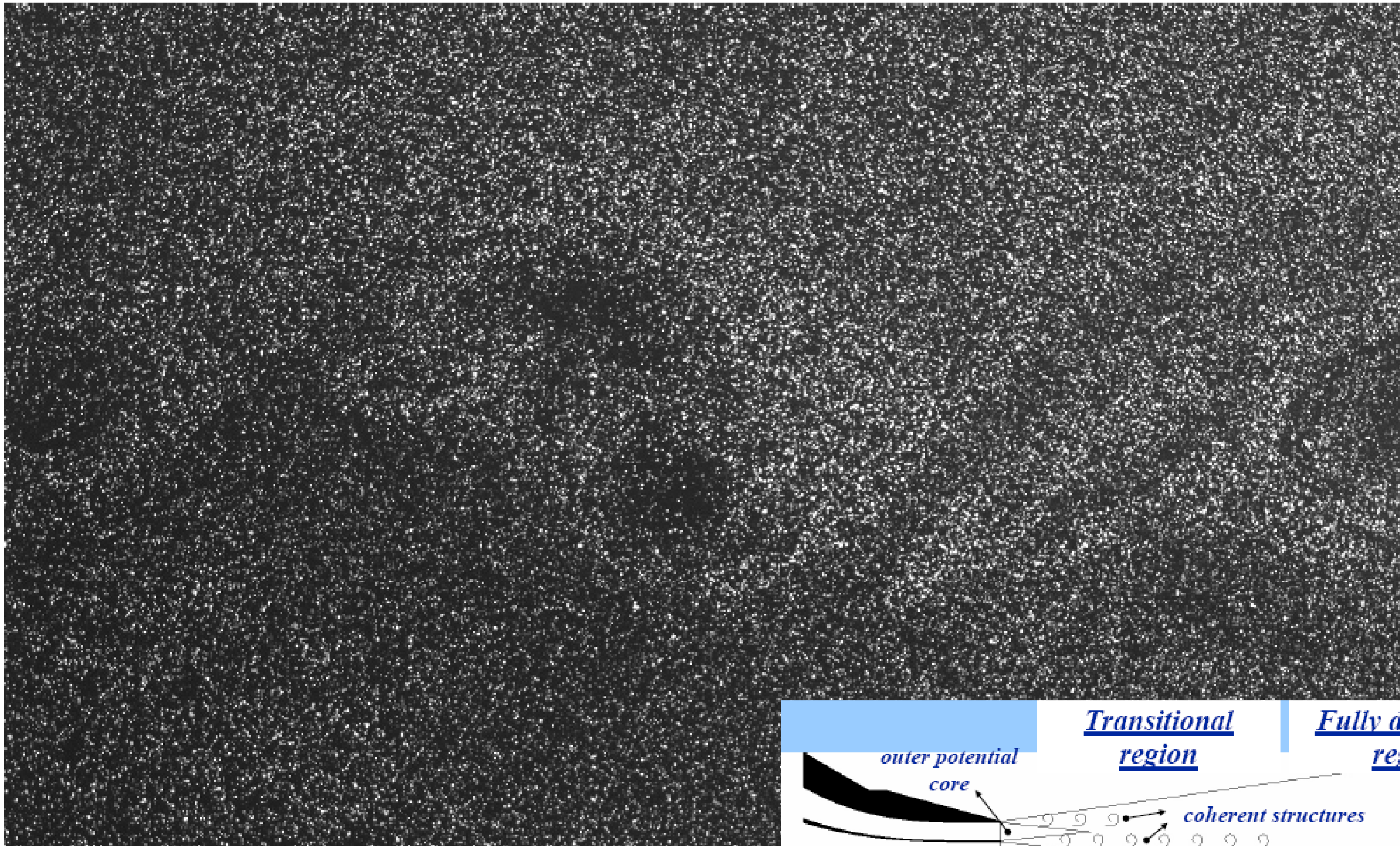
Turbulent pipe flow
***Re* = 5300**
100×85 vectors

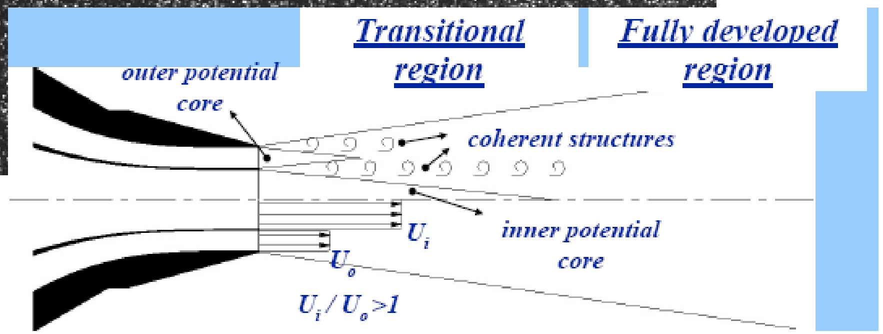
"Hairpin" vortex



Example: Annular vortex in jets

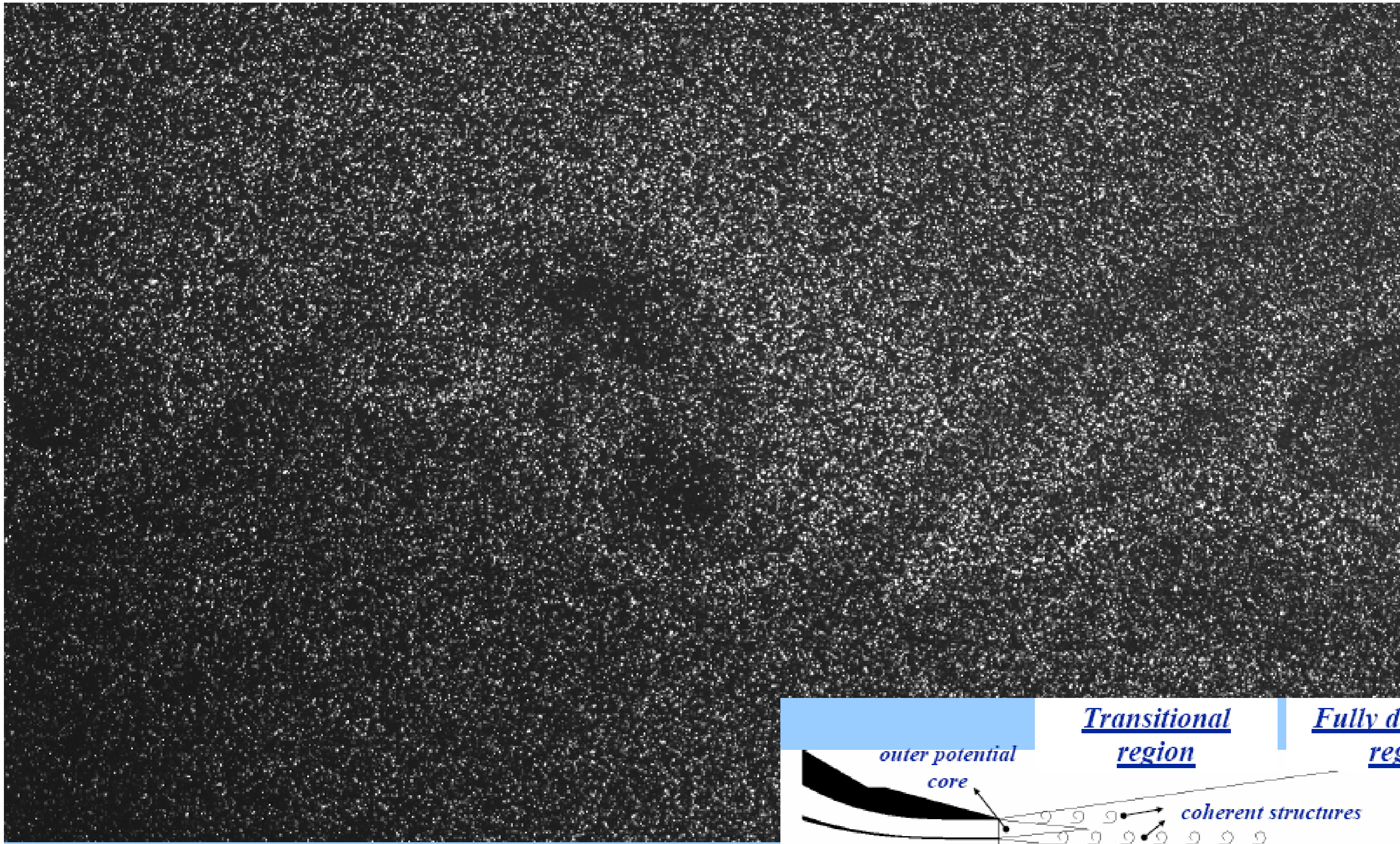
$t=t_0$

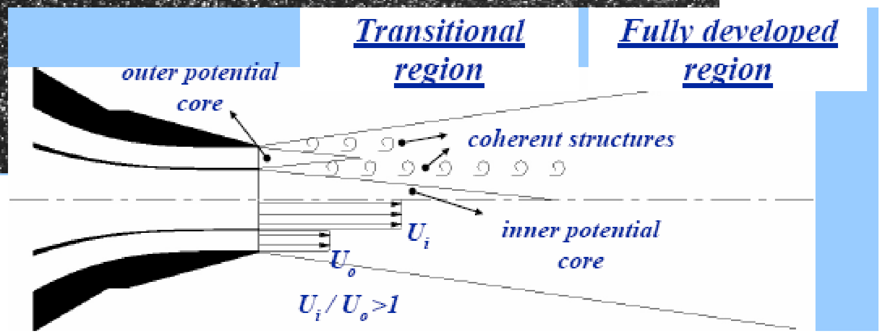




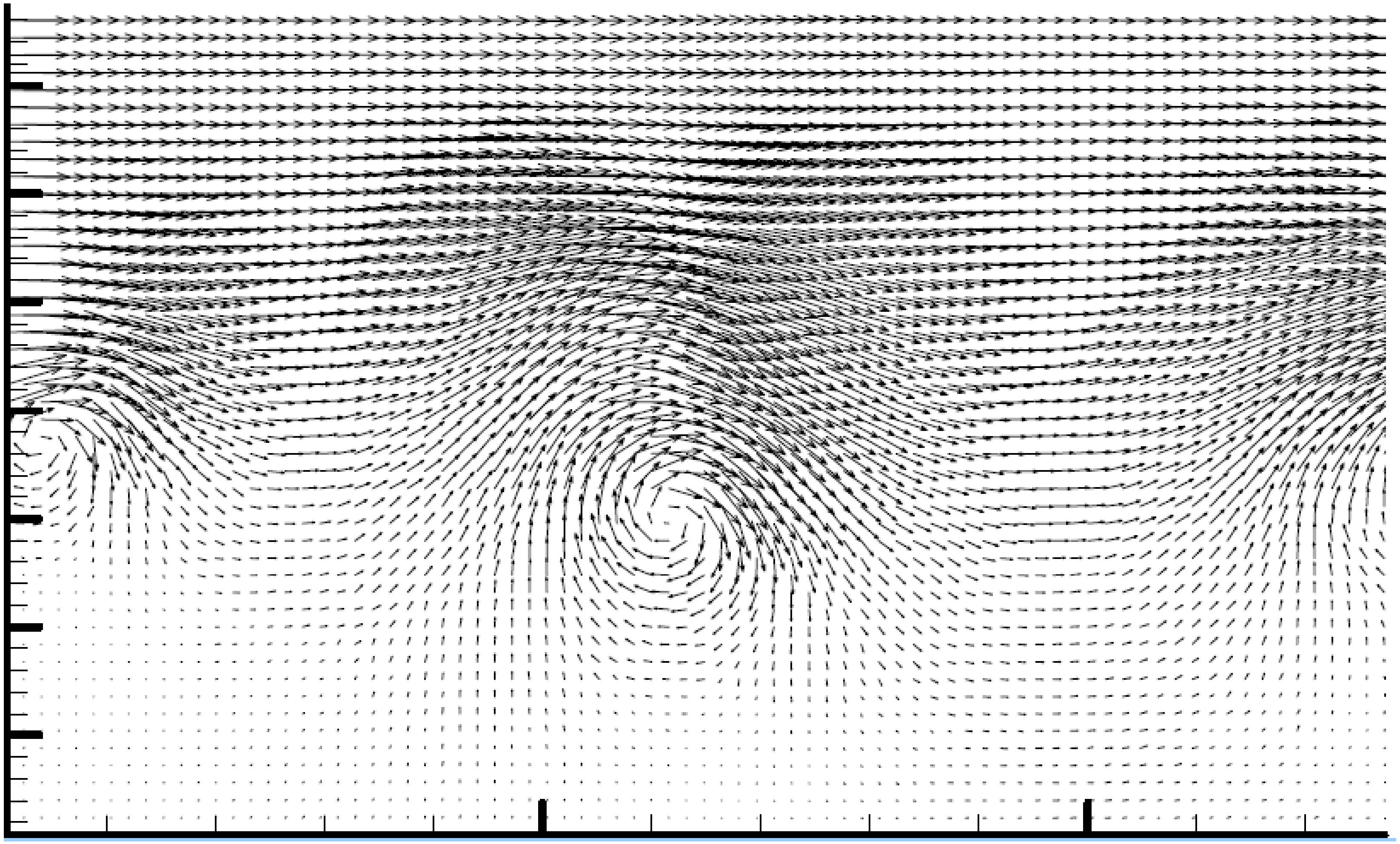
Example: Annular vortex in jets

$t=t_0+\Delta t$

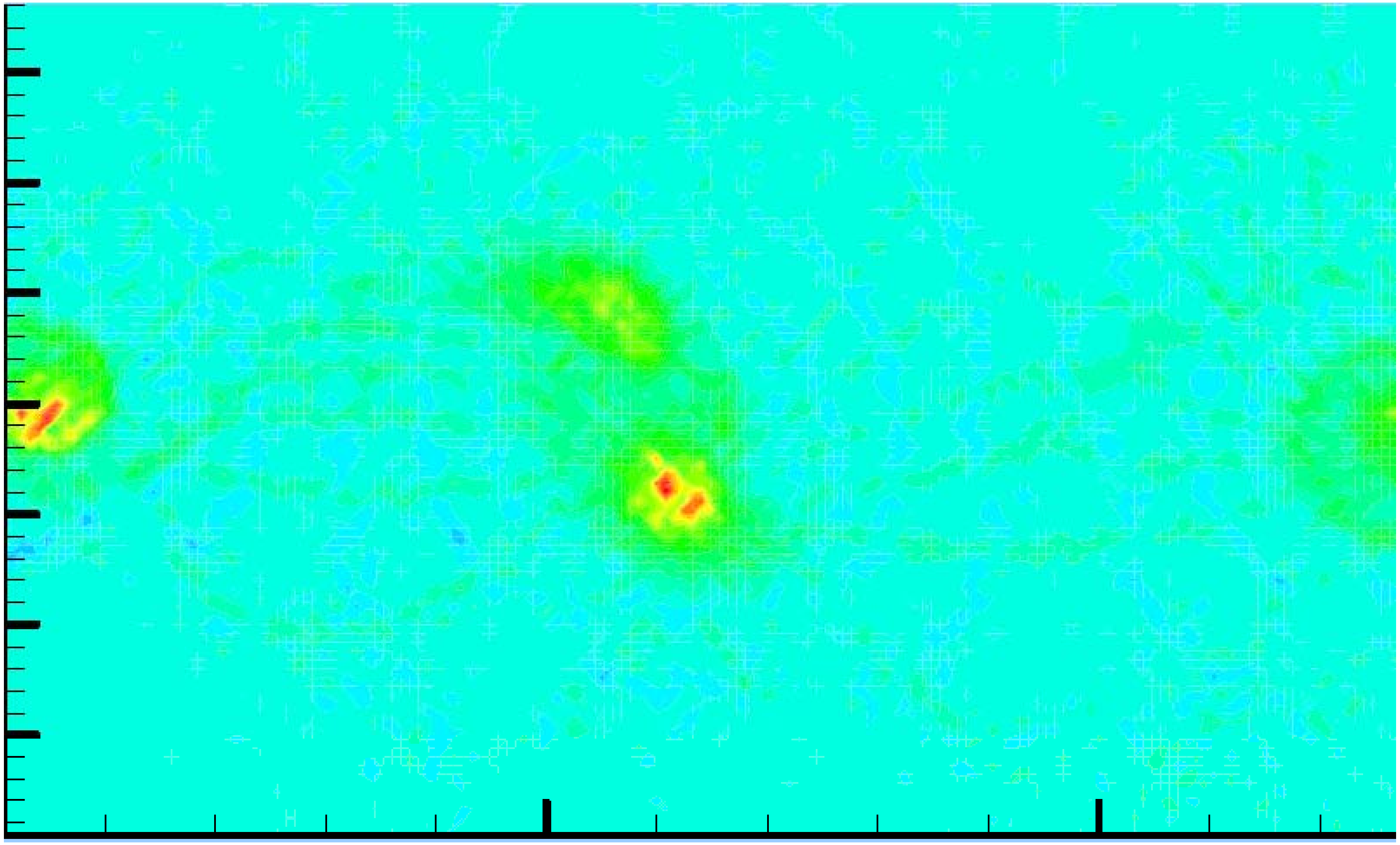




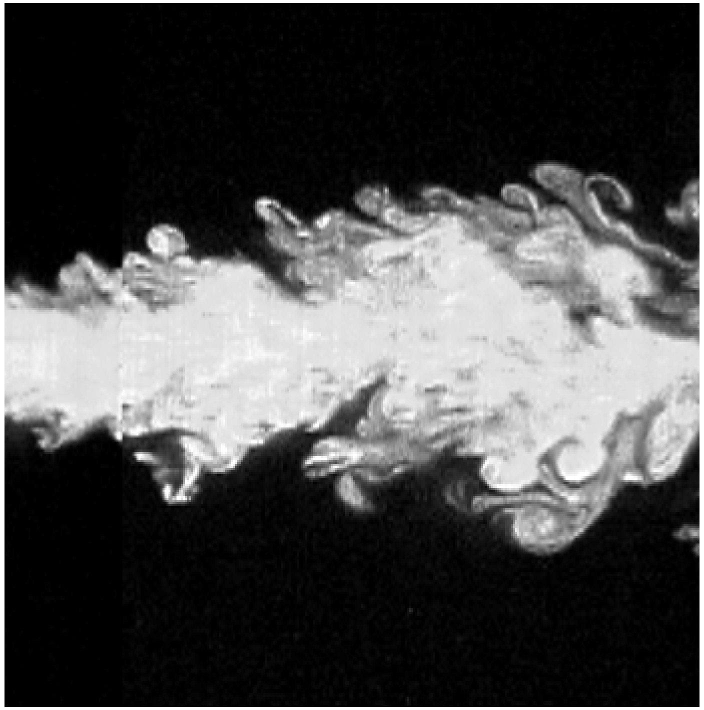
Velocity vectors



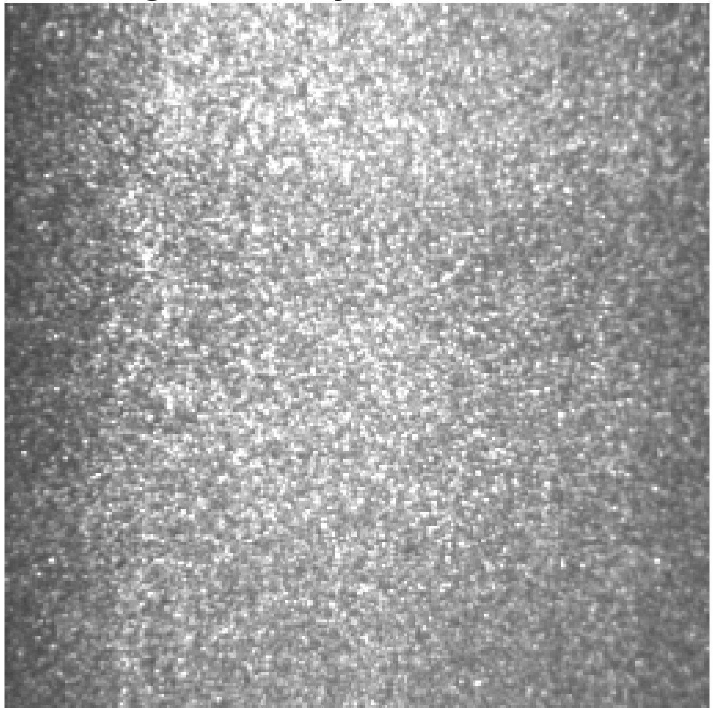
Vorticity



Visualization vs. Measurement

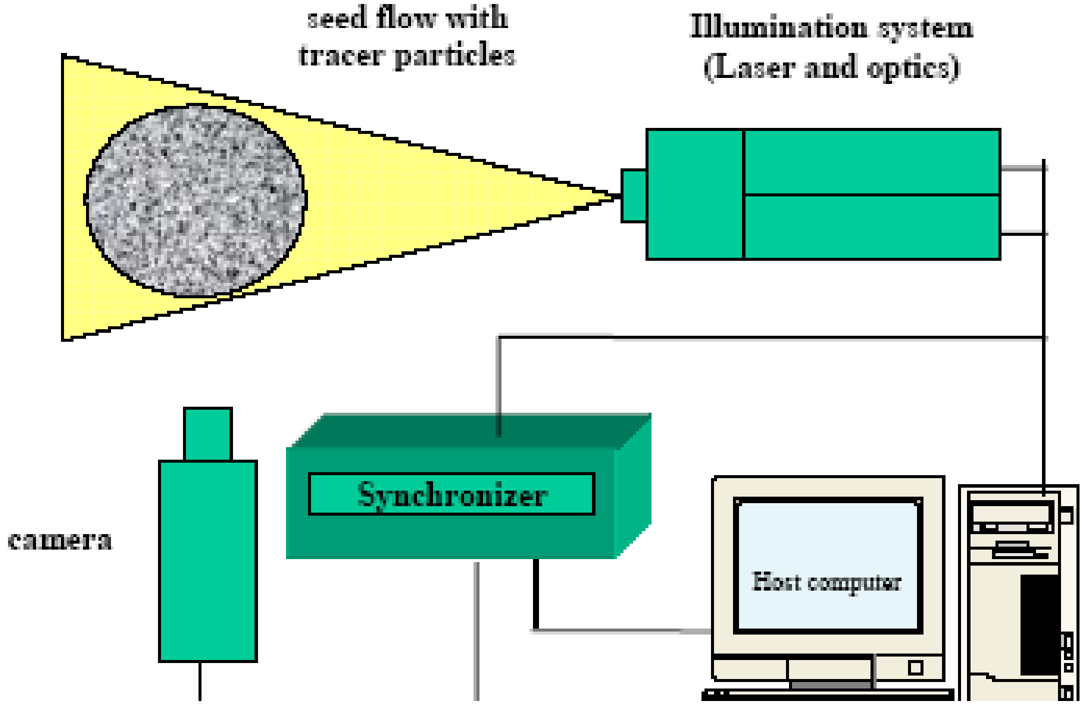


PIV the seeding should be applied *homogeneously.*



PIV System Setup

Particle tracers:	*to track the fluid movement.*
Illumination system:	*to illuminate the flow field in the interest region.*
Camera:	*to capture the images of the particle tracers.*
Synchronizer:	*the control the timing of the laser illumination and camera acquisition.*
Host computer:	*to store the particle images and conduct image processing.*



Tracer Particles for PIV

- *Tracers for PIV measurements in liquids (water):*
  - *Polymer particles (d=10~100 μm, density = 1.03 ~ 1.05 kg/cm^3)*
  - *Silver-covered hollow glass beams (d =1 ~10 μm, density = 1.03 ~ 1.05 kg/cm3)*
  - *Fluorescent particle for micro flow (d=200~1000 nm, density = 1.03 ~ 1.05 kg/cm3).*
  - *Quantum dots (d= 2 ~ 10 nm)*

- *Tracers for PIV measurements in gaseous flows:*
  - *Smoke …*
  - *Droplets, mist, vapor…*
  - *Condensations ….*
  - *Hollow silica particles (0.5 ~ 2 μm in diameter and 0.2 g/cm3 in density for PIV measurements in combustion applications.*
  - *Nanoparticles of combustion products*

Definitions for PIV

- **Source density:** $N_S = \frac{C\Delta z_0}{M^2}\frac{\pi}{4}D_P^2$

- **Image density:** $N_I = \frac{C\Delta z_0}{M^2}\frac{\pi}{4}D_I^2$

$$D_I = \sqrt{(M^2 D_P + D_E)}$$

$$D_E = 2.44(1+M)\,f_{\#}\lambda$$

C	tracer concentration [m^{-3}]
Δz_0	light-sheet thickness [m]
M	image magnification [-]
D_P	particle-image diameter [m]
D_I	interrogation-spot diameter [m]
$f_{\#}$	f-number of the recording optics
λ	wavelength of the laser [m]

•**The source density represents the type of image that is recorded**. A source density larger than one means that the image is a speckle pattern (images of individual particles overlap to cause a random interference pattern). When the source density is less than one the image consists of individual particle images.

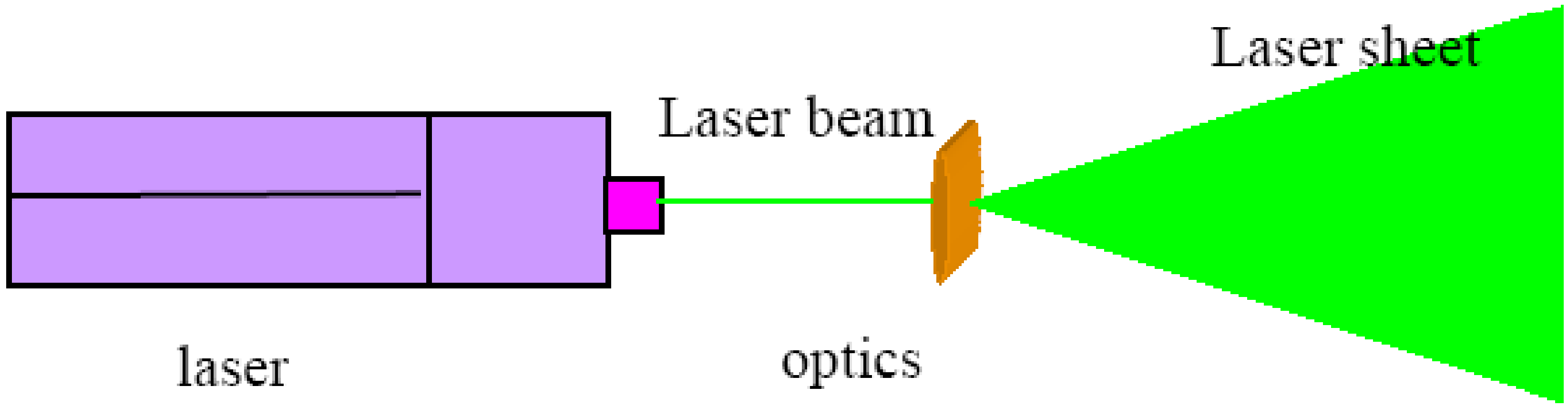
•**The image density represents the mean number of particle images in an interrogation region.** For a successful PIV measurement it is important that this number is larger than about 10-15.

Illumination system of PIV

• The illumination system of PIV is always composed of light source and optics.

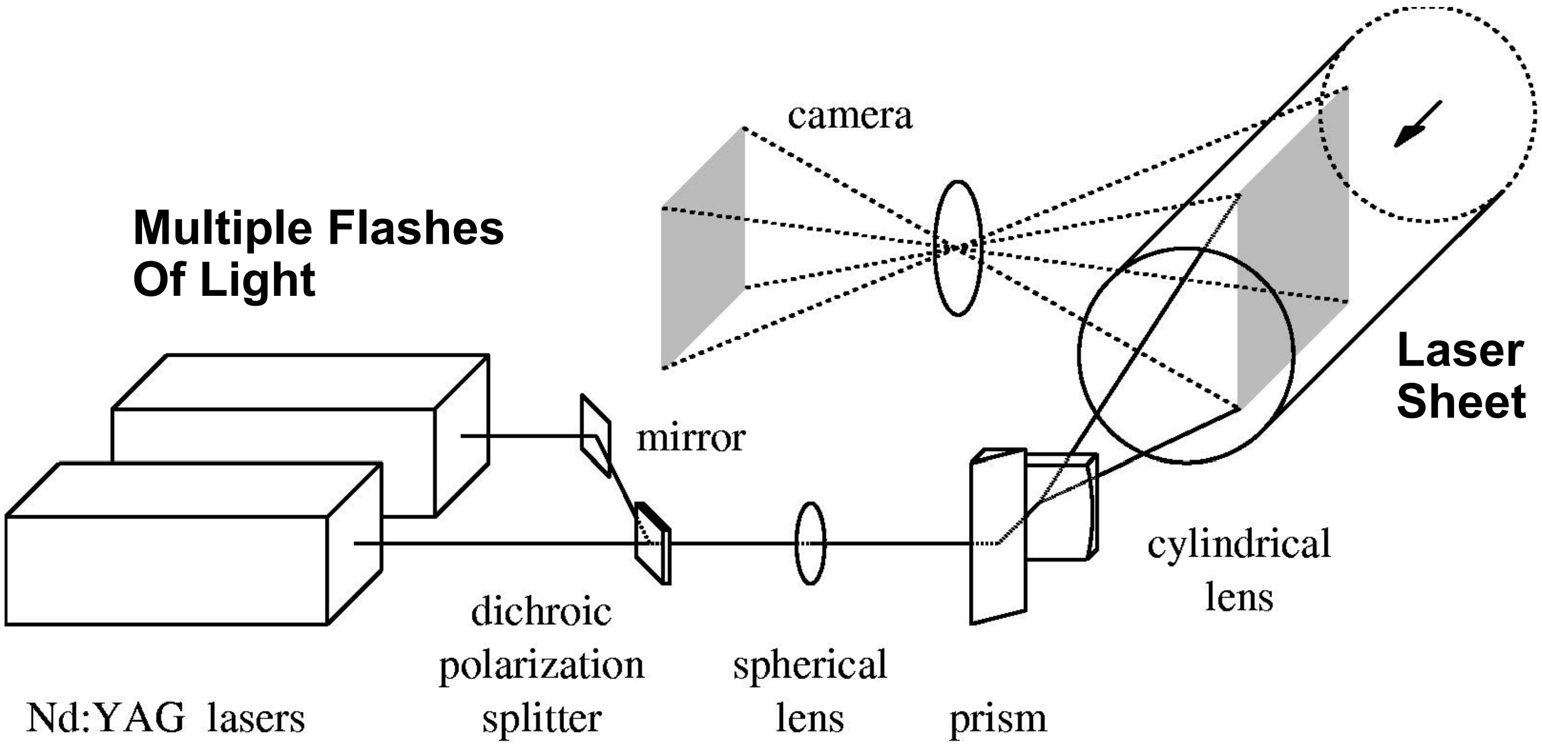
• Lasers: such as Argon-ion laser and Nd:YAG Laser, are widely used as light source in PIV systems due to their ability to emit monochromatic light with high energy density which can easily be bundled into thin light sheet for illuminating and recording the tracer particles without chromatic aberrations.

• Optics: always consisted by a set of cylindrical lenses and mirrors to shape the light source beam into a planar sheet to illuminate the flow field.



PIV optical configuration

The typical optical configuration of a PIV set-up includes a light source (usually a double-pulse laser), light-sheet optics (beam combining optics, beam delivery, and light-sheet formation optics), tracer particles, and a camera (imaging lens and recording media).



Double pulsed Nd:YAG laser for PIV

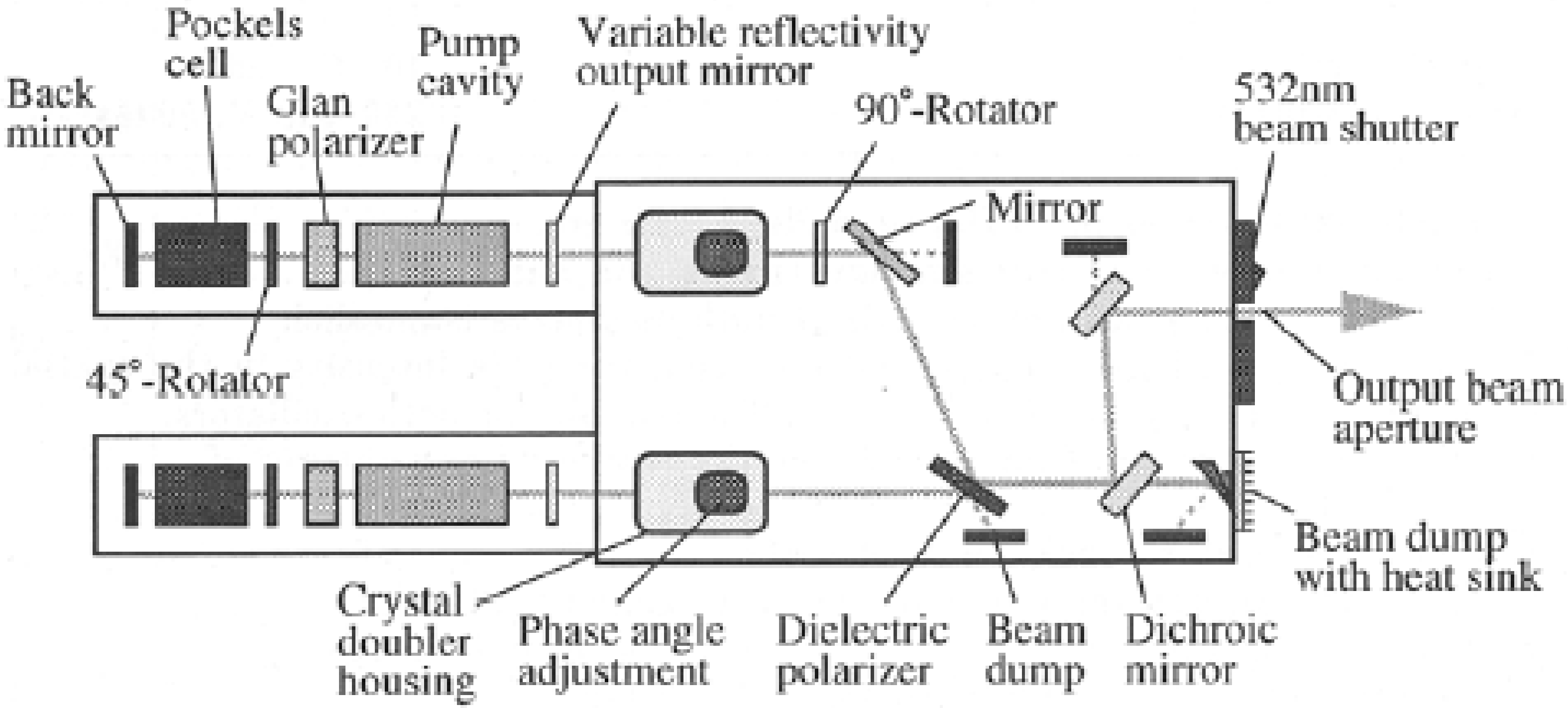
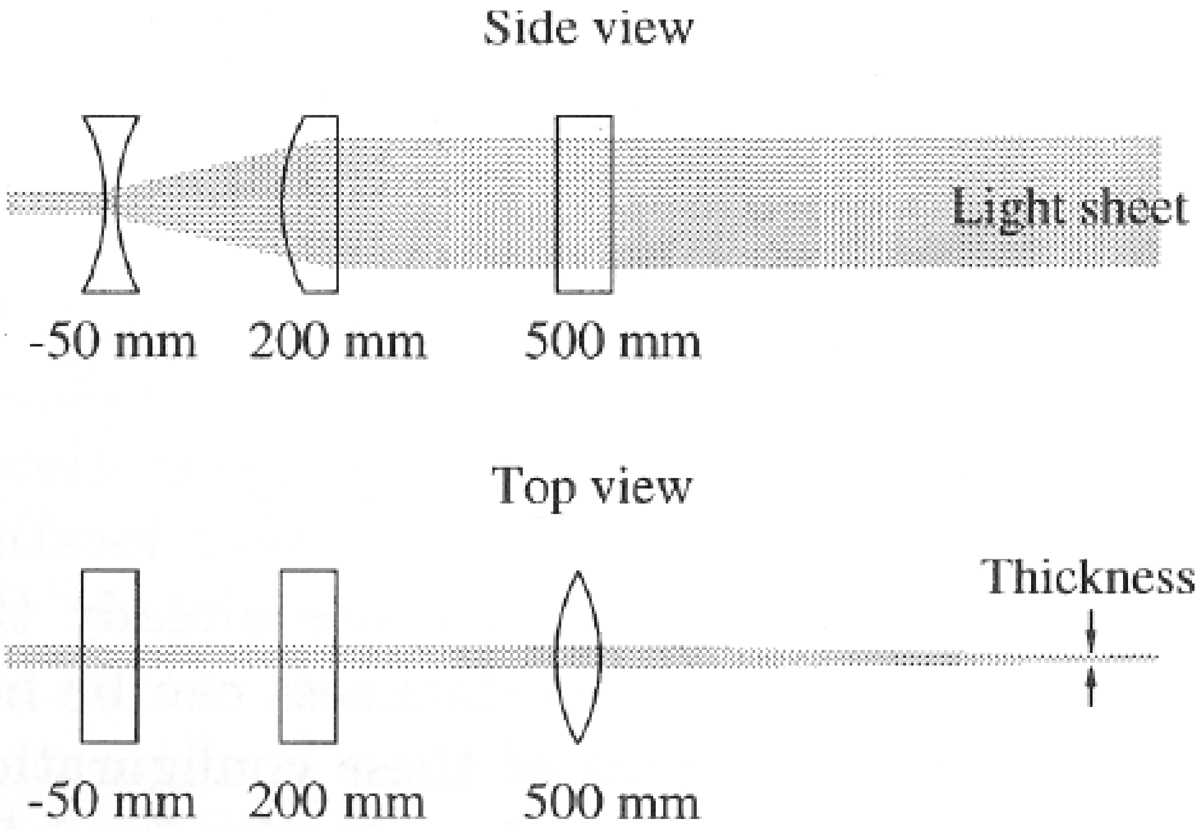


Fig. 2.17. Double oscillator laser system with critical resonators

Optics for PIV

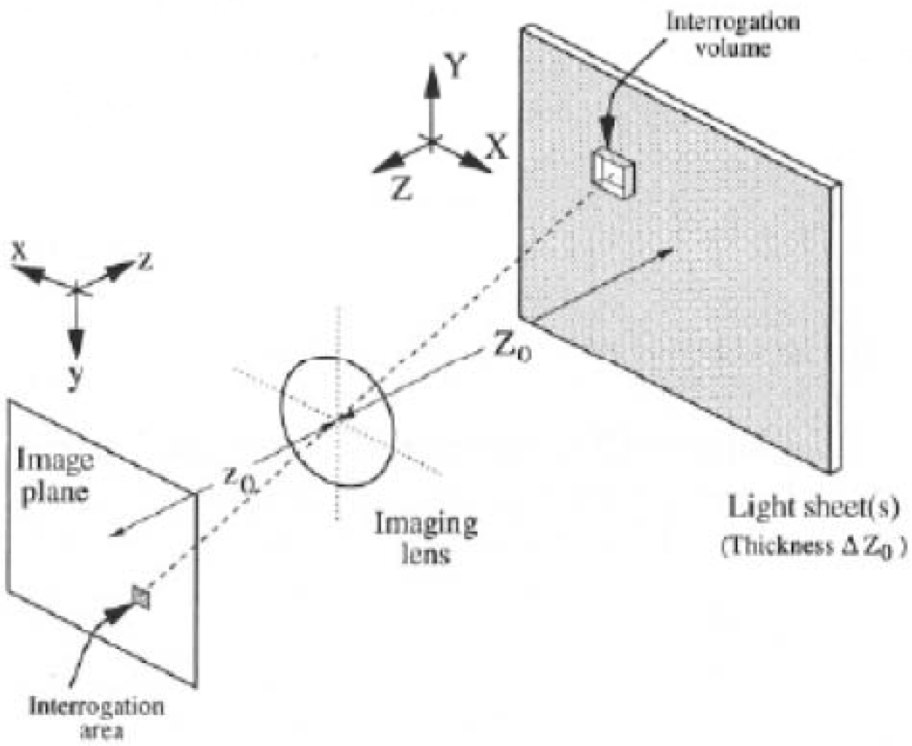


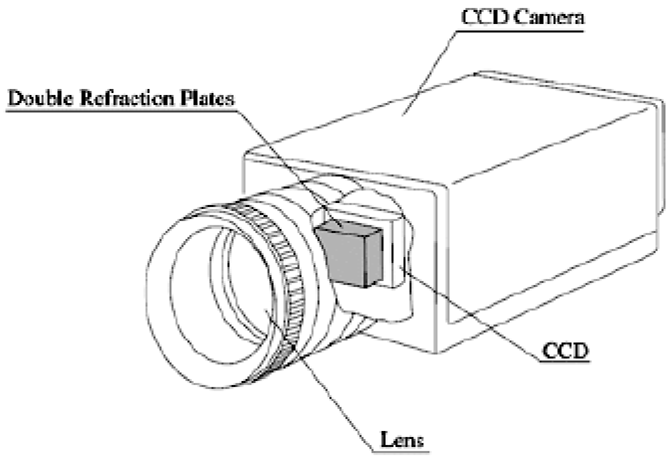
Cameras

- The widely used cameras for PIV:
    - Photographic film-based cameras or Charged-Coupled Device (CCD) cameras.

- Advantages of CCD cameras:
    - It is fully digitized
    - Various digital techniques can be implemented for PIV image processing.
    - Conventional auto- or cross- correlation techniques combined with special framing techniques can be used to measure higher velocities.

Light sensing and recording





Lenses

$f_{\#}$ (f-number or focal ratio) is defined as the ratio of focal distance of the lens and its clear aperture diameter.

f2 F2.8	*f4 f5.6 f8 f11*	*f16 f 22*
wide aperture		*small aperture*
more light		*less light*
small number		*larger number*
		

Filters

Particularly important in PIV and PLIF applications, the correct filtering scheme ensures the collection of appropriate light signals, while rejecting unwanted wavelengths, in order to obtain data of the highest possible quality and thus the highest measurement accuracy.

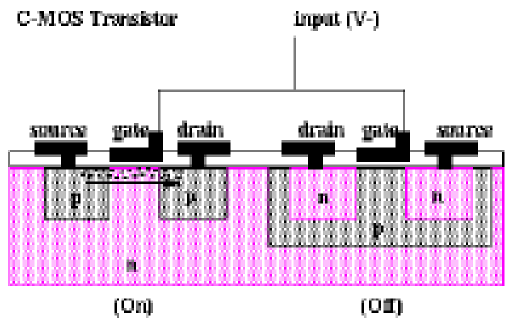
Features and Benefits

- Full range of transmission wavelengths
- Long wave pass, short wave pass, and band pass filters
- Built in threaded mounts for direct attachment to camera lens

TSI

Digital Camera

- *CCD camera and Intensified CCD (ICCD) camera:*
  - *Spatial resolution: 1K by 1k, 4K by 4K*
  - *Frame rate : 30 Hz, High speed camera 1khz ~10K hz*
  - *In a CCD sensor, every pixel's charge is transferred through a very limited number of output nodes (often just one) to be converted to voltage, buffered, and sent off-chip as an analog signal. All of the pixel can be devoted to light capture, and the output's uniformity (a key factor in image quality) is high.*
- *CMOS (Complementary metal-oxide semiconductor) cameras*
  - *In a CMOS sensor, each pixel has its own charge-to-voltage conversion, and the sensor often also includes amplifiers, noise-correction, and digitization circuits, so that the chip outputs digital bits*
  - *These other functions increase the design complexity and reduce the area available for light capture. With each pixel doing its own conversion, uniformity is lower. But the chip can be built to require less off-c*
- *In summary for CMOS cameras*
  - *Low cost*
  - *Operation versatility*
  - *High speed*
  - *Quality is not as high as CCD cameras*



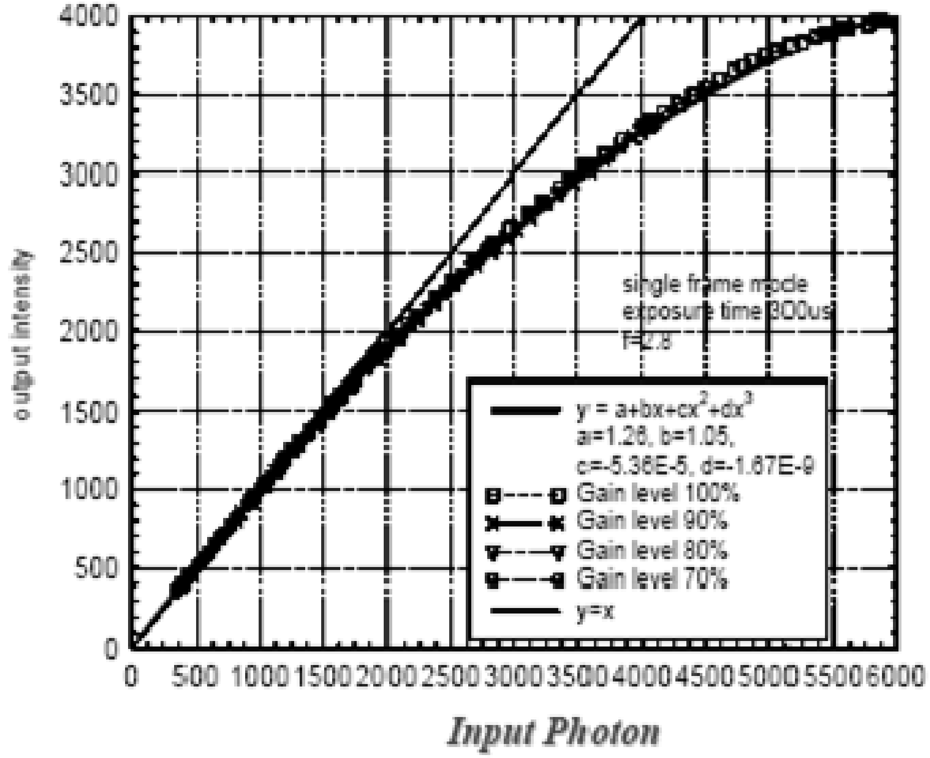
Linearity and Dynamic Range of a Digital Camera

Linearity:

- *Intensified CCD cameras usually need to check its linearity*

Dynamic Range:

- *The ratio between the full-well capacity and the dark current noise.*
- *For example, for a 8-bit CCD camera, maximum intensity is $2^8=256$, dark current noise is about 25, then Dynamic range is about 10.*
- *Available bits number:*
  - *8 bit, 16 bit, 24 bit*

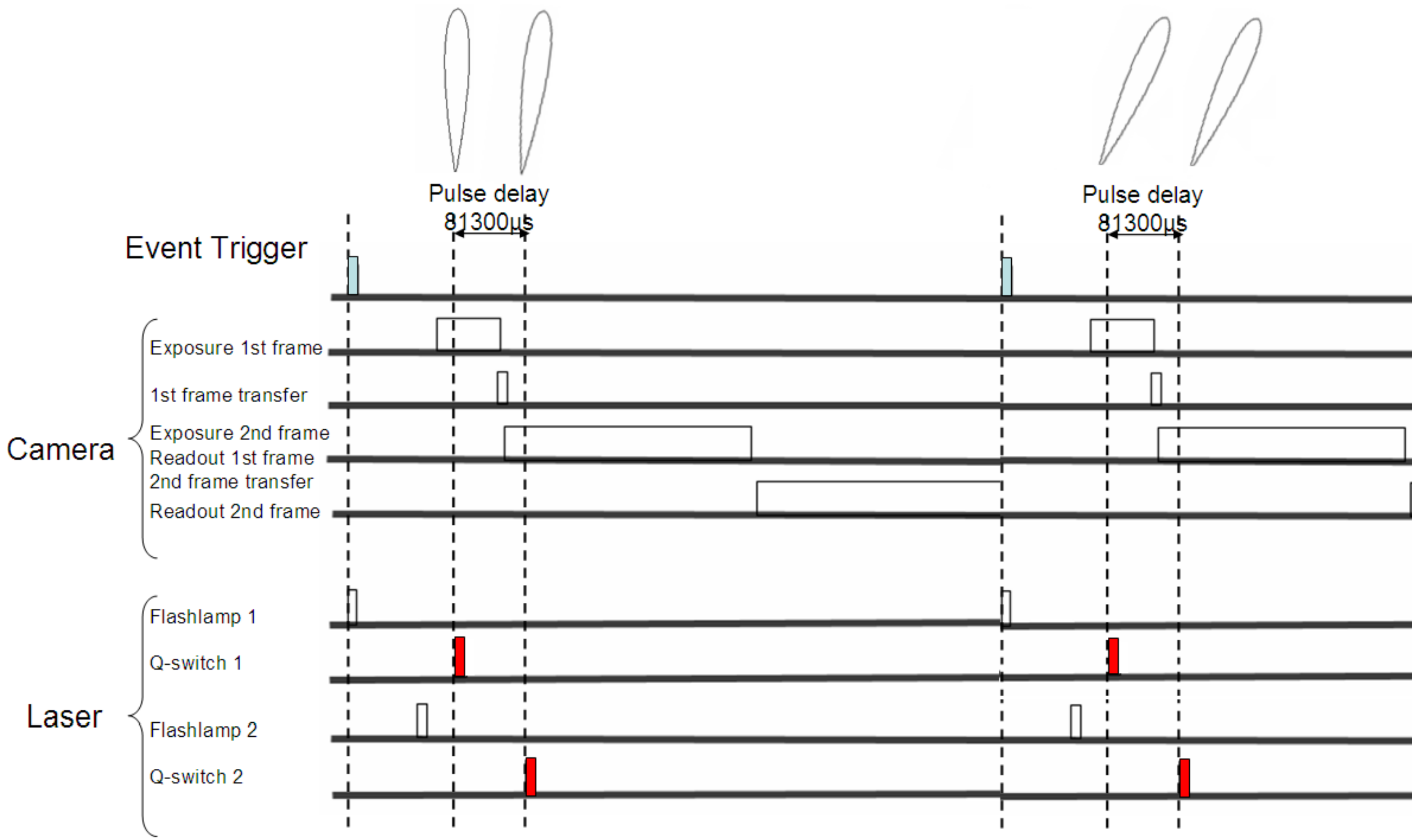


TSI models

	Model HS-200	Model HS-650	Model HS-2000	Model HS-3000
Maximum frames per second at full resolution	200	636	2000	3000
Pixel resolution	480 x 640	1280 x 1024	1024 x 1024	1024 x 1024
Digitization	12 bit	10 bit	10 bit	10 bit
Pixel type	7.4 μm x 7.4 μm	12 μm x 12 μm	17 μm x 17 μm	17 μm x 17 μm
Sensor type	CCD	CMOS	CMOS	CMOS
Standard on-board memory	Cameralink output	2GB	2.6GB	2.6GB
Maximum on-board memory	Cameralink output	4GB	8GB	16GB

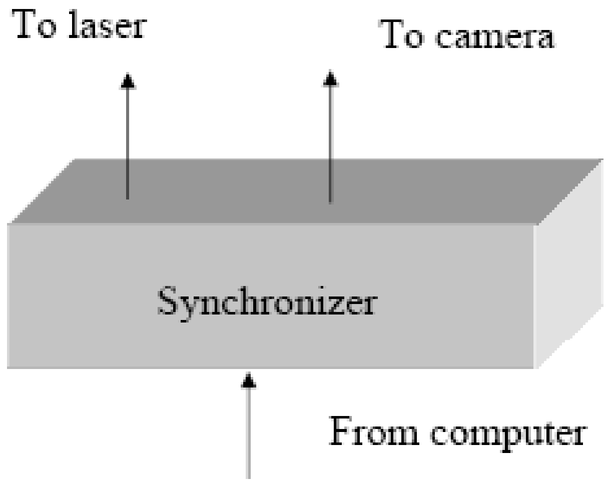
Frame rate from 3000 to 250000 fps

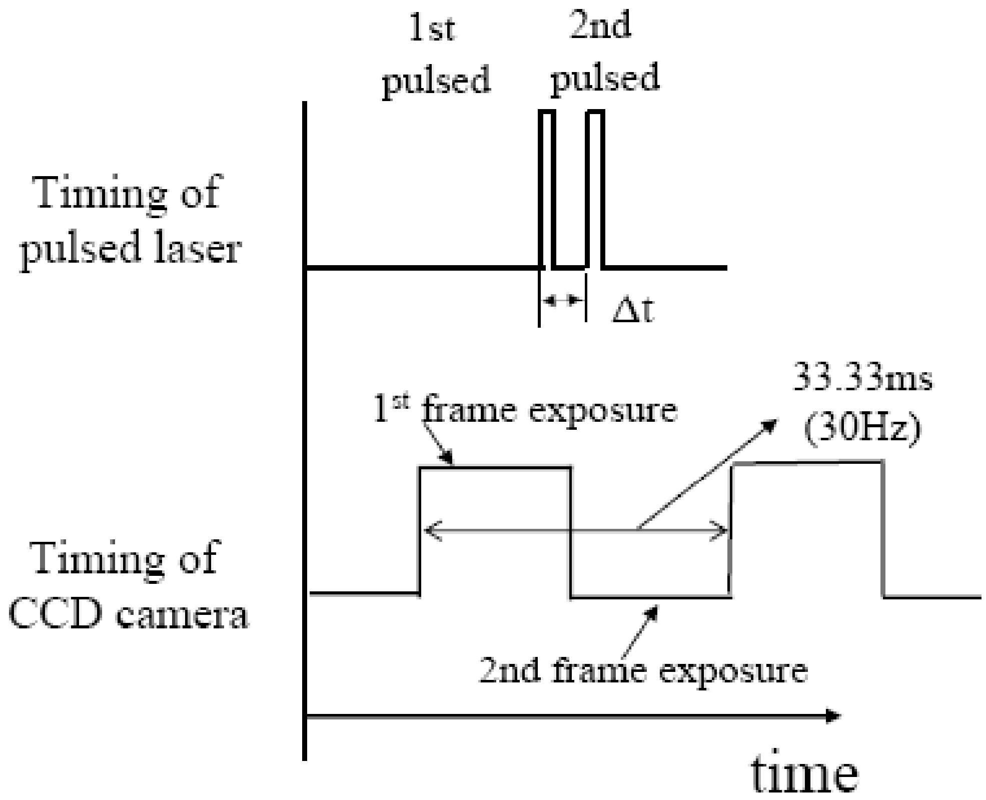
An example Time Chart of PIV measurement



Synchronizer

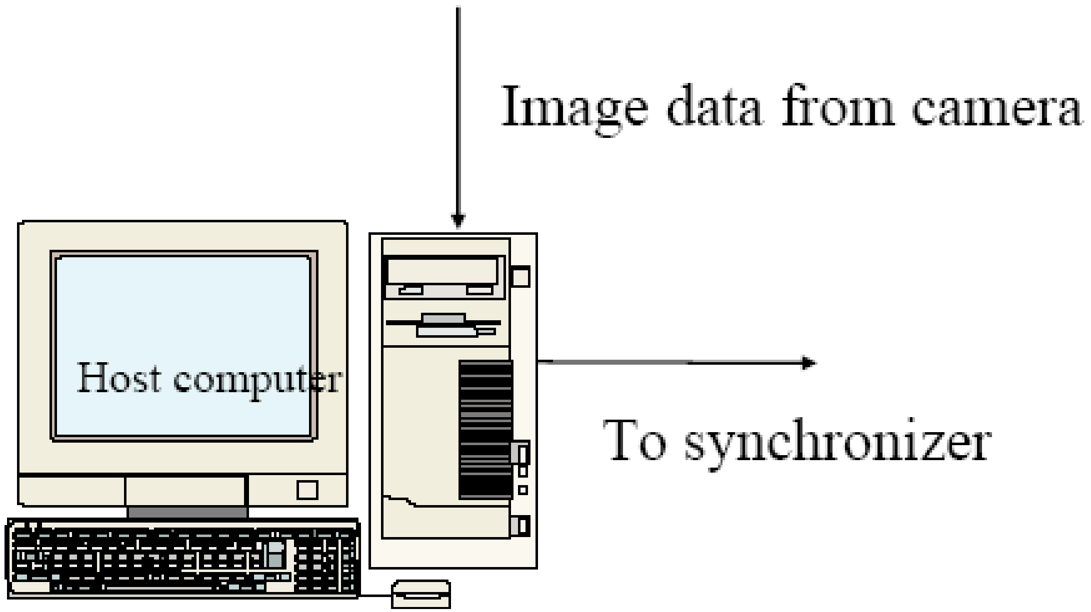
- ***Function of Synchronizer:***
    - ***To control the timing of the laser illumination and camera acquisition***



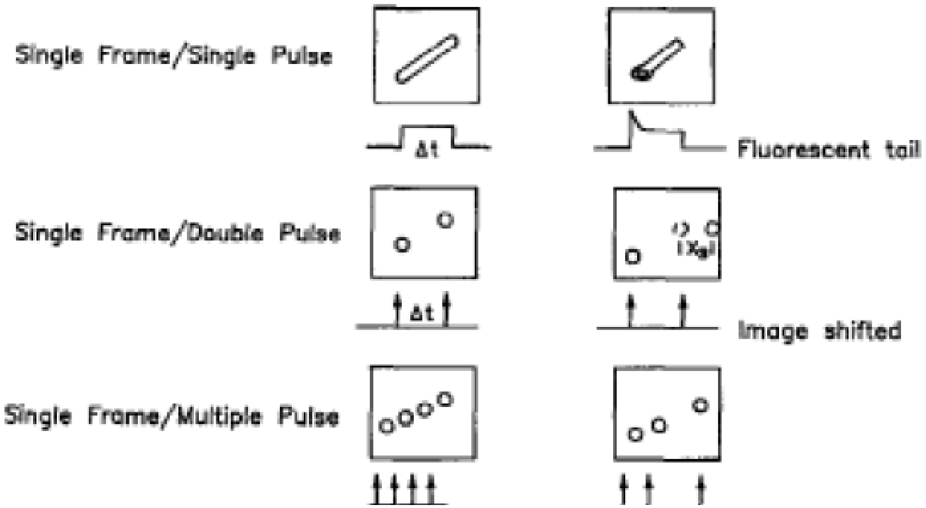


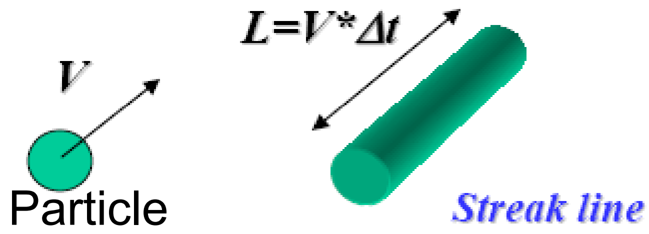
Host Computer

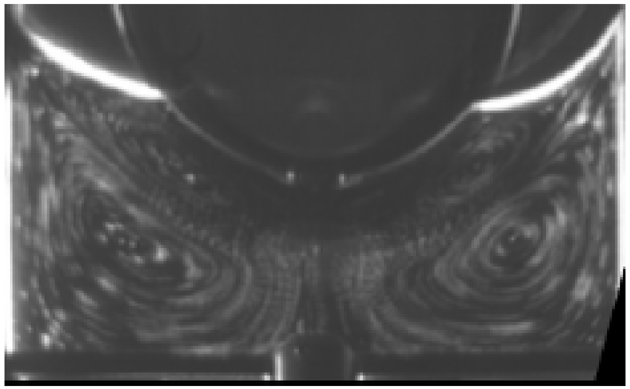
- **To send timing control parameter to synchronizer.**
- **To store the particle images and conduct image processing.**

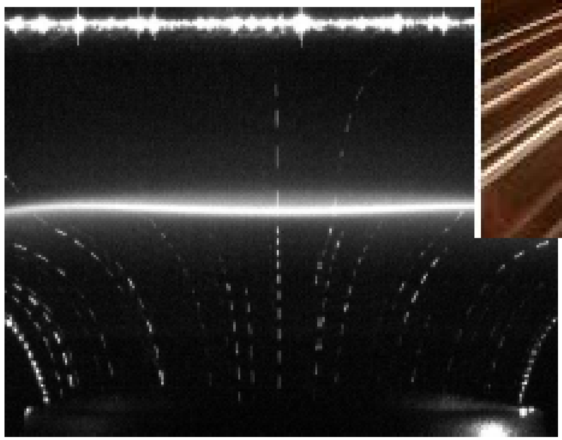


Single Frame Technique







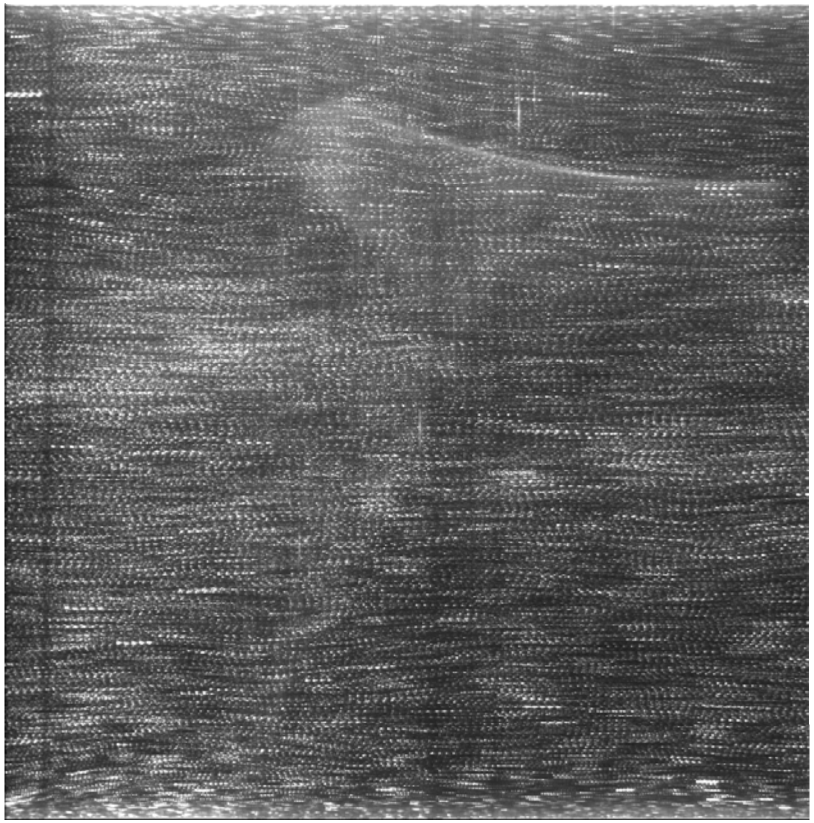


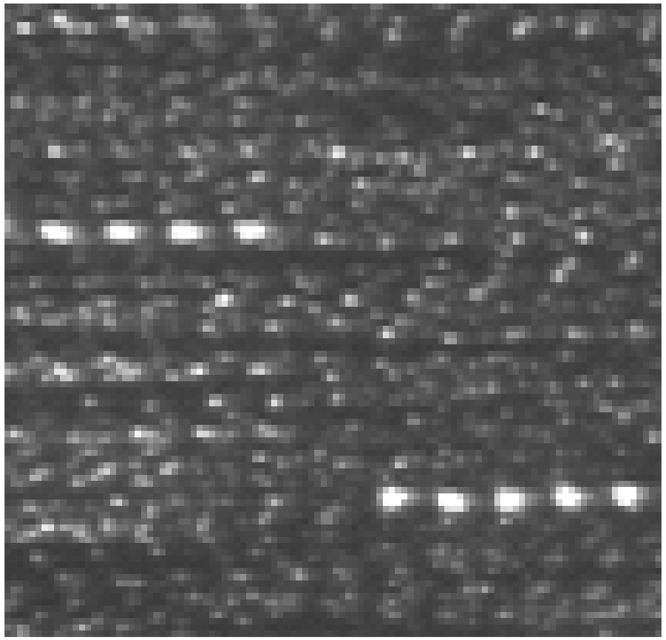
single-pulse

Multiple-pulse

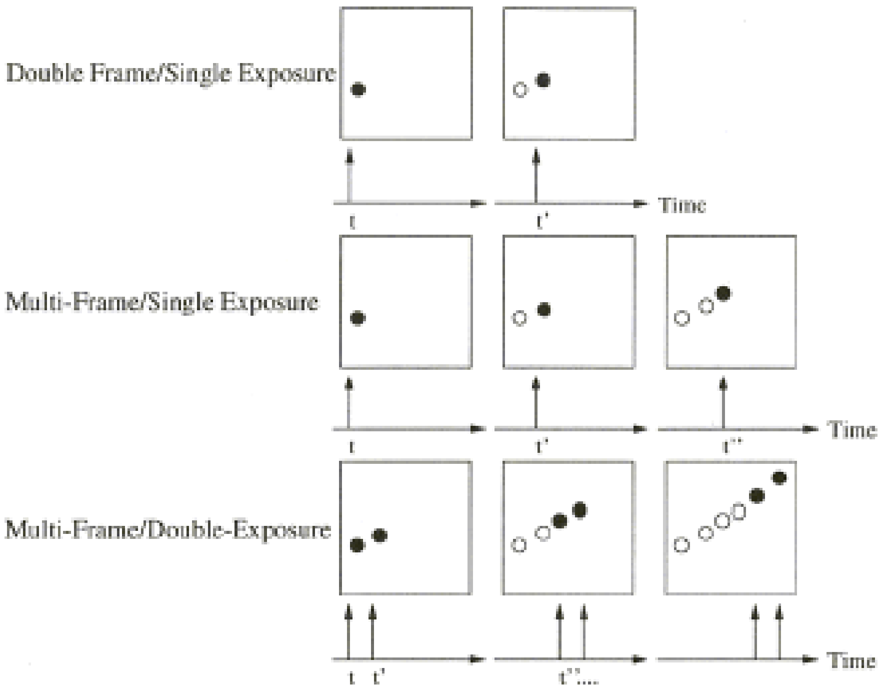
Multiple Exposure PIV image on a Single Frame

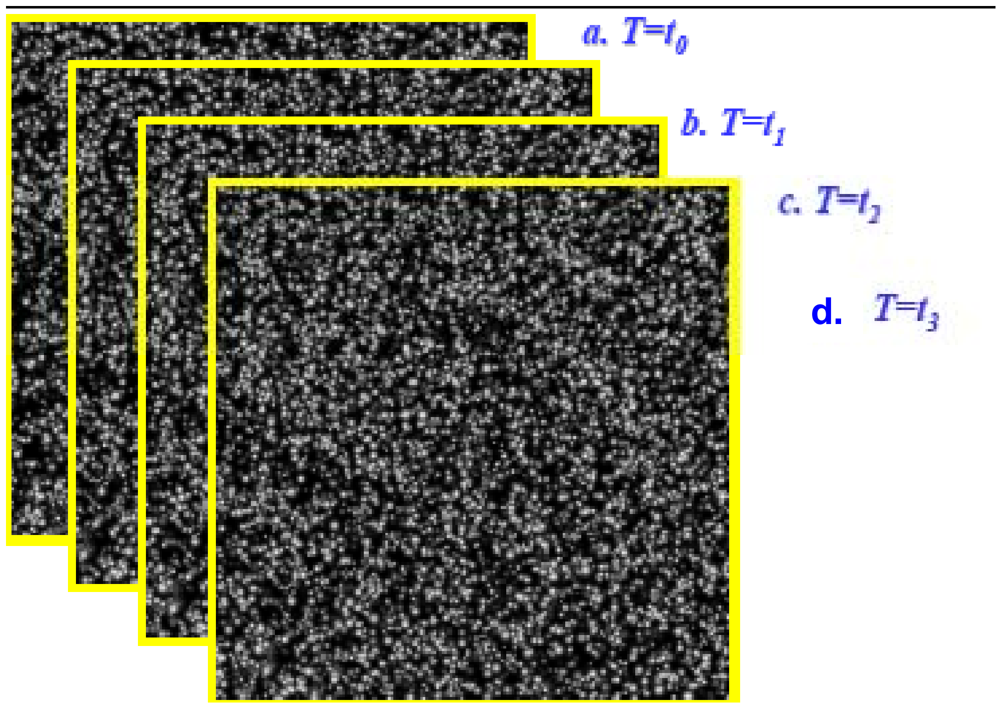
The images of the tracer particles are recorded at least twice with a small time-delay. The displacement of the particle images represents the fluid motion.

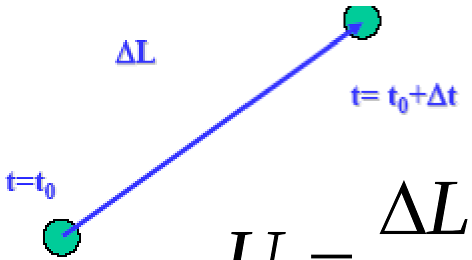




Multiple Frame Technique



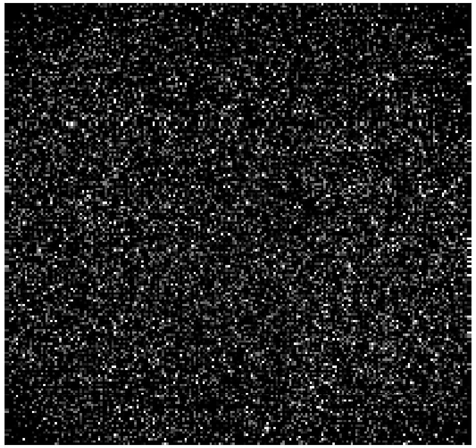




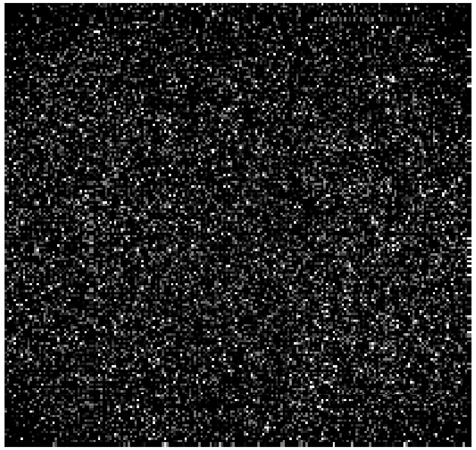
$$U = \frac{\Delta L}{\Delta t}$$

Image Processing for PIV

- To extract velocity information from particle images.



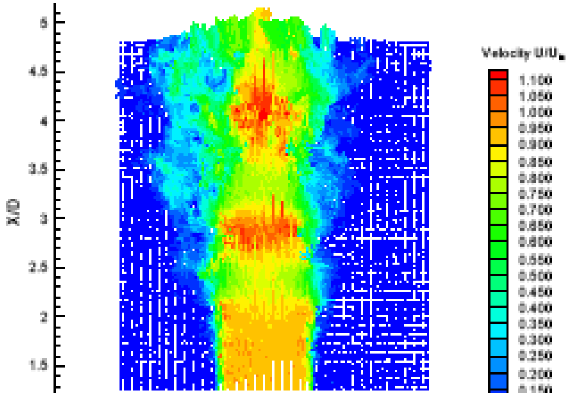
t=t0



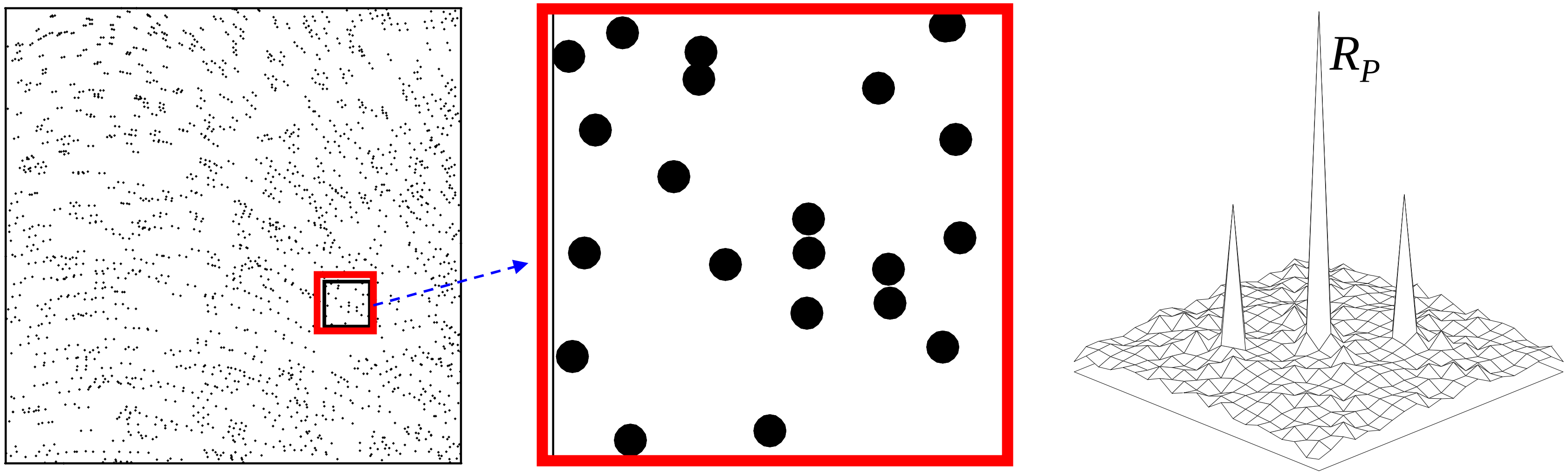
t=t0+4ms

A typical PIV raw image pair

Image processing



PIV Interrogation analysis



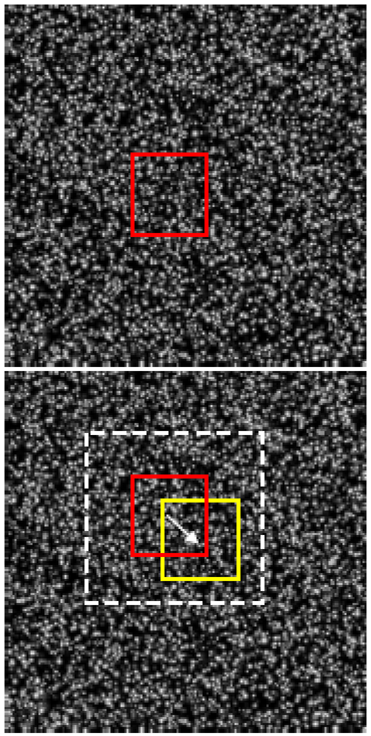
Double-exposure image **Interrogation region** **Spatial correlation**

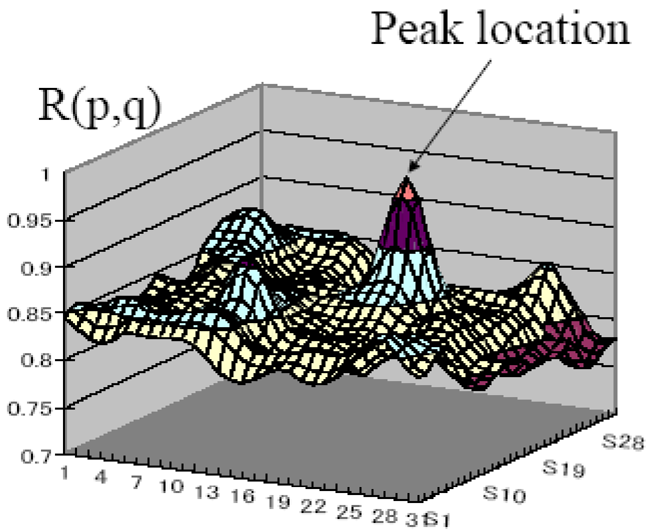
PIV images are analyzed by subdividing the image into small interrogation regions. Each interrogation region contains many particle-image pairs.

It is not possible to find individual matching pairs, because the displacement is greater than the mean spacing between particle images. Therefore a statistical method is used to find the particle-image displacement.

By computing the spatial auto-correlation for a double-exposure image, the correlation domain contains three dominant peaks (provided that a sufficient number of particle images is present within the interrogation region, and that the displacement is almost uniform over the interrogation region): a central self-correlation peak, and to displacement-correlation peaks on either side of the self-correlation peak.

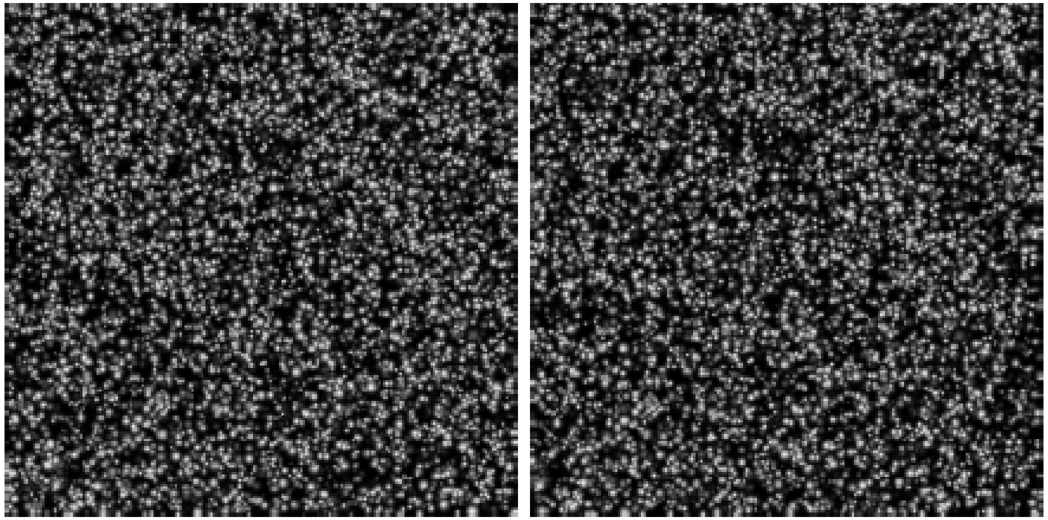
The location of the displacement-correlation peak yields the particle-image displacement. (A 180-degree directional ambiguity occurs due to the symmetry of the auto-correlation.)





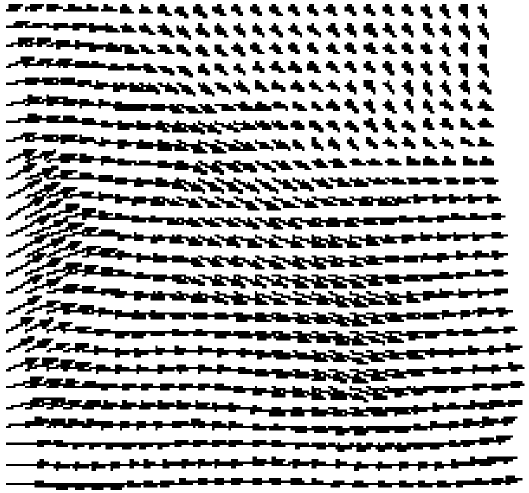
$$R(p,q)=\frac{\int (f(x,y)-\overline{f})(g(x,y)-\overline{g})dv}{\sqrt{\int (f(x,y)-\overline{f})^2 dv \int (g(x,y)-\overline{g})^2 dv}}$$

Correlation based PIV



$t=t_0$ $t=t_0+\Delta t$

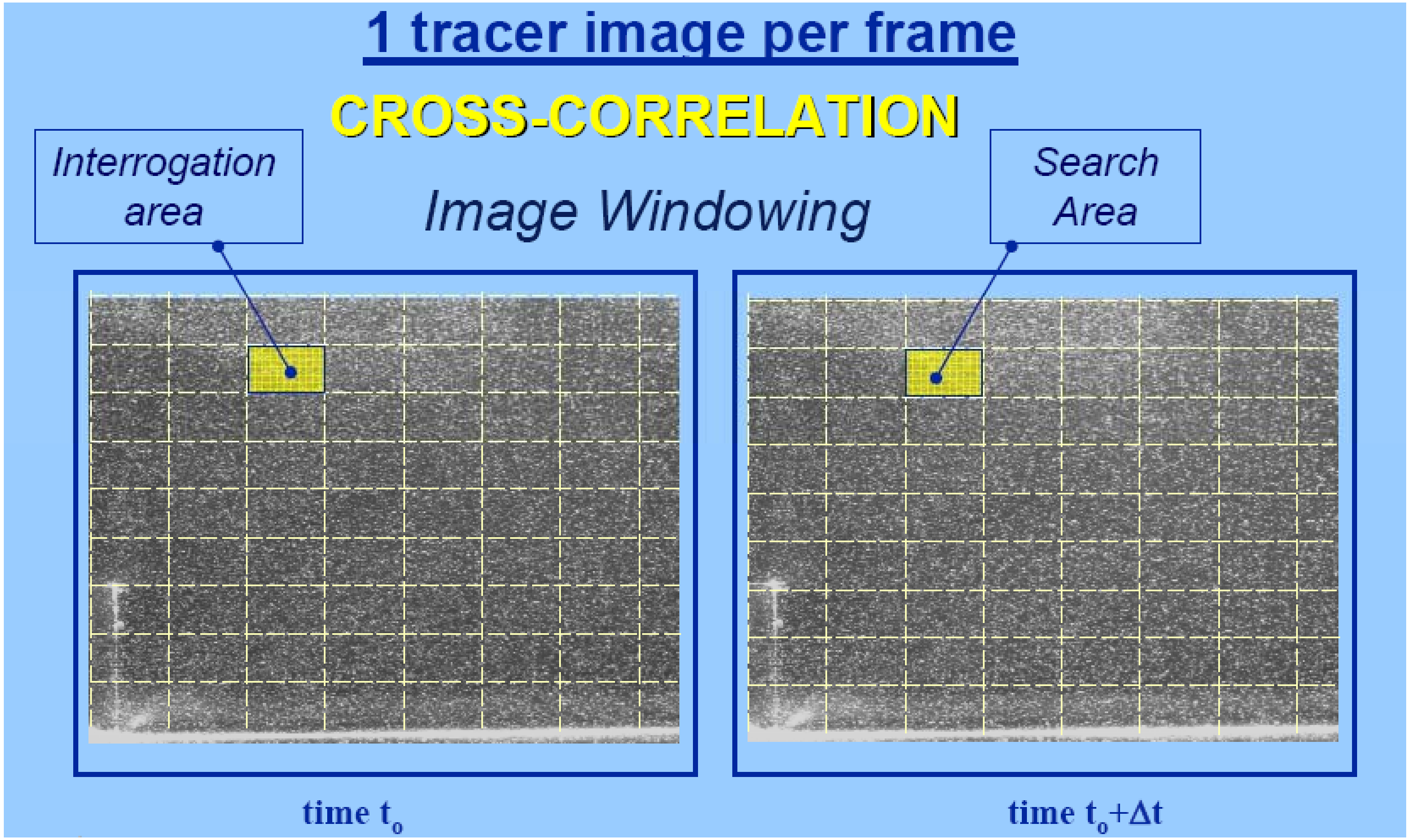
high particle-image density



Corresponding flow velocity field

PIV Image Processing

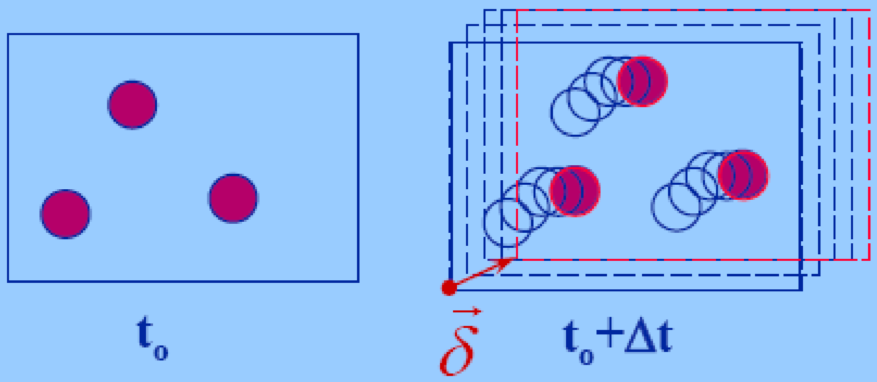
Cross- Correlation based PIV

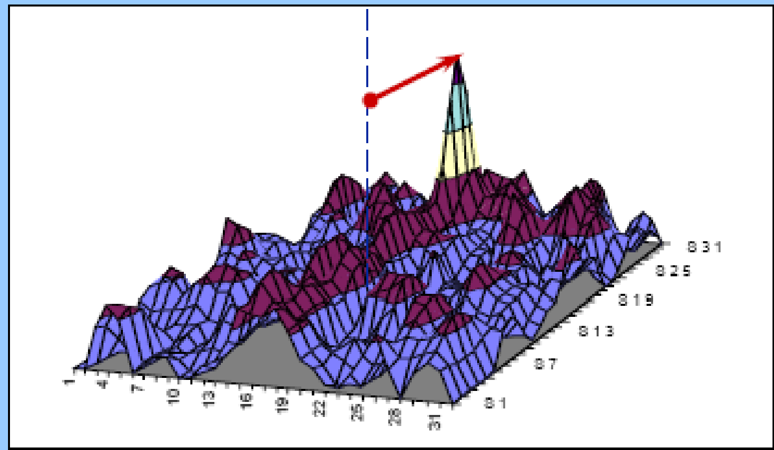


PIV Image Processing

Cross- Correlation based PIV

Cross - Correlation Function

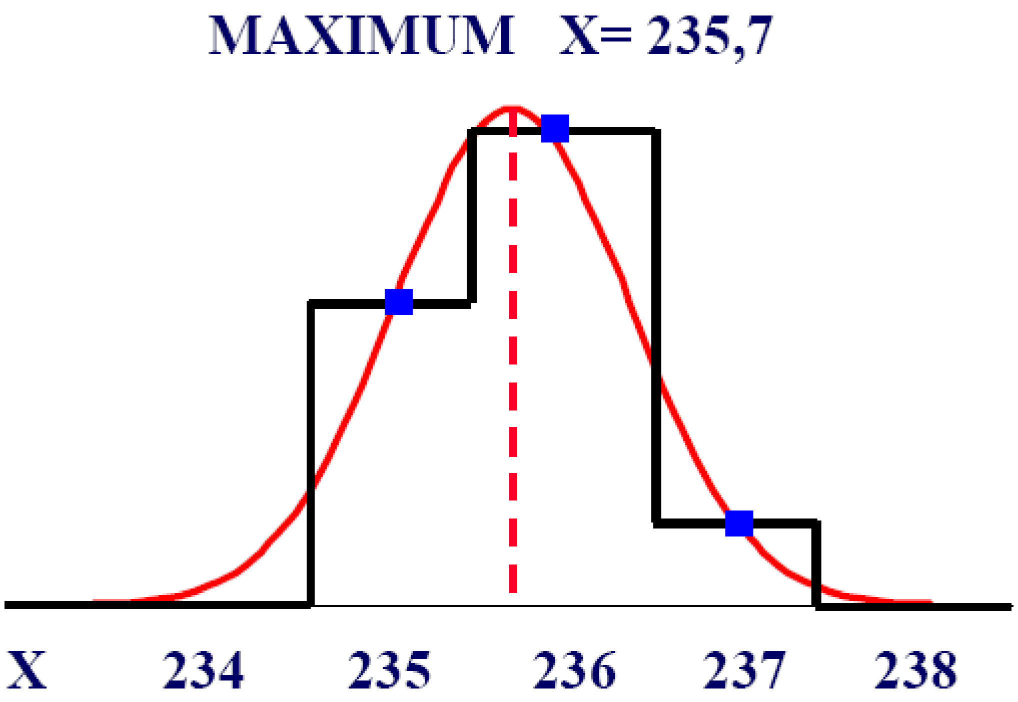




$$R(m,n) = \frac{\sum_{i=-N}^{N} \sum_{j=-N}^{N} I(i,j) \cdot S(i-m, j-n)}{\sqrt{\sum_{i=-N}^{N} \sum_{j=-N}^{N} I^2(i,j) \cdot \sum_{i=-N}^{N} \sum_{j=-N}^{N} \cdot S^2(i,j)}}$$

Location of Correlation Peak

Sub-pixel Interpolation
Gaussian Function



Correlation Coefficient Distribution

In PIV, two sequential digital images are sub-sampled at one particular area via an interrogation window.

Within these image samples an average spatial shift of particles may be observed from one sample to its counterpart in the other image.

The idea is to find the best match for the shifted particle pattern in the interrogation windows in a statistical sense.

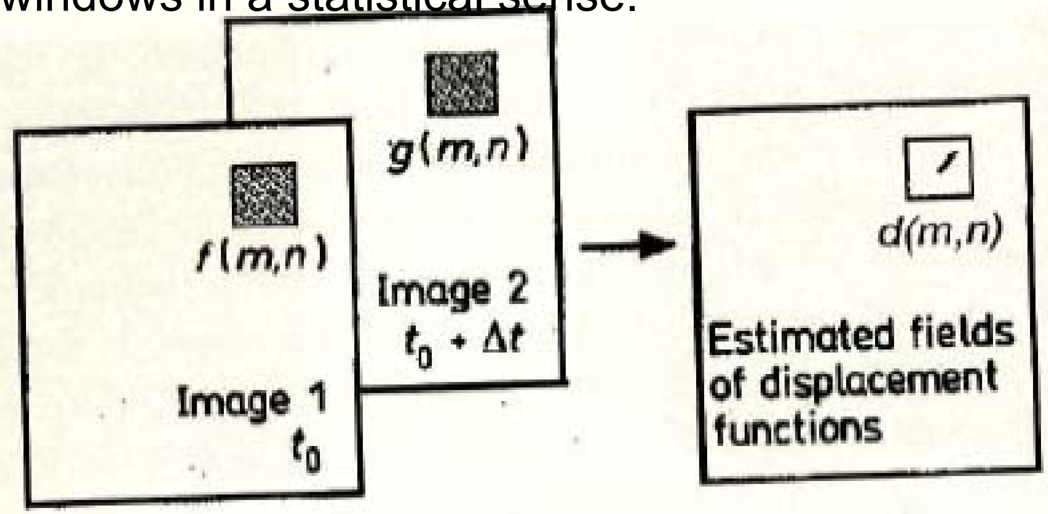


Fig. 6.3. Sequential images are subsampled with interrogation windows producing displacement vectors.

Correlation Coefficient Distribution

Discrete cross correlation function: $C(i', j') = \sum_{i=-k}^{k} \sum_{i=-l}^{l} f(i, j) g(i+i', j+j')$

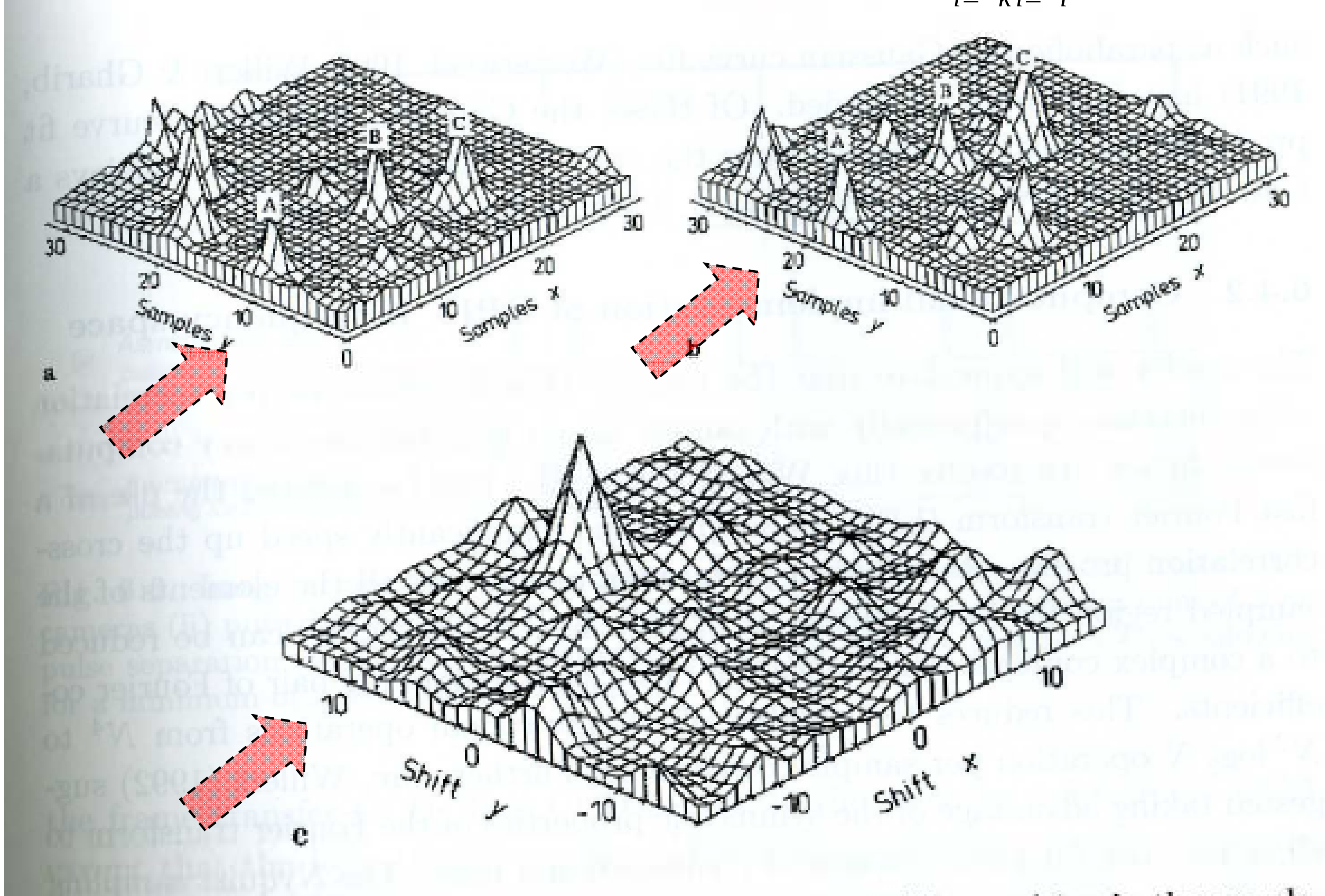


Fig. 6.5. Cross-correlation estimate between image **a** and **b**, resulting in the correlation domain **c**. Particle displacements are 8 pixels in the y-direction.

FFT Based Cross-Correlation

FFT-based Cross-correlation method

- ***advantage: Fast***
- ***disadvantage: additional error.***

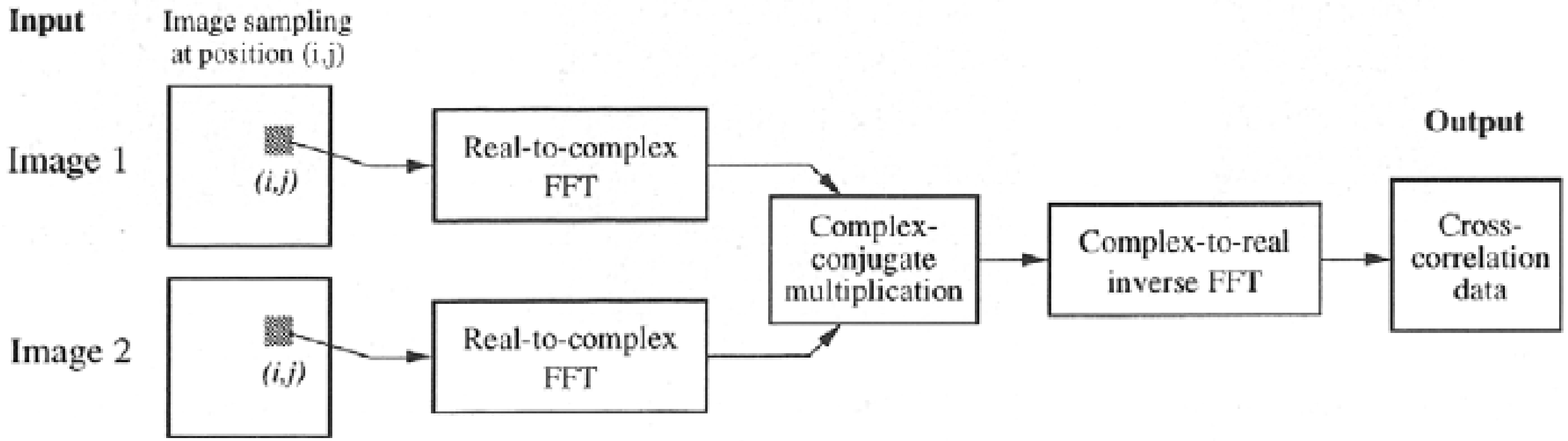
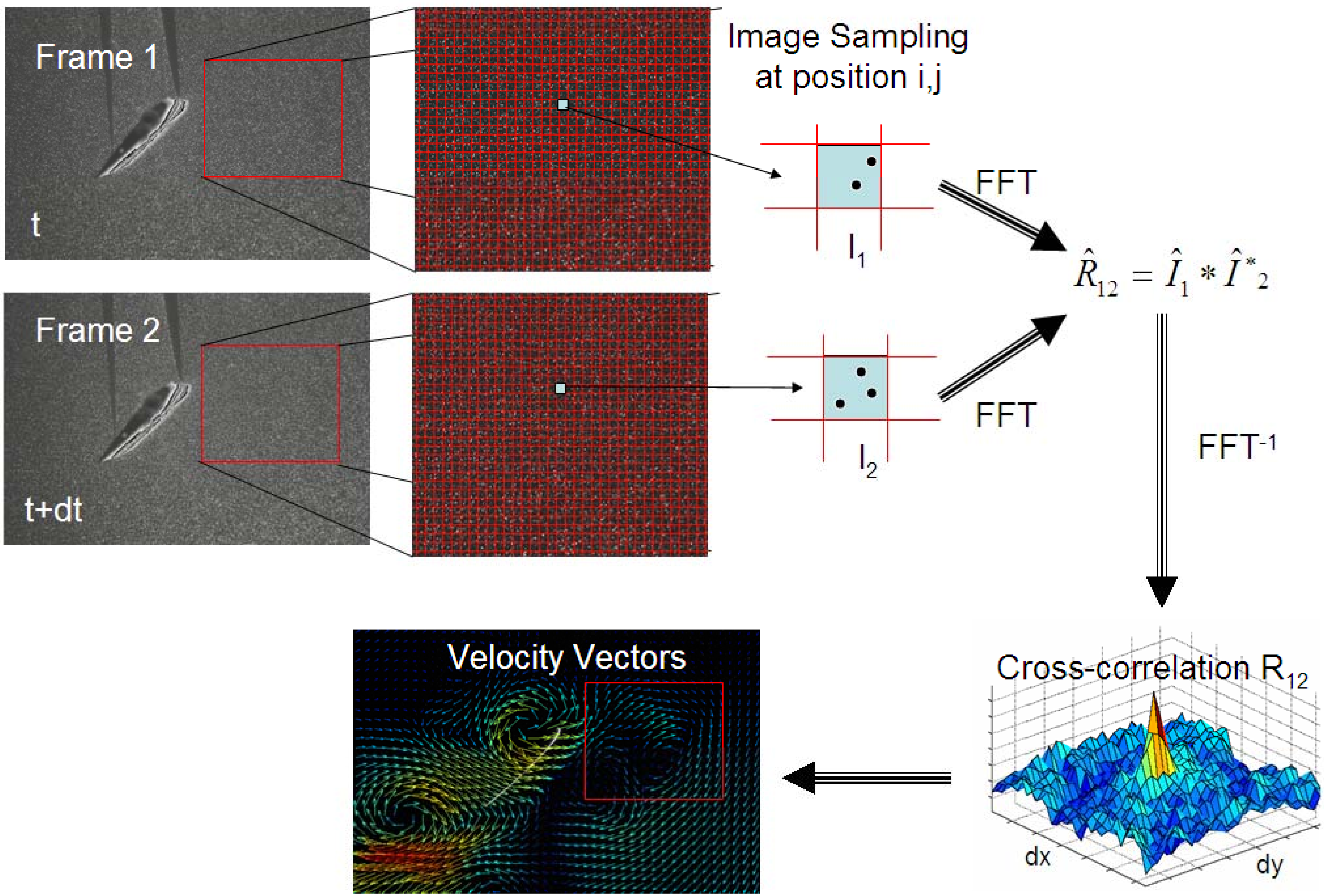
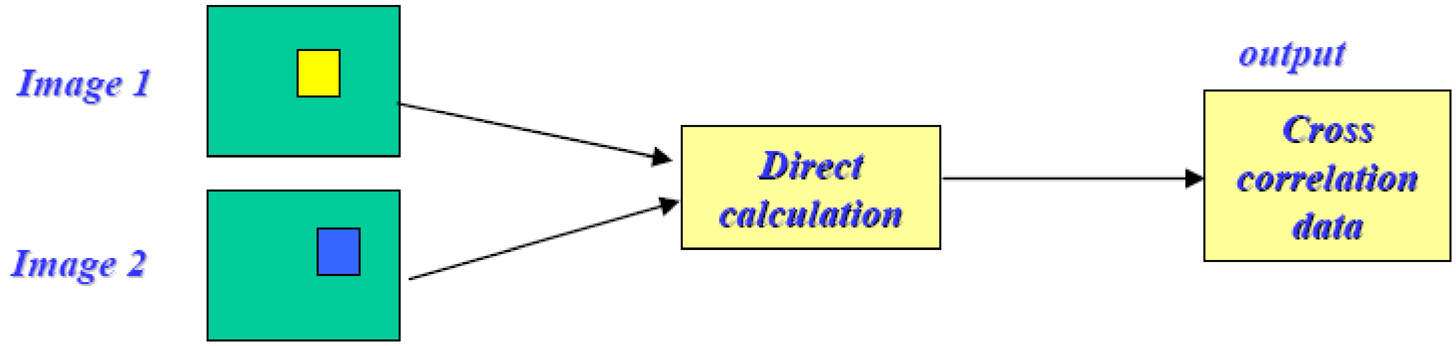


Fig. 5.16. Implementation of cross-correlation using fast Fourier transforms.



Double frame/double exposure and cross correlation.

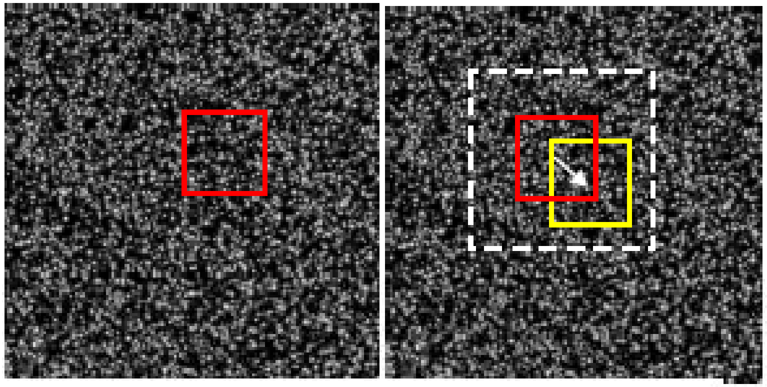
Direct Cross-Correlation

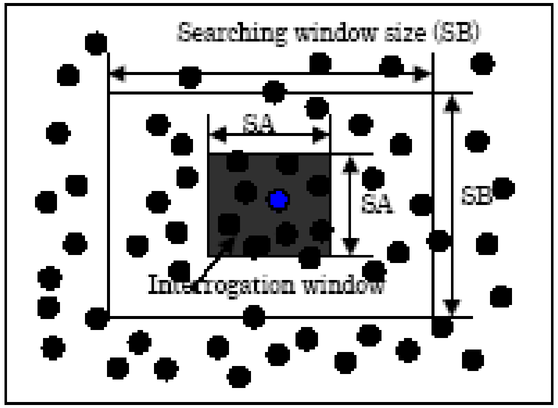


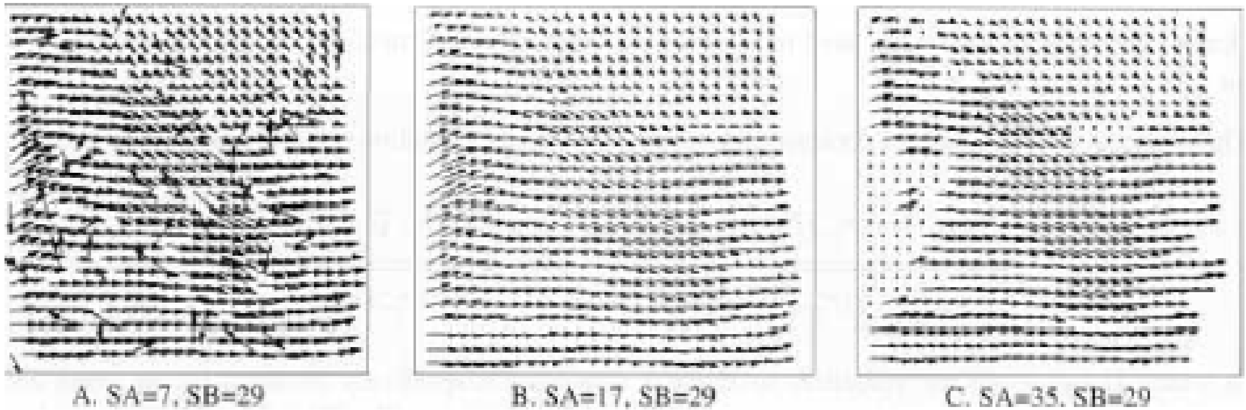
Direct cross-correlation method
- *advantage: accurate*
- *disadvantage: time consuming*

Effect of Interrogation Window Size

- *Interrogation size usually determines the spatial resolution of the PIV measurements.*
- *Smaller interrogation window size will give better spatial resolution of the PIV measurement.*
- *However, too small interrogation window size would result in many bad vectors.*
- *Usually to have about 10 ~ 20 particles inside an interrogation window would give a good PIV result!*





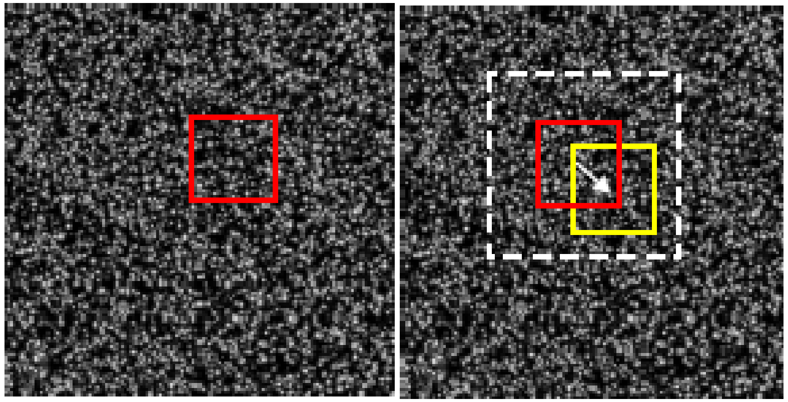


Bad vectors!

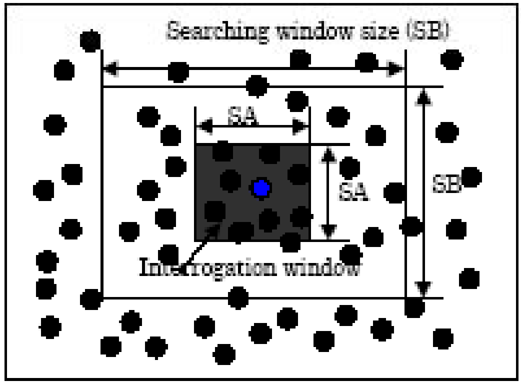
Effect of Searching Window Size

- *The size of the search window size would determine total time required for the cross correlation processing*

- *Smaller search window size could save the computational time, however, would result in error vectors for the particles with larger displacement.*



As SB increase error decrease, however total time required to perform calculations increases



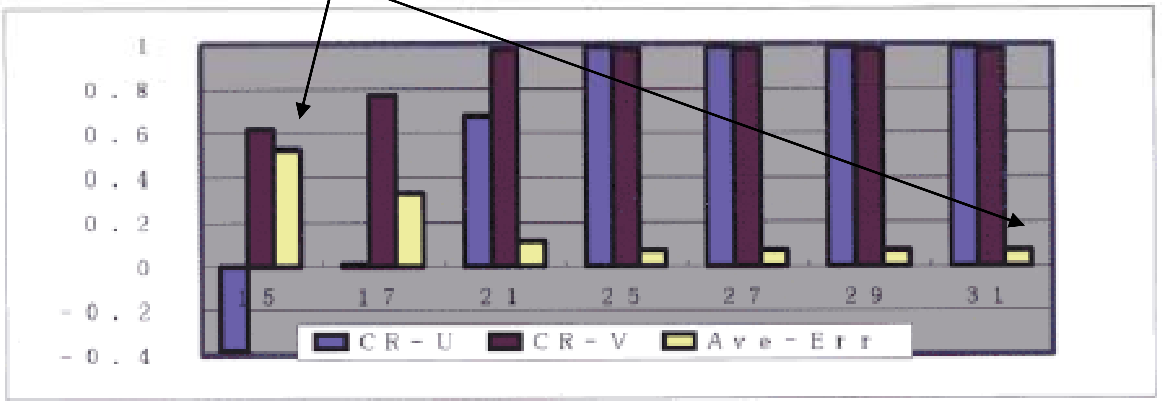
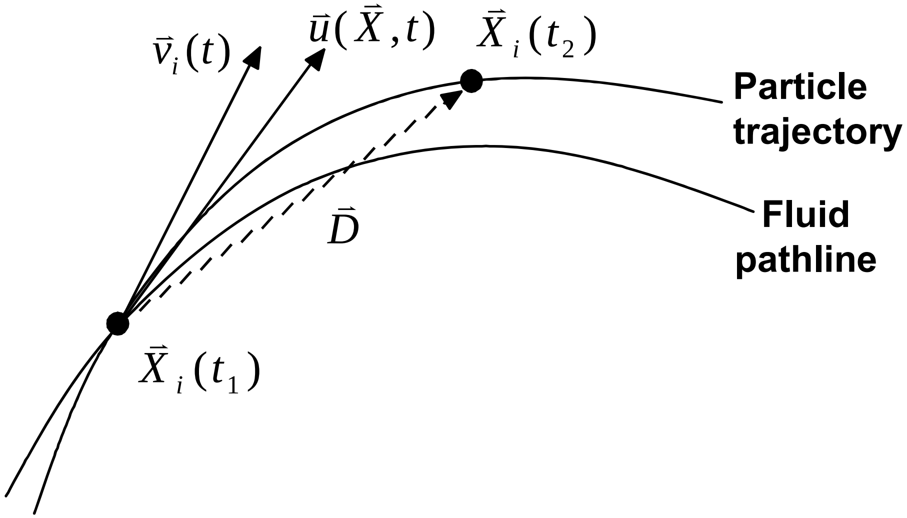


Fig. 5. The effect of the search window size (case A, SA=17).

The displacement field

- The fluid motion is represented as a displacement field



After: Adrian, *Adv. Turb. Res.* (1995) 1-19

$$\vec{D}(\vec{X};t',t'') \approx \int_{t'}^{t''} \vec{u}\left[\vec{X}(t),t\right]dt$$

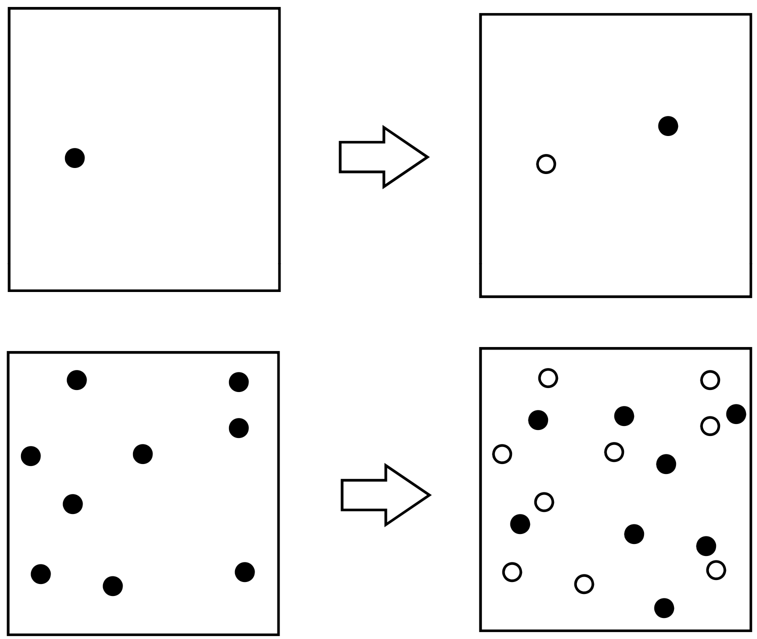
For an optically homogeneous fluid, it is not possible to observe the fluid motion directly. It is therefore necessary to add tracer material that serves as scattering sites for the light.
Ideal tracers do not alter the flow or the fluid properties, and follow the motion of the fluid exactly.
The *motion* of the fluid can now be detected as a *displacement* of the tracer particles; we thus measure the velocity indirectly.

Inherent assumptions

- Tracer particles follow the fluid motion
- Tracer particles are distributed homogeneously
- Uniform displacement within interrogation region

Velocity from tracer motion

image density (N_I)



Low image density

$N_I << 1$

Particle tracking velocimetry

High image density

$N_I >> 1$

Particle image velocimetry

Velocity from tracer motion

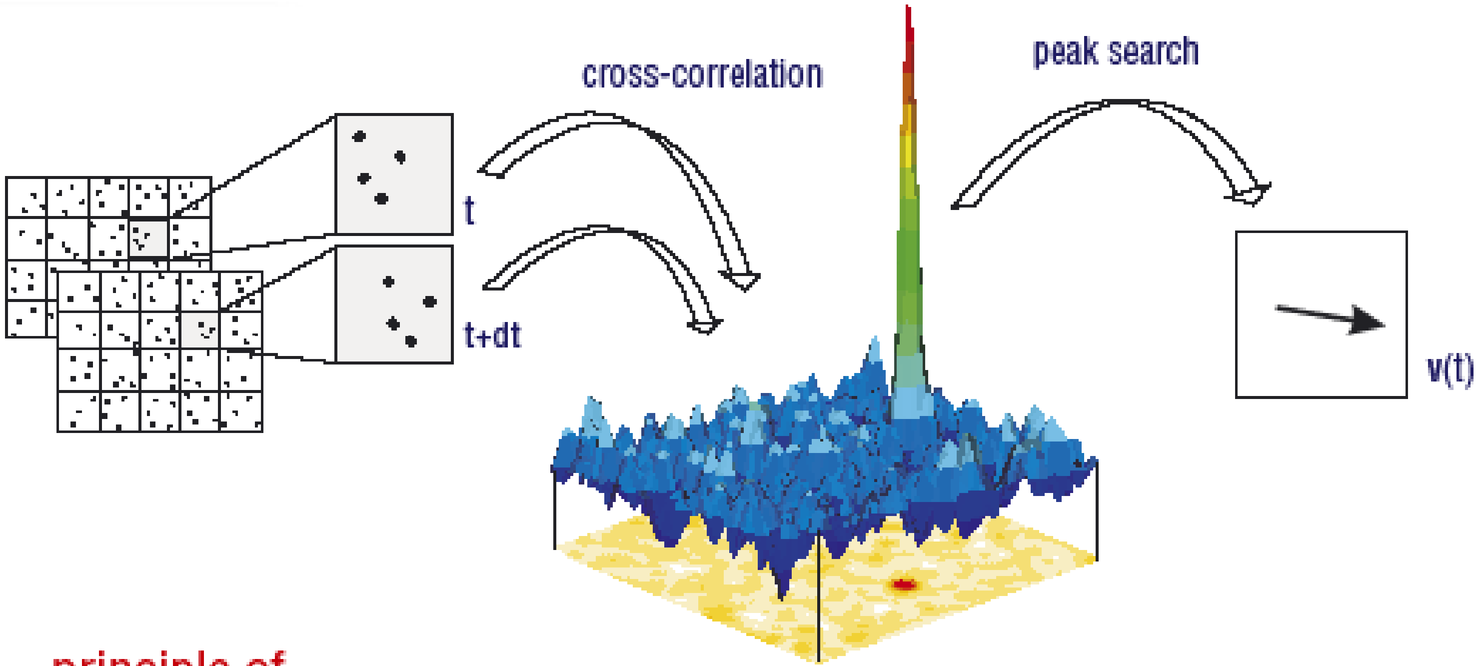
✓ The motion of the fluid is visualized by the motion of small tracer particles added to the fluid. These tracer particles constitute a *pattern* that can be used to evaluate the fluid motion.

If the density is very low (i.e., the distance between distinct particles is much larger than the displacement) then it is very easy to evaluate the displacement from individual tracer particles.
This mode of operation is generally referred to as *particle tracking velocimetry*.

However, in this manner the amount of information that can be retrieved from an image is very low.

✓ If we increase the concentration of tracer particles, then their displacement becomes *larger* than their spacing, and it is no longer possible to identify matching pairs make unambiguously.

This mode of operation is generally referred to as *Particle Image Velocimetry*.



principle of cross-correlation PIV

The position of the highest peak in the correlation plane indicates the mean displacement **ds** of the particles in a particular interrogation window. The displacement vectors of all interrogation windows are finally transformed into a complete instantaneous velocity map.

image preprocessing

- masking with arbitrary shape, user-defined, automatically criteria based, high-pass filter, general n x n filter
- two phase separation on structure differences
- removal of unwanted image features (e.g. reflections)

image correction

- correction of image distortions: self-calibration procedures for 2D-PIV for angular viewing and 3D-Stereo PIV

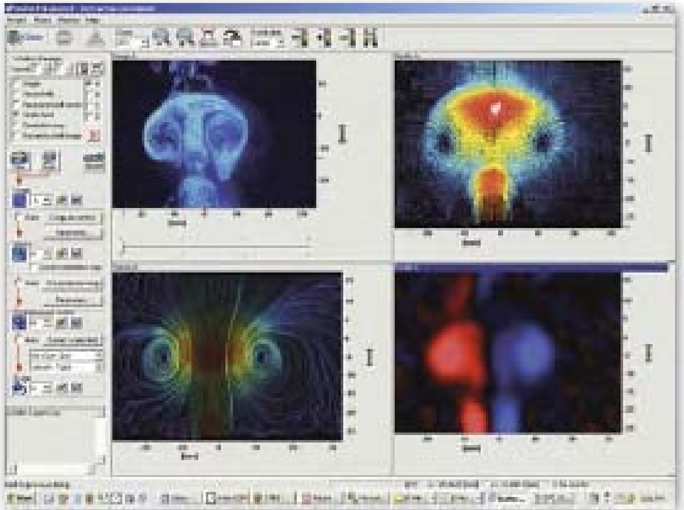
PIV algorithms

- various auto- and cross-correlation functions: standard FFT, normalized
- advanced 2D- and 3D-particle tracking algorithms for lower seeding density
- second-order correlation
- vector calculation by sum of correlation planes of n images
- adaptive multi pass (highest resolution and stability)
- high accuracy (no peak locking)
- correlation with dynamically deformed interrogation windows

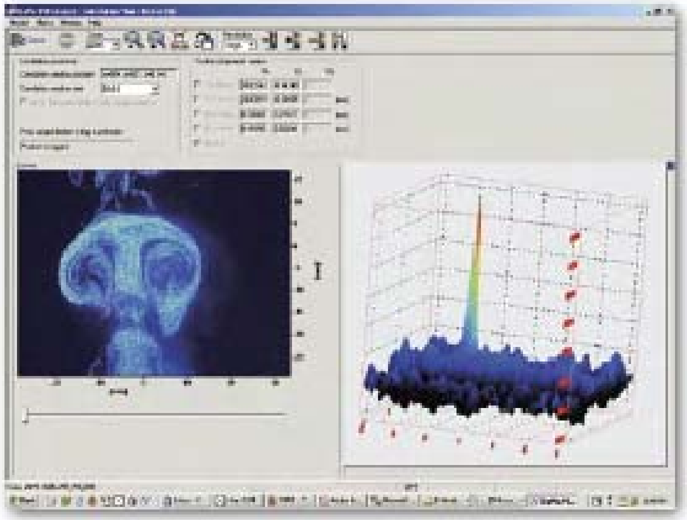
vector postprocessing and validation

- correlation peak height ratio filter
- local and regional median filter incl. replacement with second choice vectors
- global vector magnitude filter
- smoothing and interpolation

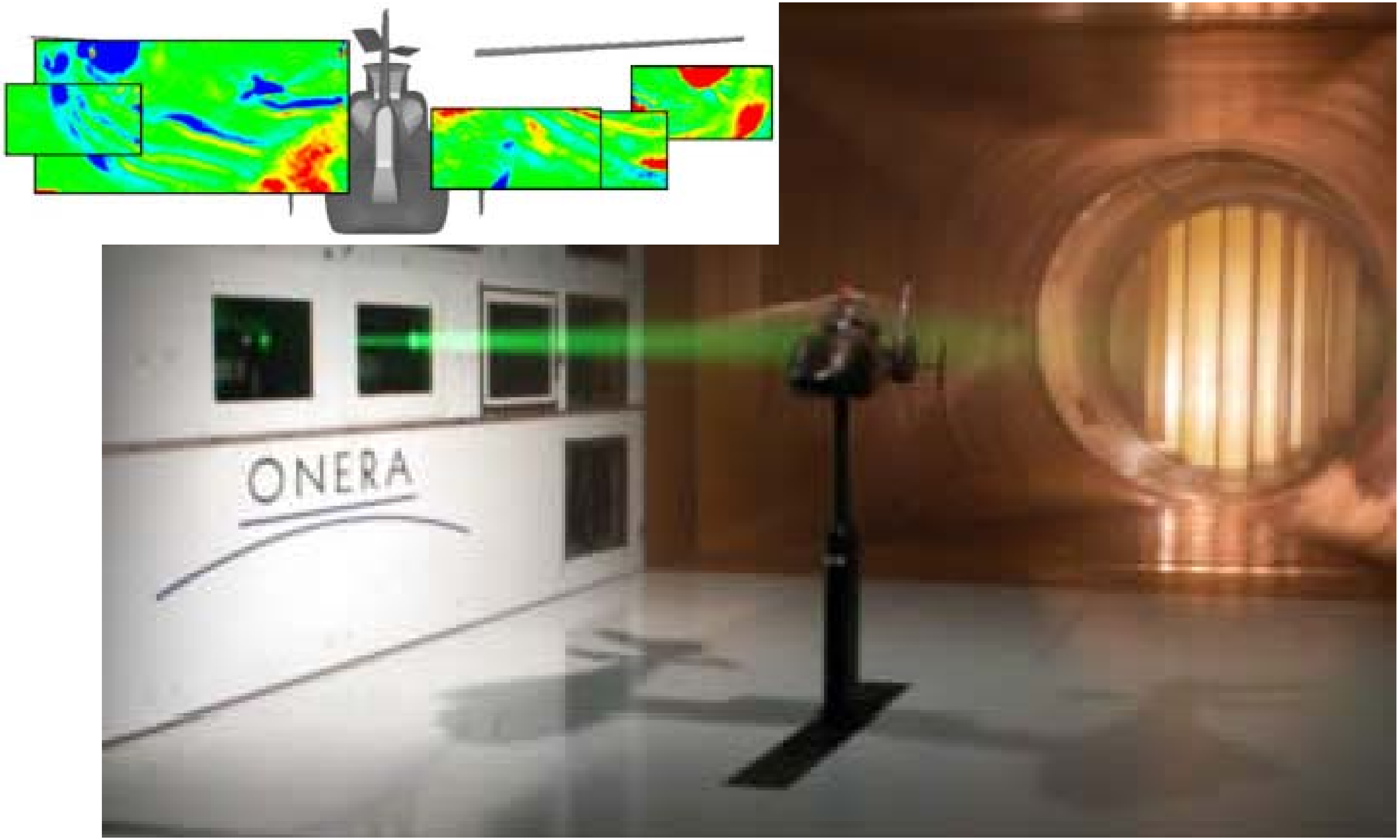
vector field processing



- scalar fields: rotation, divergence, stress
- statistics: mean, rms, PDF, scatter plots
- contour maps, streamlines, streaklines
- vortex analysis: center, strength and velocity
- space and space-time correlation
- user-defined operations
- proper orthogonal decomposition (POD)

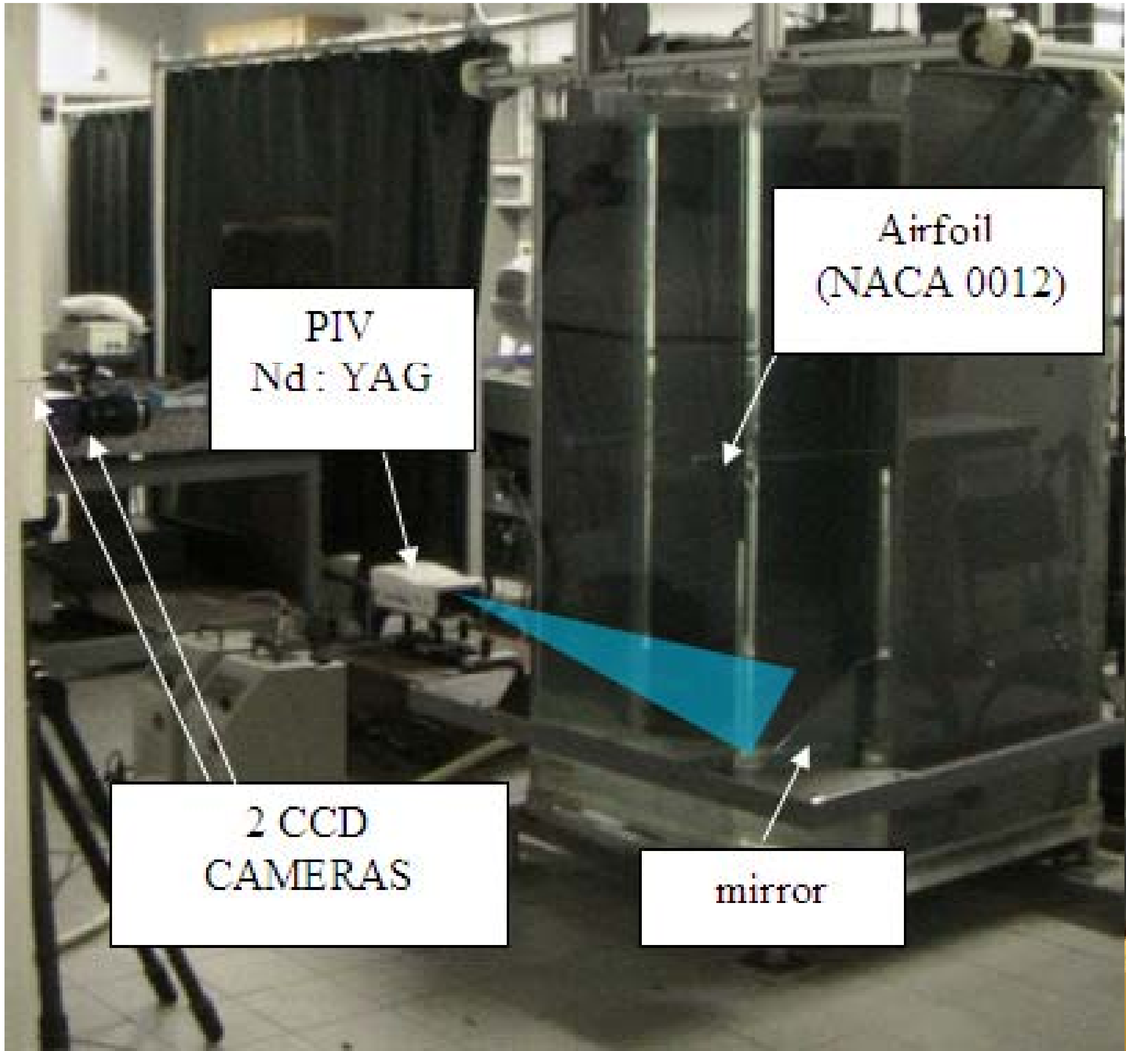


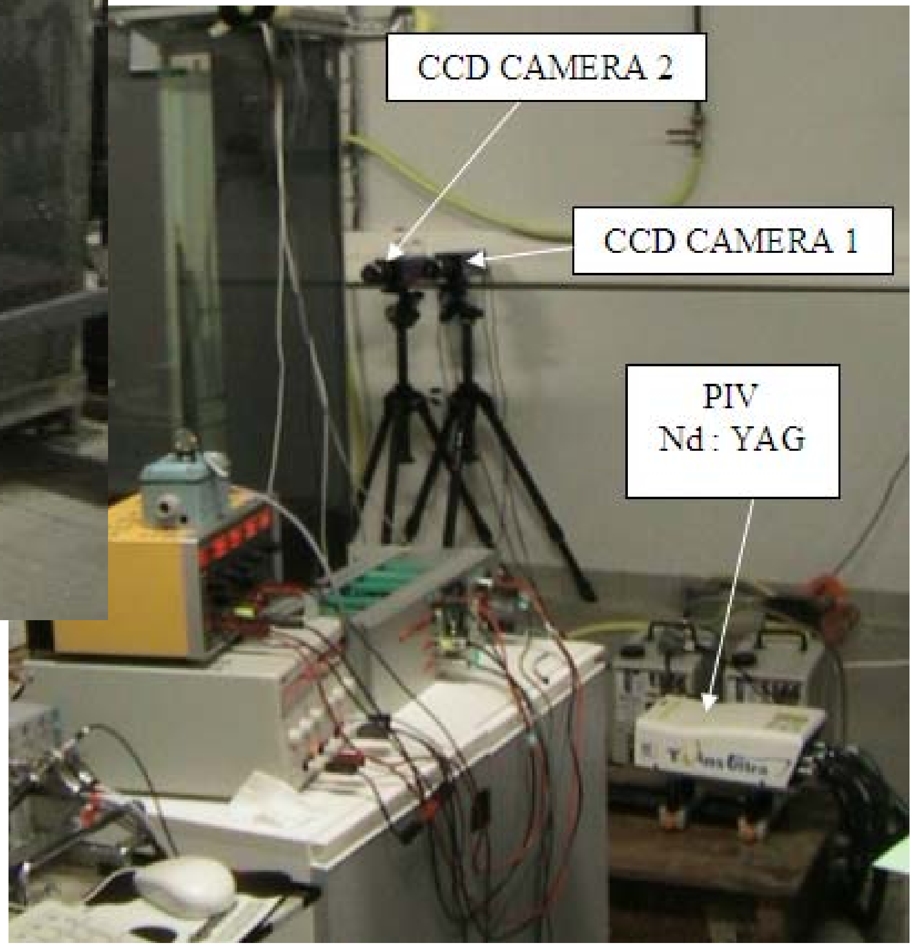
DaVis – the graphical user interface to PIV algorithms



Rotor-fuselage interactions are the most difficult to compute, because they require a full modeling of the entire helicopter. An experimental approach is often necessary, to get a global understanding of the problem and to provide a database to validate the calculation codes.

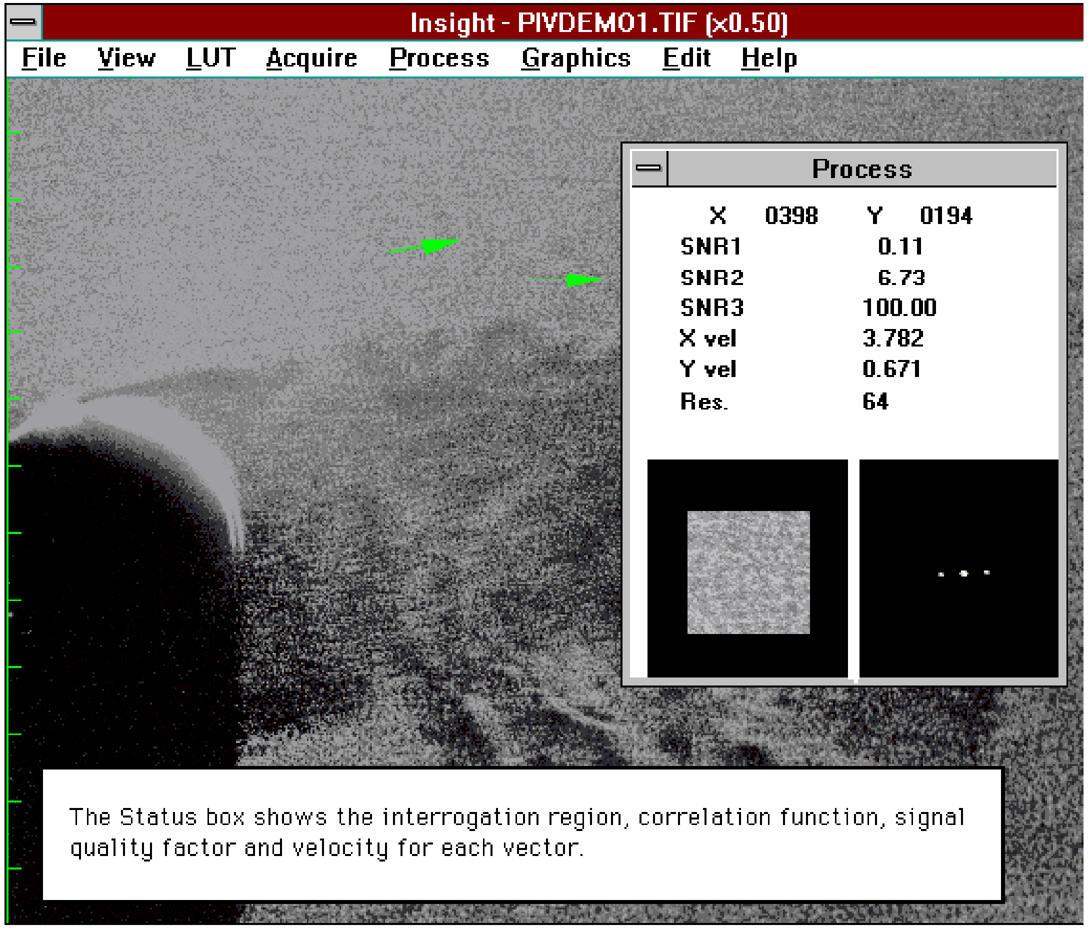
A model of the Dauphin Helicopter was tested in Onera's F1 wind-tunnel for this purpose.



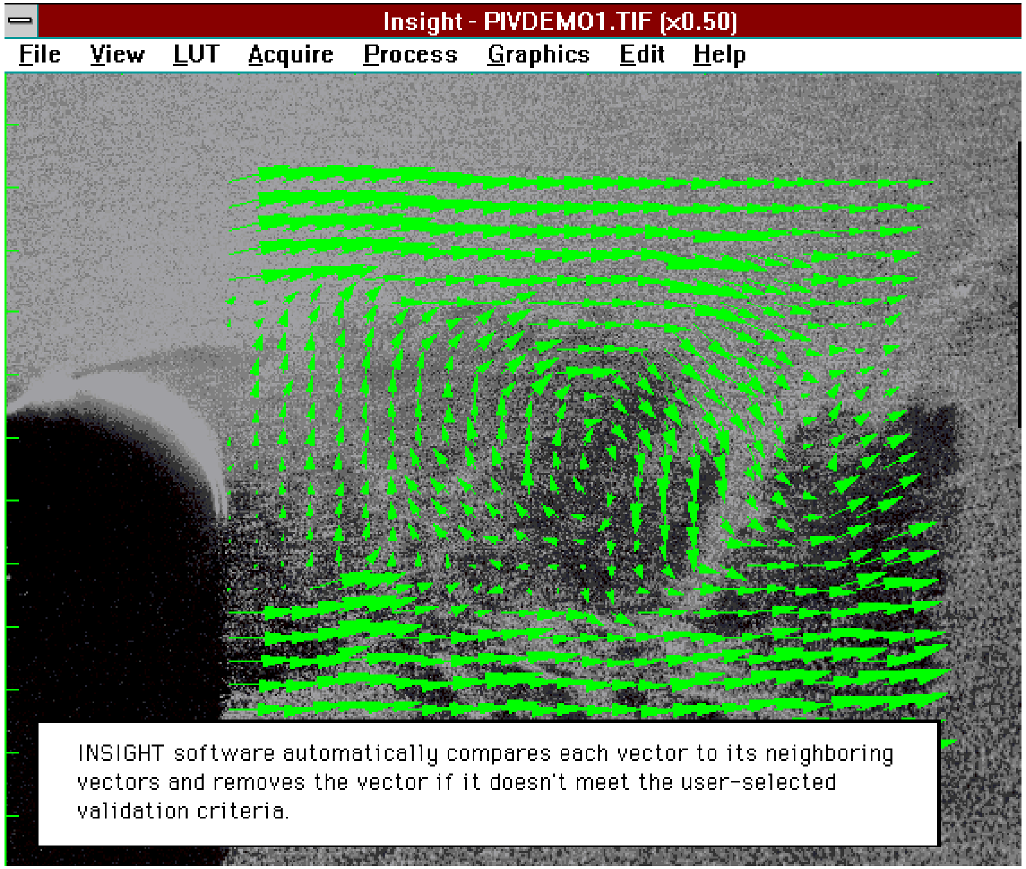


ENSMA- Poitiers (Flapping Motion setup)


Insight - PIVDEMO1.TIF (x0.50)
File View LUT Acquire Process Graphics Edit Help
Let's say this is the image you've just captured. This is an image of a flow around a cylinder with a free stream velocity of M=0.6. . .
(Image courtesy of FAMU/FSU)

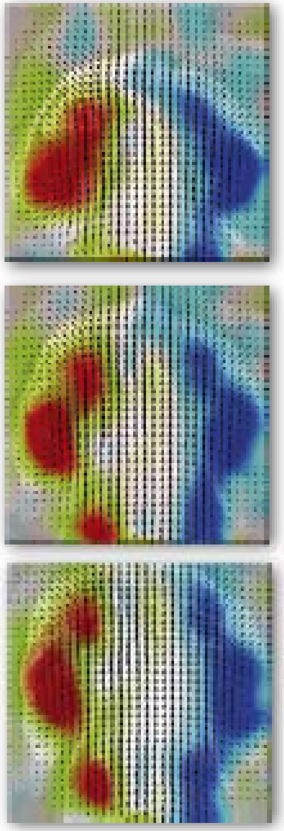

Insight - PIVDEMO1.TIF (x0.50)
File View LUT Acquire Process Graphics Edit Help
Process
X 0398 Y 0194
SNR1 0.11
SNR2 6.73
SNR3 100.00
X vel 3.782
Y vel 0.671
Res. 64
The Status box shows the interrogation region, correlation function, signal quality factor and velocity for each vector.

Vector field



Time-Resolved PIV- LaVision

FlowMaster
Time-Resolved PIV



high speed PIV image sequence

FlowMaster High-Speed opens new areas of fluid dynamic analysis. It combines the spatial information of digital PIV with the temporal evolution of each point.
The system measures velocity and acceleration fields and turbulence quantities of transient phenomena. The time-resolved PIV information opens a new area for velocity derivations or correlations in time. With time-resolved PIV the user is able to calculate temporally dependent quantitative turbulence information. It provides information about:

- time dependence of POD-modes
- vortex characteristics with time
- space-time correlations
- flow element tracking
- power spectra
- acceleration fields
- flow time scales

LaVision's **FlowMaster High-Speed** systems include state-of-the-art digital high-speed cameras with up to 5 kHz frame rate at full resolution of 1k x 1k pixel and up to several 100 kHz frame rate at reduced resolution. Single or dual cavity high-repetition rate solid state lasers up to 50 mJ per pulse are available. All components are integrated and controlled from the **DaVis** software.

Time-Resolved PIV- Dantec

It consists of a high repetition rate laser with 50 W or 2 x 12.5 mJ at 2 kHz, a high frame rate CMOS camera that is able to record frames with 30 Hz to 4,000 Hz in the standard version (an upgrade to 10,000 Hz is available).

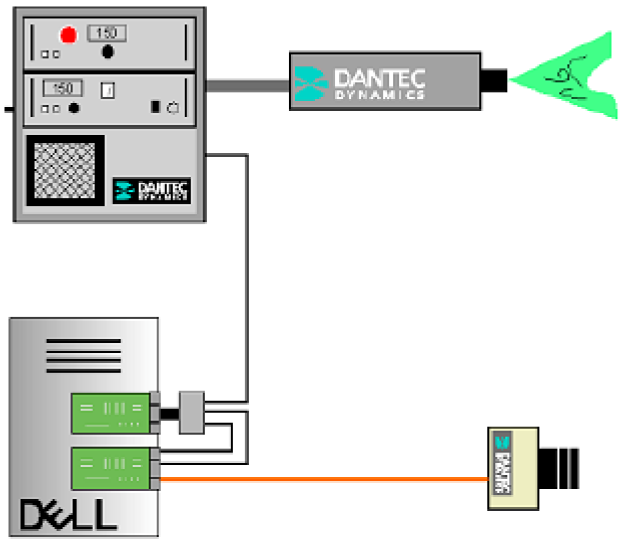


Figure 3. Time Resolved PIV system in single laser configuration

pixel Resolution		Frame rate (Camera)					
Hor	Ver	0.5k	1k	2k	4k	8k	16k
1280	1024						
1280	512						
640	512						
1280	256						
640	256						
320	256						
640	128						
320	128						
160	128						
640	64						
320	64						
80	64						
320	32						
160	32						

Lasers for Time Resolved PIV are available either as Nd:YAG lasers @ 532 nm or as Nd:YLF lasers @ 527 nm. Thus both types work within the green range of the visible light. In both cases lasers operate either with a single or a double cavity.

Nd:YLF lasers can operate down to small Δt (time between pulses) while their energy output decreases rapidly at frequencies higher than 1 kHz.

On the other hand, Nd:YAG lasers with a single cavity have a limit of approx. Δt=40 μs for the time between pulses while they provide twice the energy at higher repetition rates.

When smaller times between pulses are needed, double cavity lasers have to be chosen. Independently of Δt the energy only depends on the repetition rate.

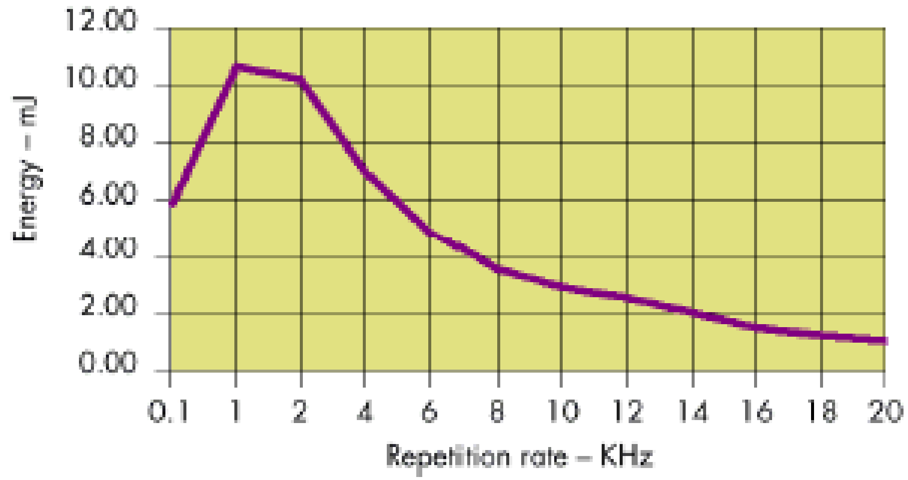


Figure 4. Energy output for a typical ND:YLF laser

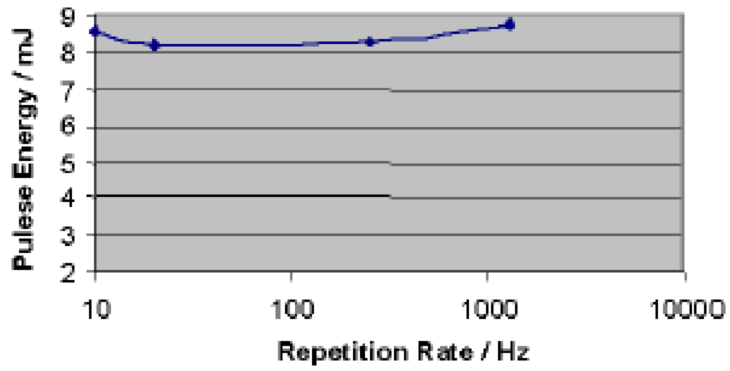


Figure 5. Energy output for a single cavity Nd:YAG laser at a Δt of 200 μs

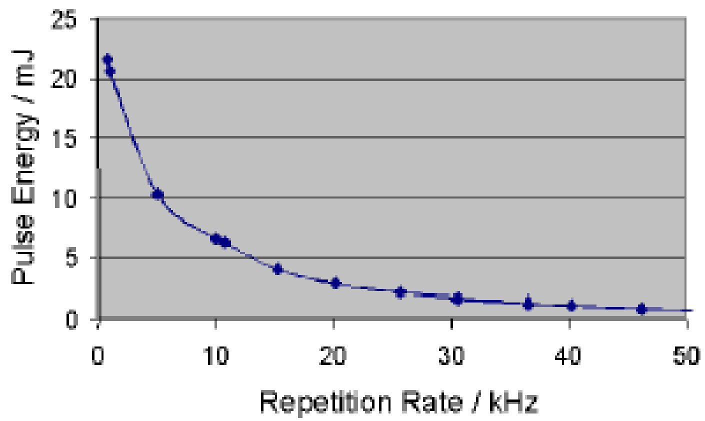


Figure 6. Energy output for a double cavity Nd:YAG laser; energy is independent of Δt

3D-PIV

- Theory of stereoscopic PIV
- 3D-PIV software

Ref. Dantec and LaVision

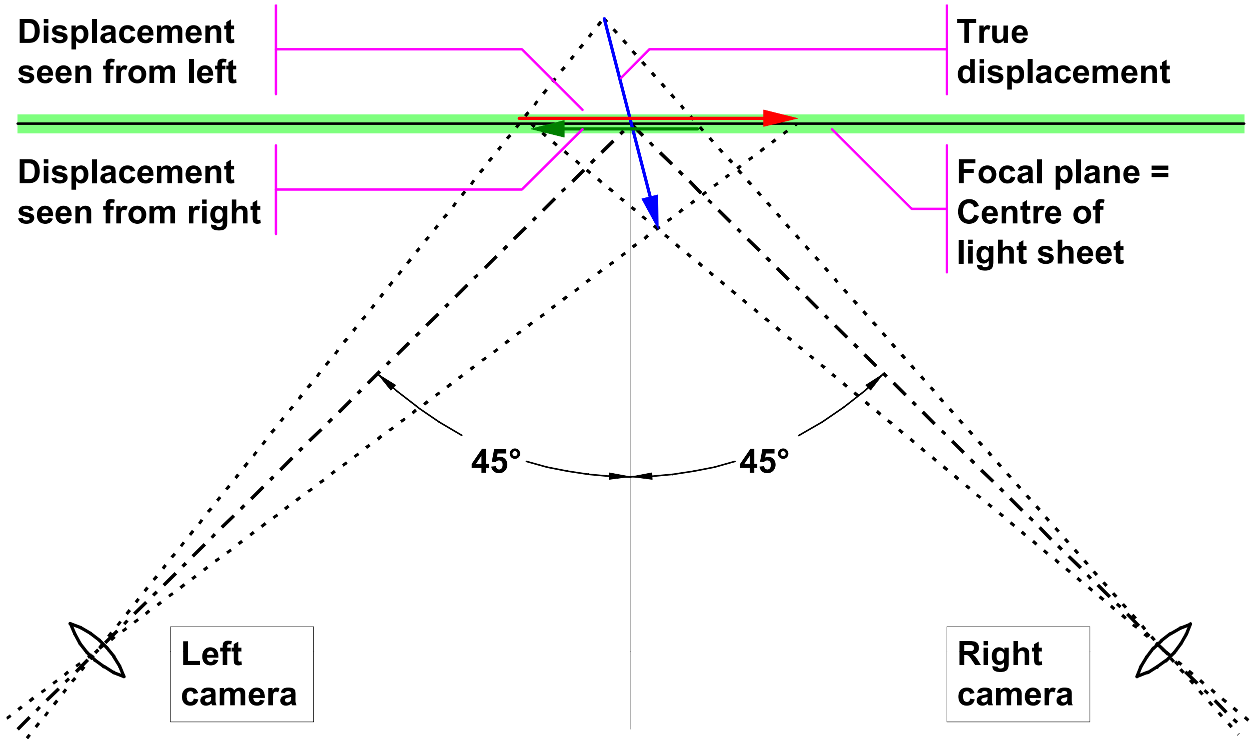
FlowMaster Scheimpflug setup
LaVision

stereoscopic imaging

3D vortex flow field

Self-Calibration

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

3D-PIV is based on the same fundamental principle as human eye-sight: Stereo vision. Our two eyes see slightly different images of the world surrounding us, and comparing these images, the brain is able to make a 3-dimensional interpretation.

As with 2D measurements, stereo-PIV measures displacements rather than actual velocities, and here cameras play the role of “eyes”.

The most accurate determination of the out-of-plane displacement (i.e. velocity) is accomplished when there is 90° between the two cameras. In case of restricted optical access, smaller angles can be used at the cost of a somewhat reduced accuracy.

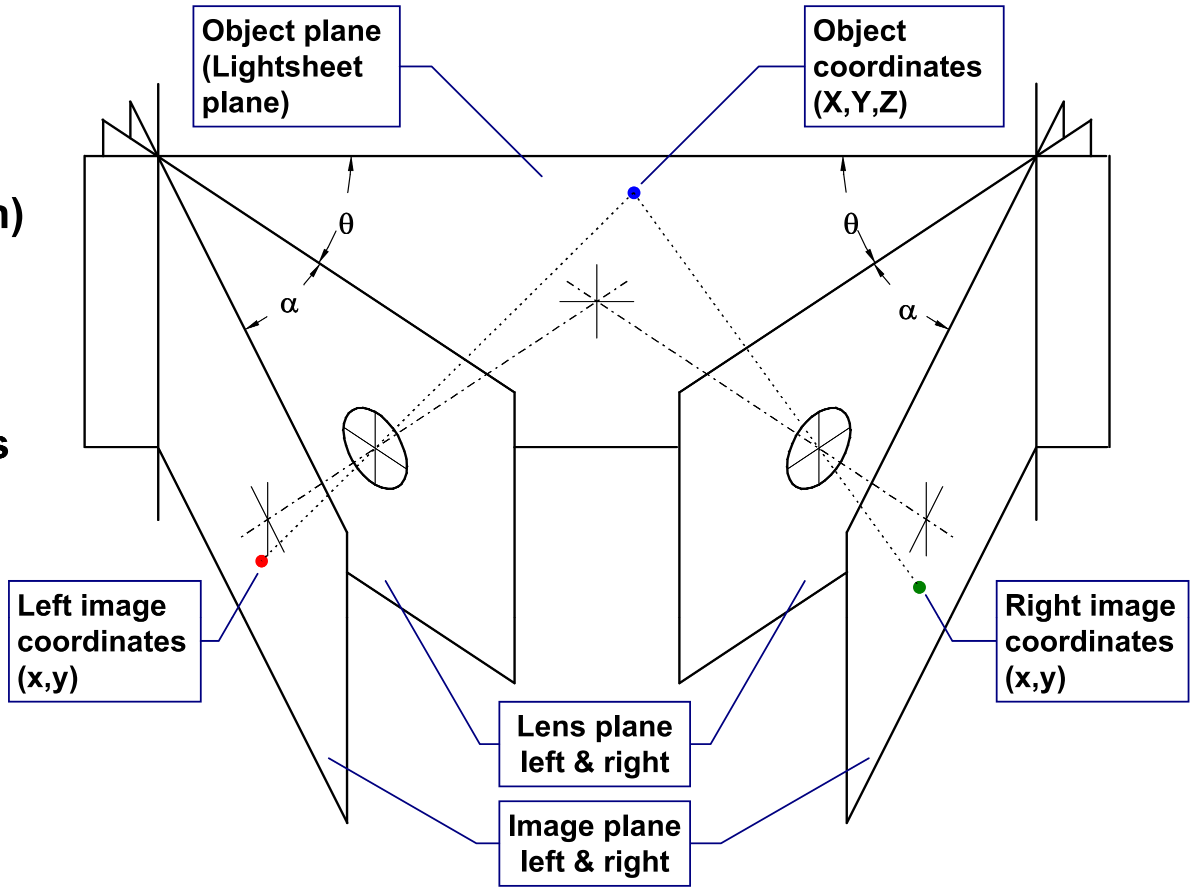
For each vector, we extract 3 true displacements (ΔX, ΔY, ΔZ) from a pair of 2-dimensional displacements (Δx, Δy) as seen from left and right camera respectively, and basically it boils down to solving 4 equations with 3 unknowns in a least squares manner. Depending on the numerical model used, these equations may or may not be linear.

Stereo recording geometry

Focusing an off-axis camera requires tilting of the CCD-chip (Scheimpflug condition)

3D evaluation requires a numerical model, describing how objects in space are mapped onto the CCD-chip of each camera

Parameters for the numerical model are determined through camera calibration

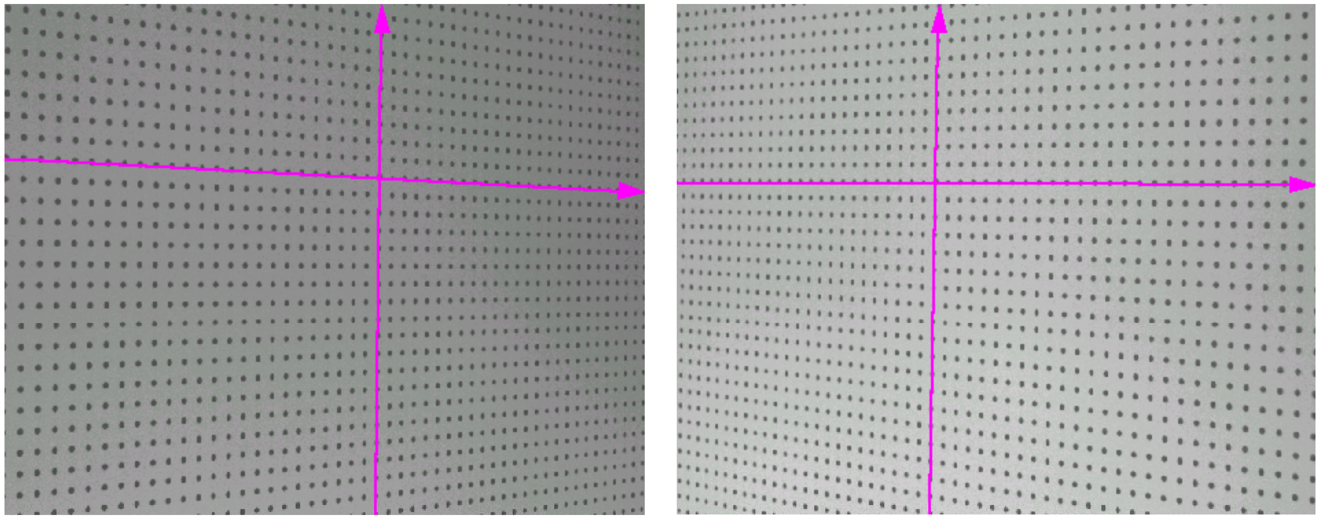


Stereo recording geometry

When viewing the lightsheet at an angle, the camera backplane (i.e. the CCD-chip) must be tilted in order to properly focus the camera's entire field of view. It can be shown that the image, lens and object plane must cross each other along a common line in space for the camera images to be properly focused in the entire field of view. This is referred to as the Scheimpflug condition, and is used in most 3D-PIV systems.

Performing the 3D evaluation requires a numerical model describing how objects in 3-dimensional space are mapped onto the 2-dimensional image recorded by each of the cameras. The pinhole camera model is based on geometrical optics, and leads to the so-called direct linear transformation:

Camera calibration



Images of a calibration target are recorded.

The target contains calibration markers (dots) 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.

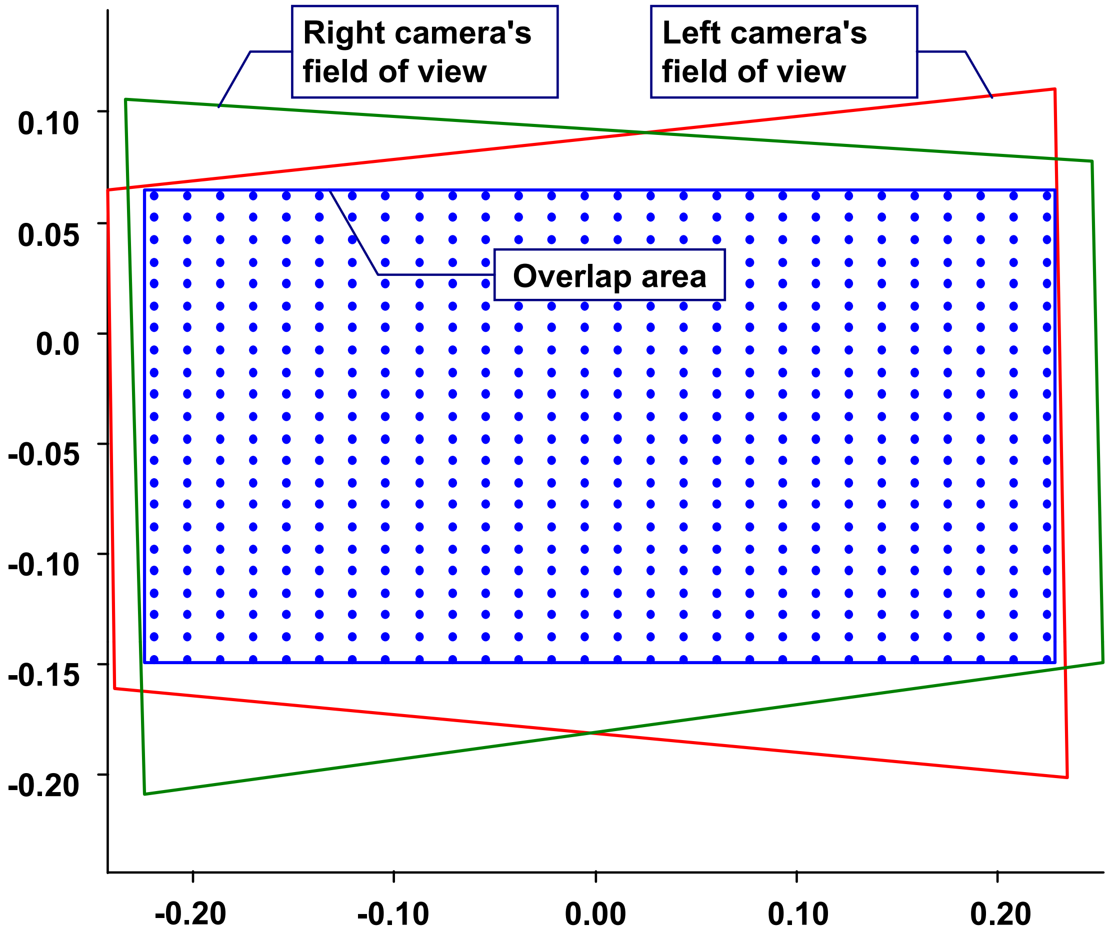
Overlapping fields of view

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.



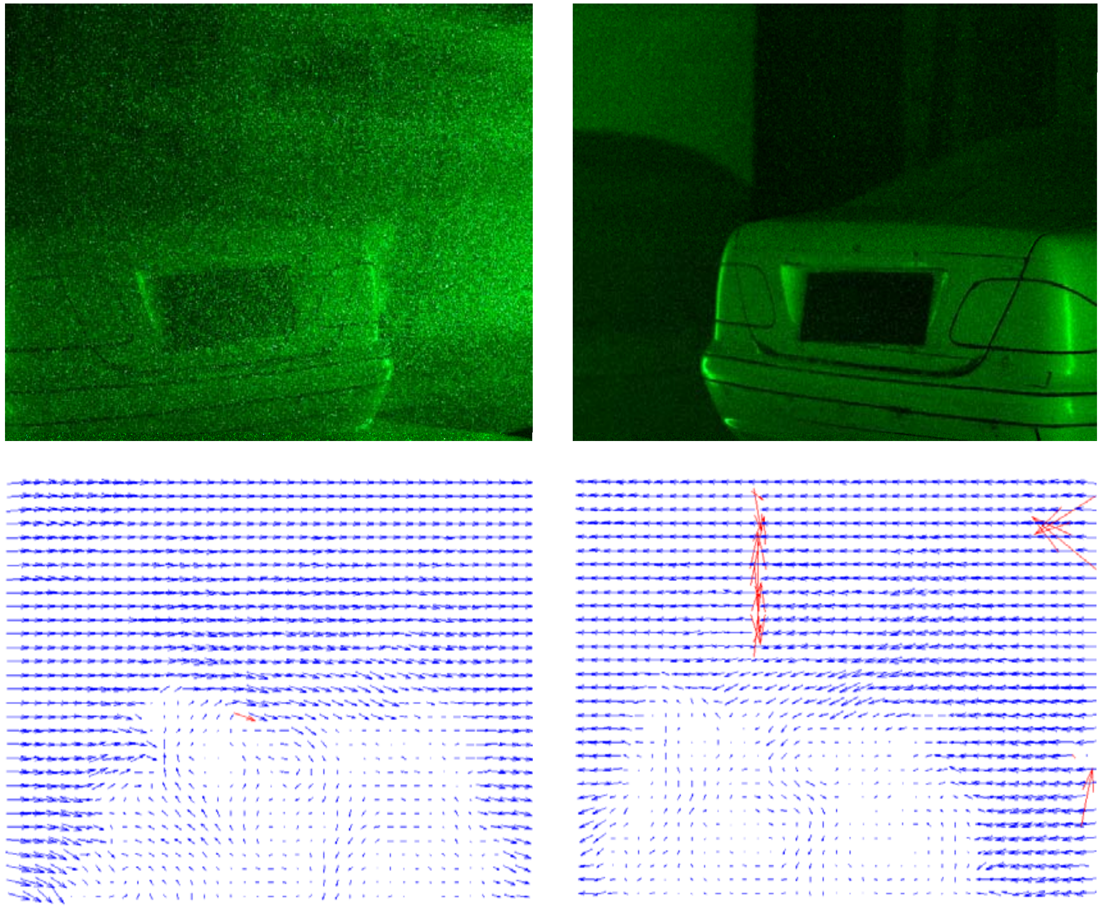
Left / Right 2D vector maps

Left & Right camera images are recorded simultaneously.

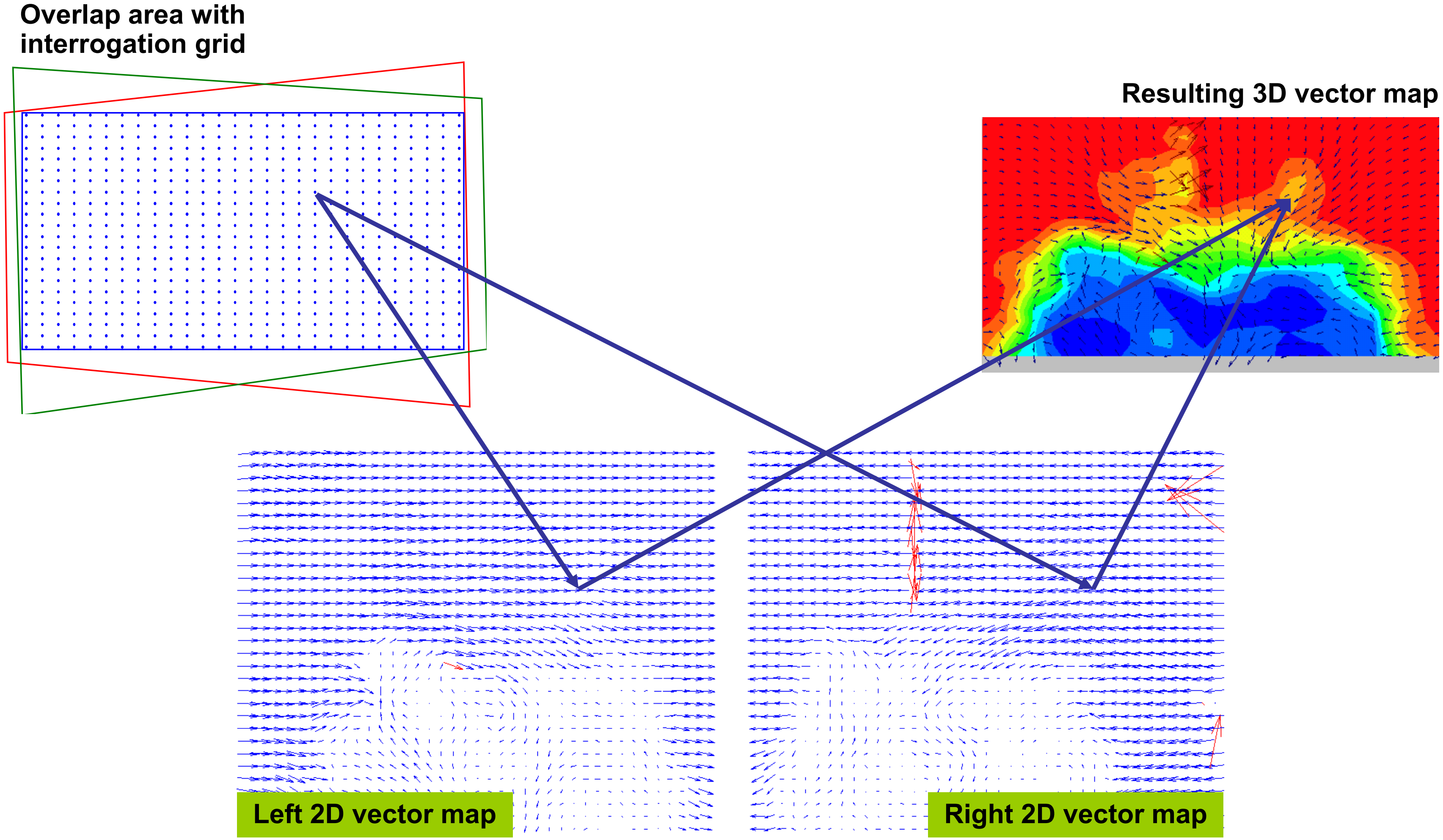
Conventional PIV processing produce 2D vector maps representing the flow field as seen from left & right.

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

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

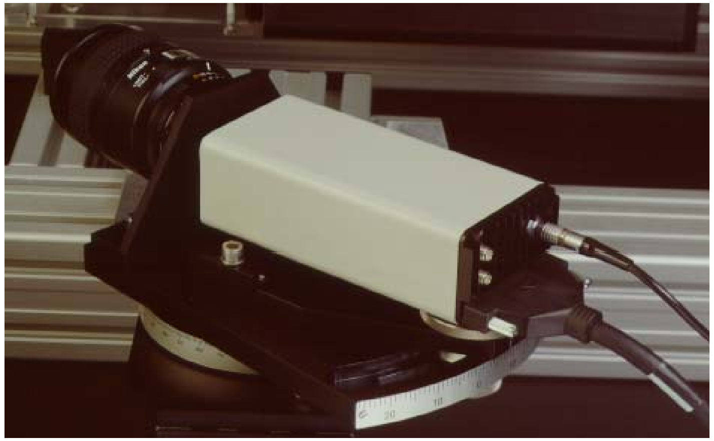


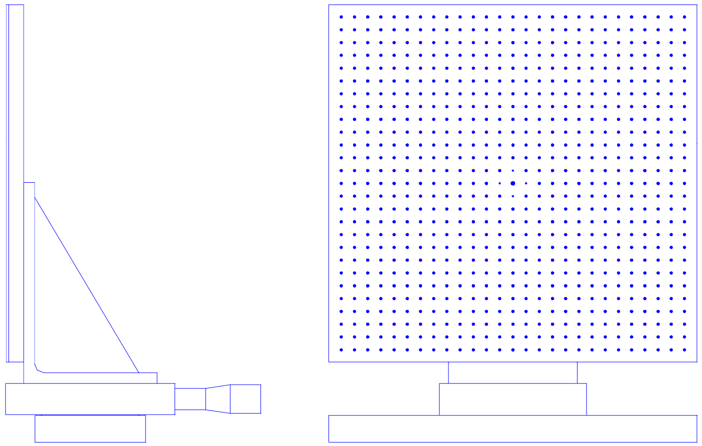
3D reconstruction



Dantec Dynamics 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

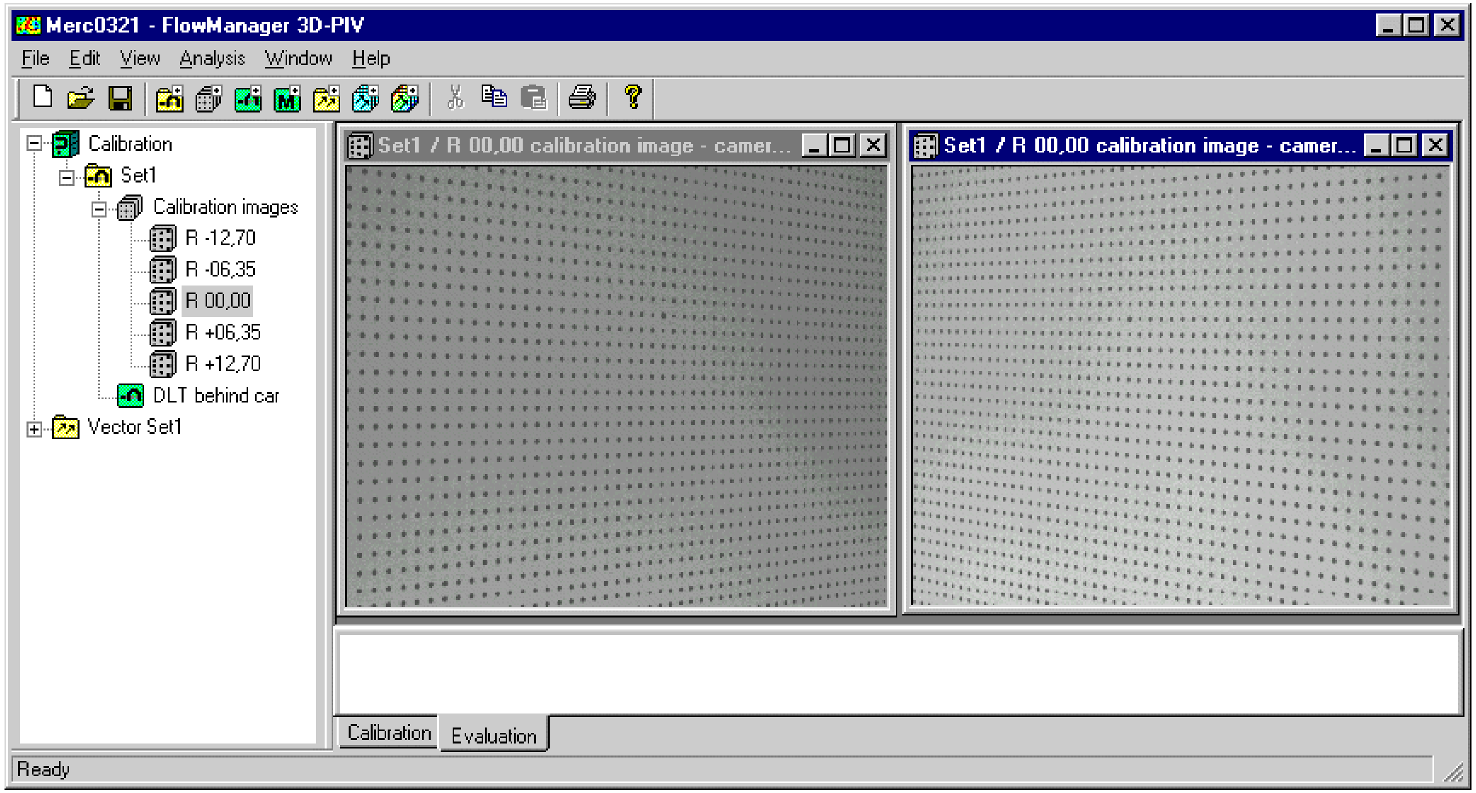




Recipe for a 3D-PIV experiment

- Record calibration images in the desired measuring position Calibration markers on the target identifies the X- & Y-axes of the coordinate system, and the traverse moving the target identifies the Z-axis.
- Since the calibration target and traverse identifies the coordinate system, care should be taken in aligning the target and the traverse with the experiment.
- Align the lightsheet with the calibration target. (The plane target must be parallel with the lightsheet. , and the target is traversed along its own surface normal to acquire calibration images covering the full thickness of the lightsheet (Images are recorded in at least 3, but typically 5 or 7 positions).
- The 3D evaluation assumes also that the central calibration image corresponds to the centre of the lightsheet, so proper alignment of the laser and the calibration target is essential for reliable results.
- 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

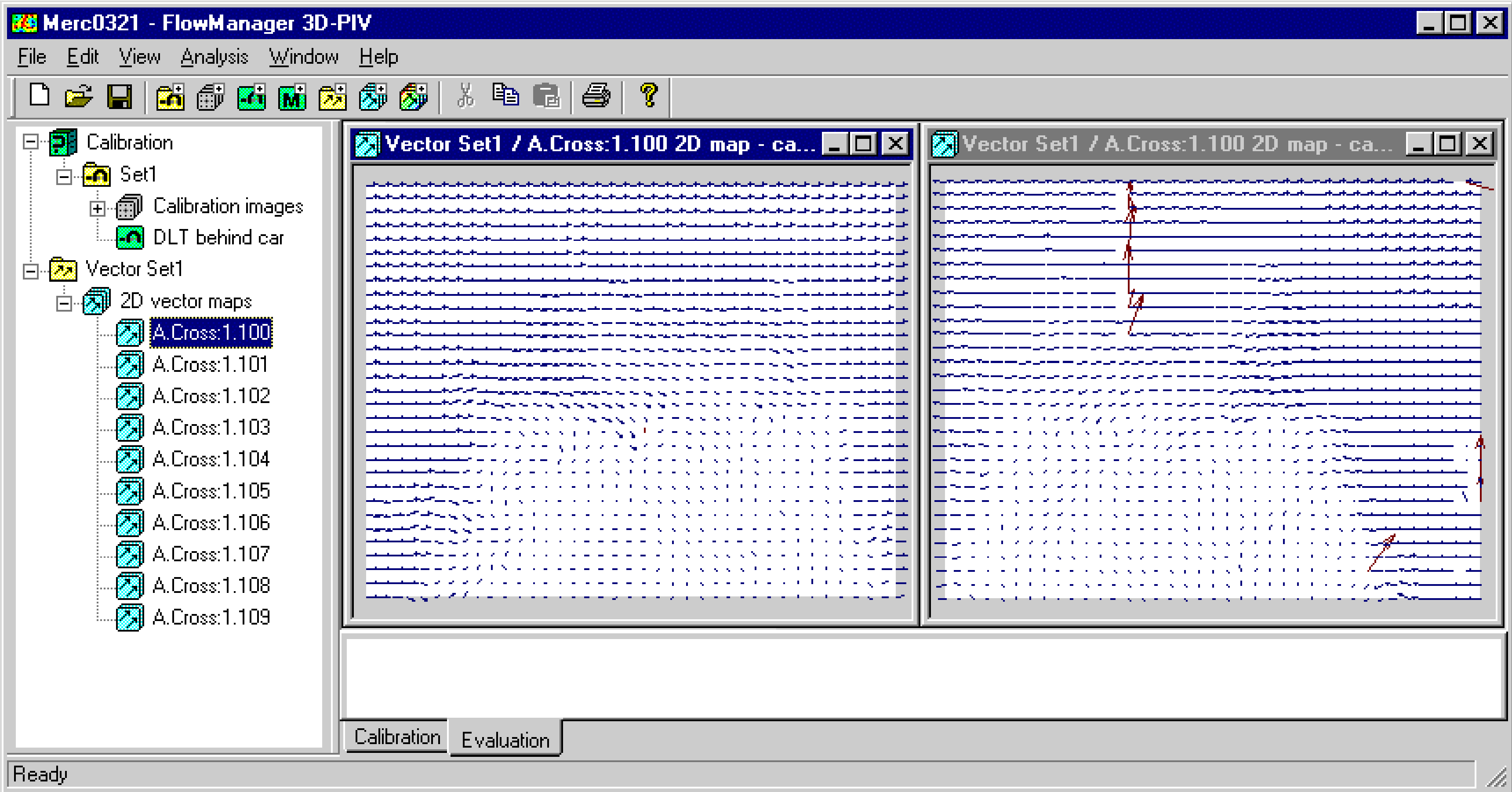


Each image pair must be related to a specific Z-coordinate, and the software will look in the log-field of the set-up for this and if a Z-co-ordinate can still not be found, the user is prompted to specify one.

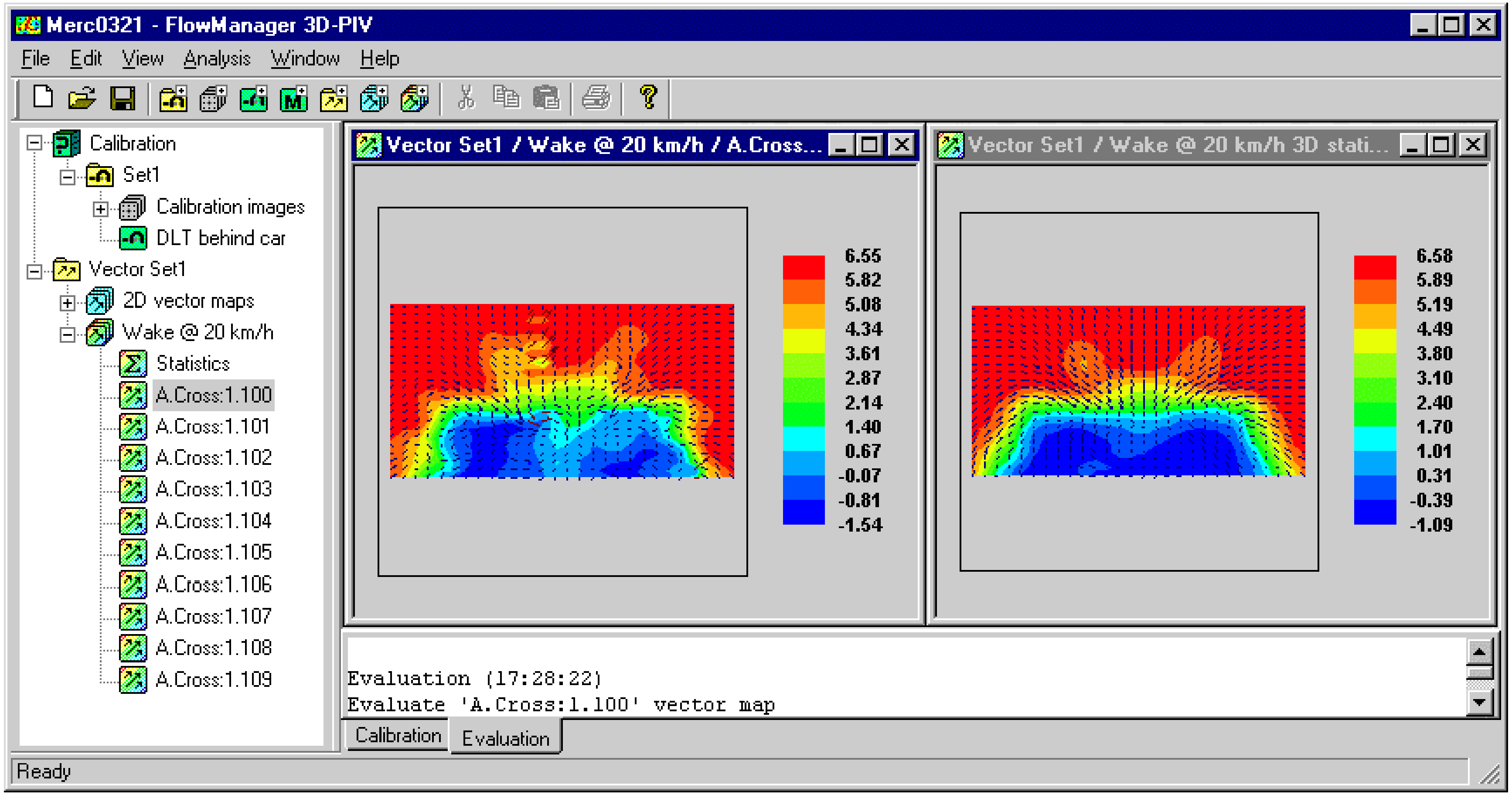
First image processing is used to derive the position of calibration markers on the camera images This produces a list of nominal marker positions and corresponding image co-ordinates on the CCD-chips of left and right camera respectively.

This list is then used to estimate parameters in the chosen numerical imaging model, to give the best possible fit between nominal calibration marker positions and their corresponding pixel-positions on the camera images.

Importing 2D vector maps



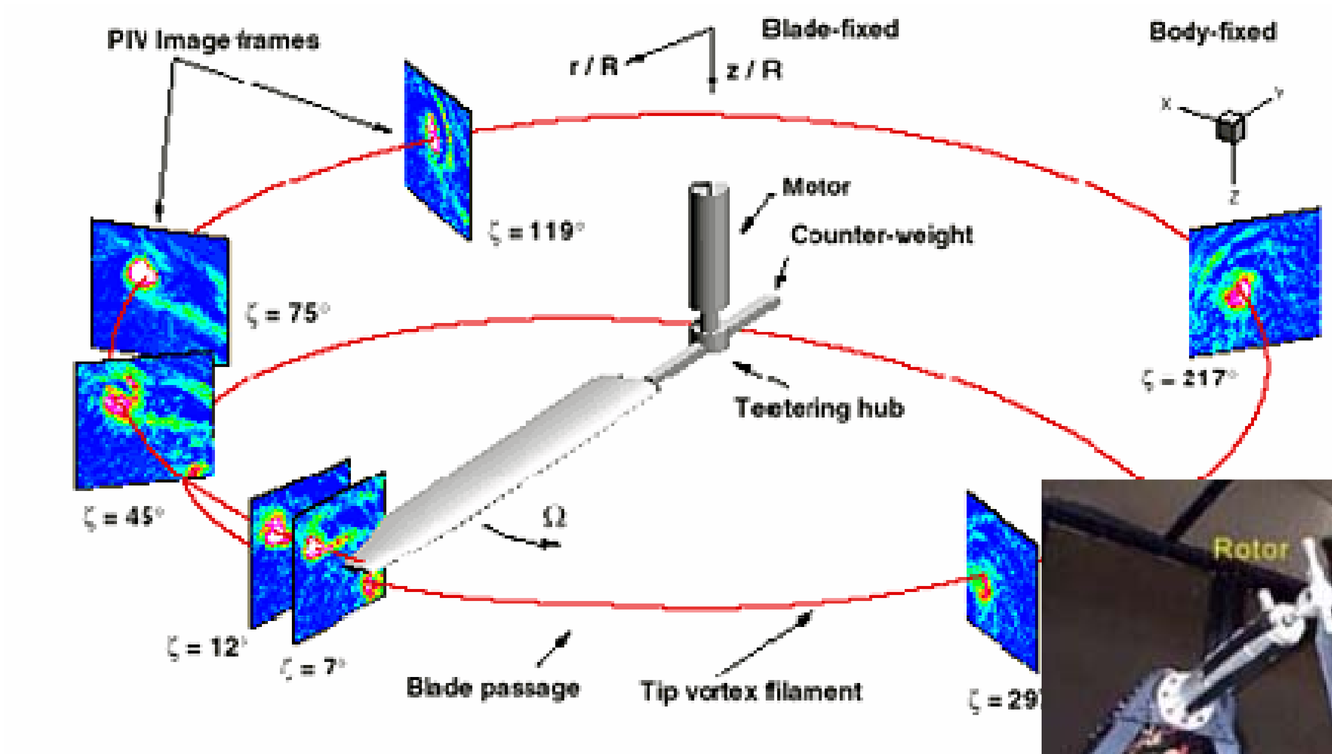
3D evaluation & statistics

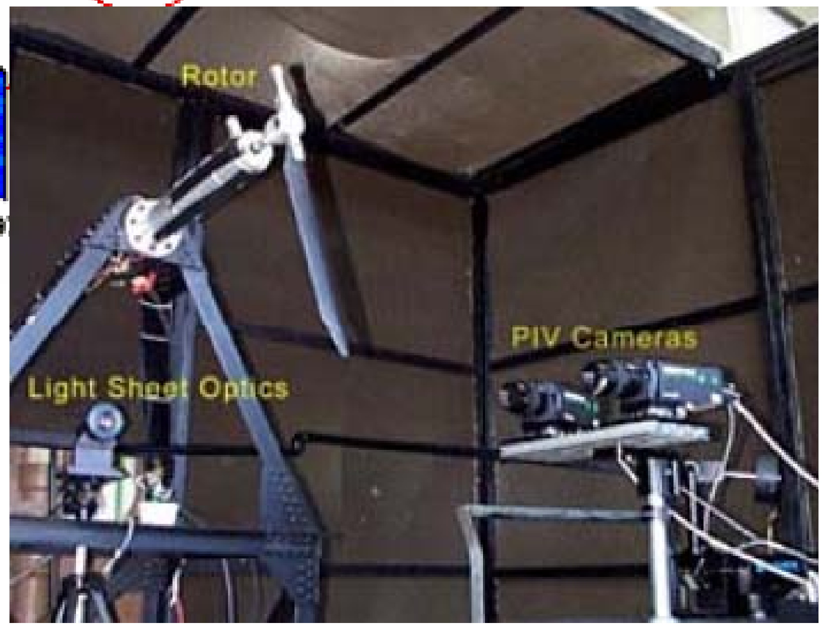


Once calibration has been performed, and 2D vector maps imported, 3D evaluation can be performed on pairs of 2D vector maps.

Hovering Helicopter Rotor Wake

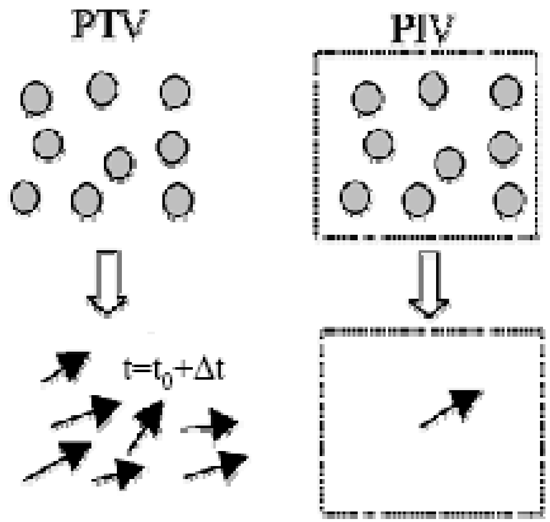
Courtesy: University of Maryland



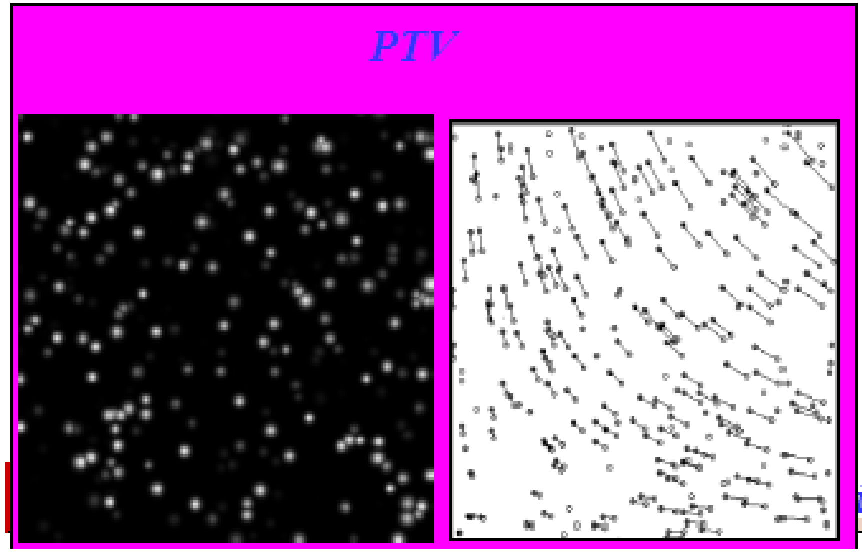


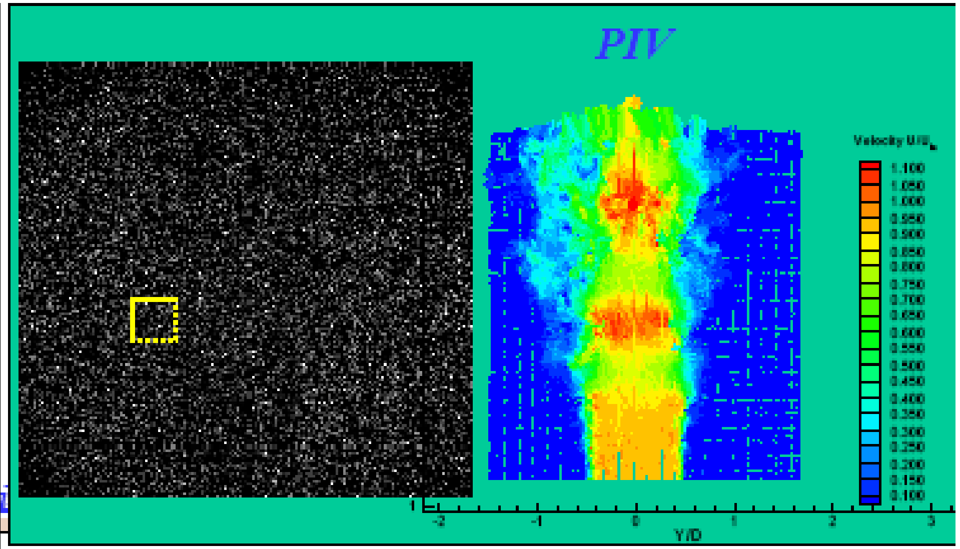
Comparison of PTV and PIV

- *Particle Tracking Velocimetry:*
  - *Tracking individual particle*
  - *Limited to low particle image density case*
  - *Velocity vector at random points where tracer particles exist.*
  - *Spatial resolution of PTV results is usually limited by the number of the tracer particles*

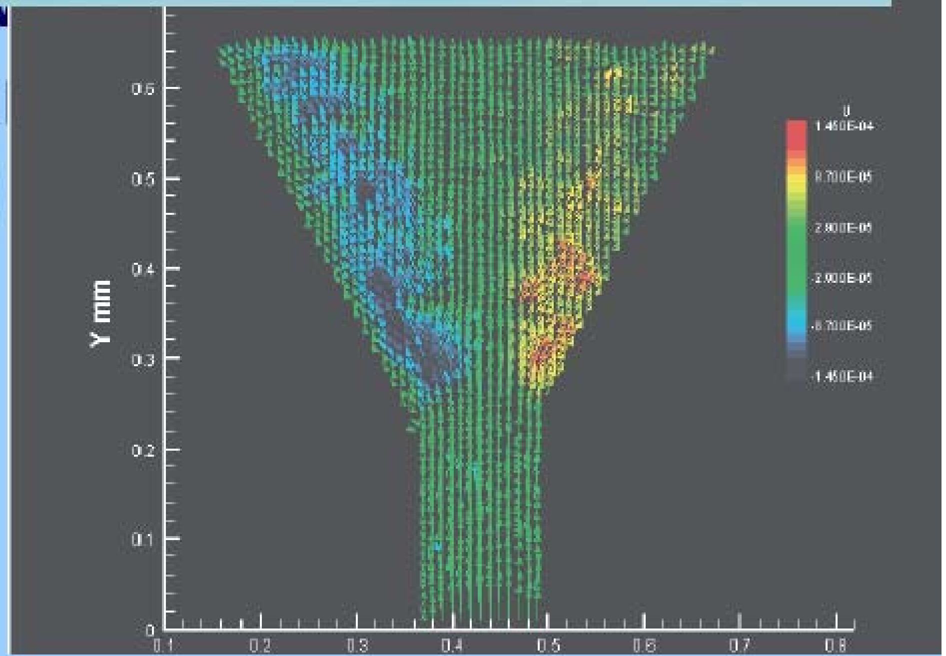


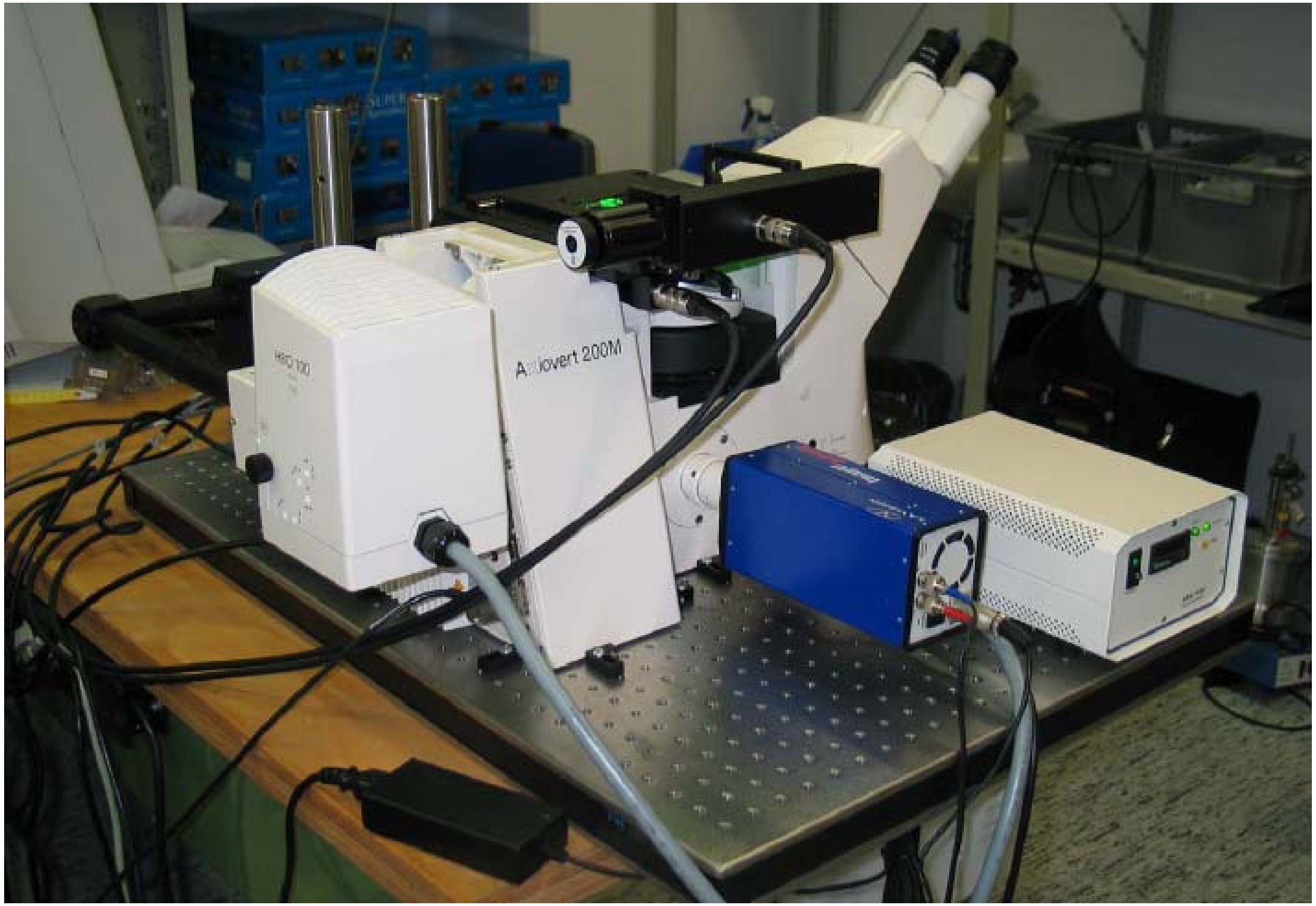
- *Correlation-based PIV:*
  - *Tracking a group of particles*
  - *Applicable to high particle image density case*
  - *Spatial resolution of PIV results is usually limited by the size of the interrogation window size*
  - *Velocity vector can be at regular grid points.*





MICRO PIV

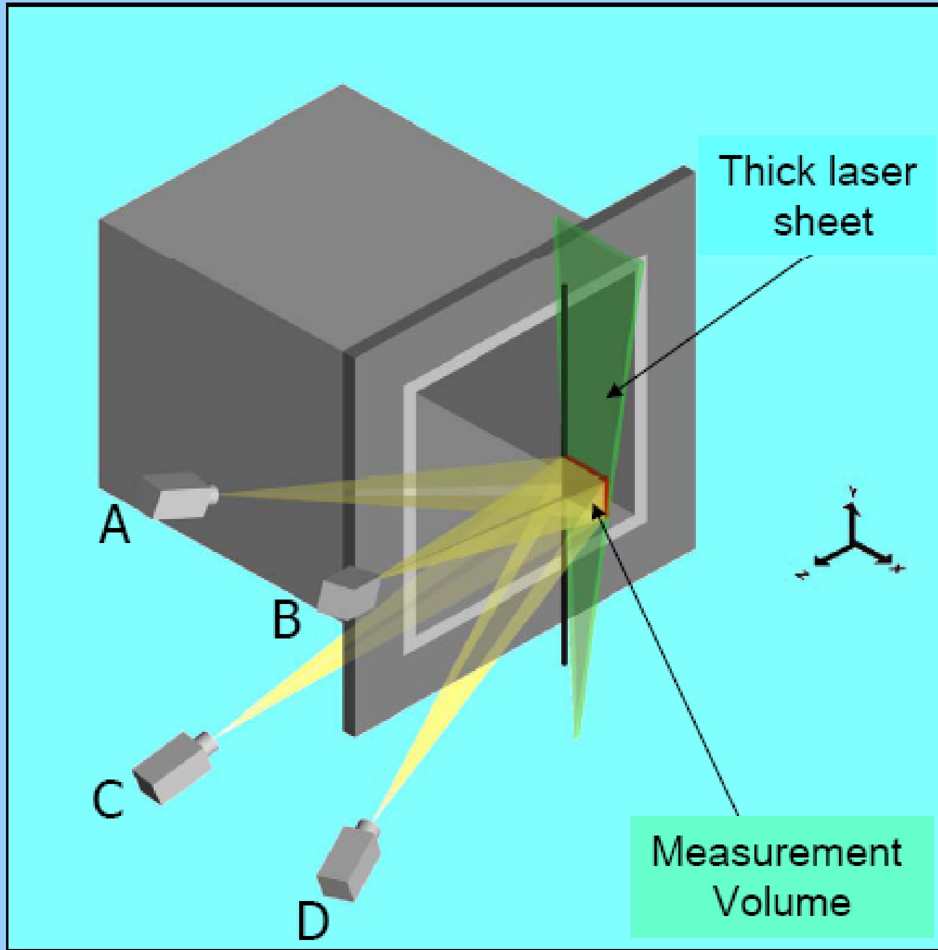

Y mm
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
U
1.450E-04
8.700E-05
2.900E-05
-2.900E-05
-8.700E-05
-1.450E-04



TOMOGRAPHIC PIV

Basic Principle (Scarano 2005)

- Instantaneous volume Illumination
- 4 simultaneous views directions
- Recording with CCD cameras
- Particle Images focused by application of Scheimpflug condition and large f#
- 3D Analysis with cross-correlation



Tomographic particle image velocimetry
G. E. Elsinga F. Scarano, B. Wieneke, B. W. van Oudheusden
Sixth International Symposium on Particle Image Velocimetry
Pasadena, California, September 21-23 2005

Aerodynamics TU Delft

- **21 January 2010- Thursday- Final Exam @ 9:30 Room AE025**

Closed book and closed note exam.

Final exam topics do not cover Midterm exam topics (i.e The lecture notes for pressure measurements are excluded.)

- You should bring your Final Lab Report and Final Project Report until **22 January 2010 at 12:00**. The Report formats must be same as M.Sc thesis format of METU.

- You should also prepare 2 posters (one for the lab and one for the project) using Power Point with **A1 paper size (594mm x 841mm)**. You should first send me the posters via email (to: funda.kurtulus@gmail.com) due to 22 January 2010. After my review and acceptance email, you should print the posters due to 26 January 2010.

- The best poster will be selected for a Bonus Point and all the posters will be hanged in Aerodynamics Laboratory.

- **You should also give all the drawings, CFD solution, results, presentations and reports in a DVD.**