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Particle Imaging Velocimetry and its applications in hydraulics.

A state-of-art review.

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EMI Commitee

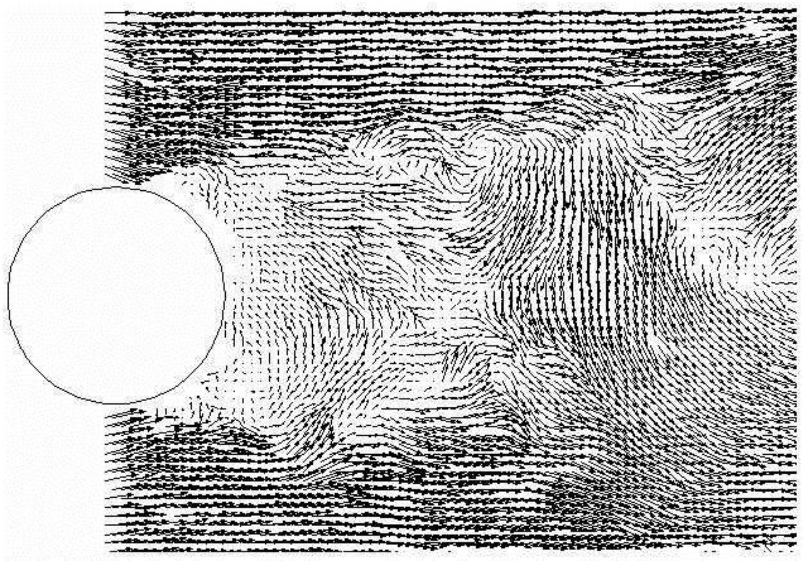
Introduction

Different image-based instruments, under the generic name of Particle Imaging Velocimetry (PIV), were developed in the last three decades.

- aerodynamics and hydraulic research
- turbulent flows

Introduction

PIV is a non-intrusive technique able to provide quantitative measurement of instantaneous velocity fields over a relatively large surface with measurements documented at a large number of points simultaneously.



Presentation layout

Overview presentation of the Particle Imaging Velocimetry (PIV) technique, actually widely used in hydraulics.

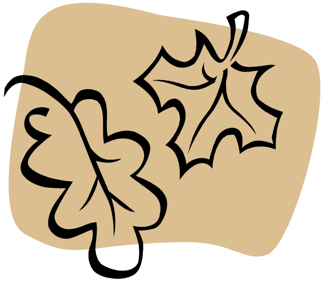
- Historical development
- Basic principles and standard setup
- Some representative applications in hydraulics

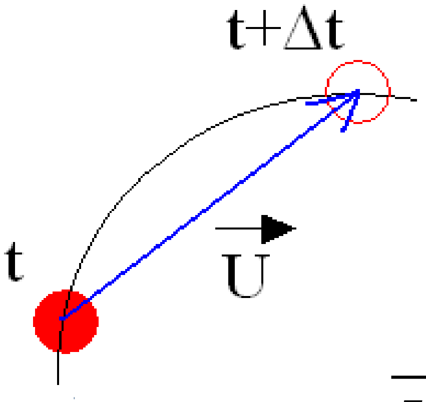
References

- Raffel et al. 2007, Adrian 1991
- *Experiments in Fluids* Journal

PIV concept

The velocity is estimated, in an indirect way, from the movement of tracers present in the flow, assumed to closely follow the flow.

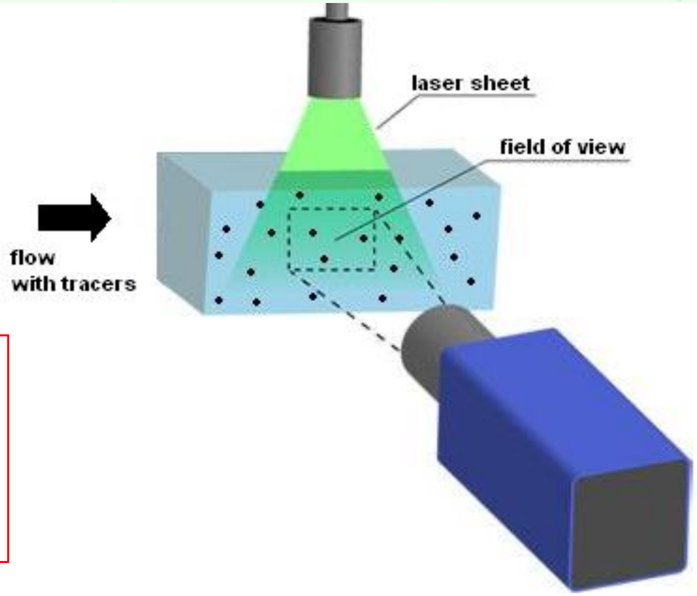




The velocity vector is calculated using velocity definition, considering the tracer displacement between two successive observations.

$$\vec{U} = s\,\frac{\vec{X}}{\Delta t}$$

Historical development

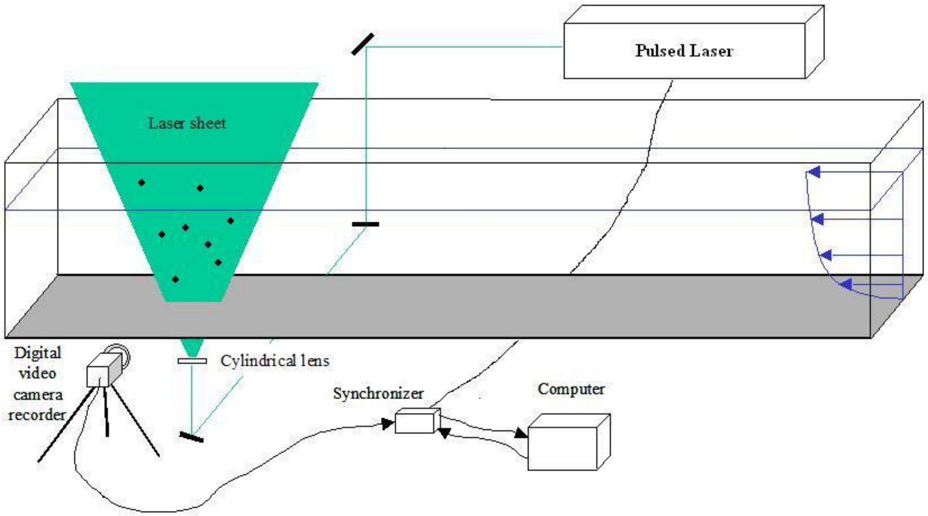


PIV first appeared in literature in the mid eighties for studying turbulence

- tracers must be small enough to follow the flow in presence of large local and randomly fluctuating accelerations
- a pulsed light is required
- the duration of the illumination light pulse must be short enough that the particles are “frozen” during the pulse

high intensity pulsed laser

Layout of a standard PIV system

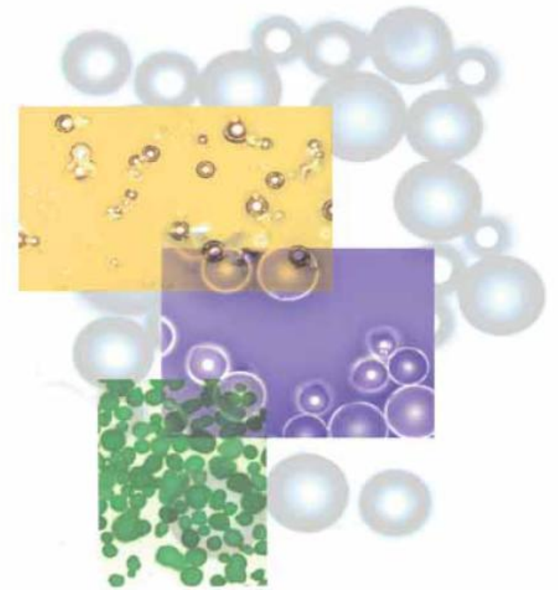


A standard PIV system consists of a pulsed laser with optics, which create an illuminated sheet in the flow with tracers, one digital camera and a computer to control the system and store the data.

2D velocity fields are measured in the planar region, illuminated by the laser light sheet and captured by the field of view of the camera.

Recording and elaborating phases

Standard PIV system
Tracer particles



- they have to follow the flow
- do not influence the flow
- do not interact each other

$$\tau_p = \frac{\rho_p}{\rho}\frac{d_p^2}{18\nu}$$

Small and light

The τp value has to be compared with eddies' characteristic time of the flow under study

- they have to generate a light signal, strong enough to be resolved by the imaging device (light scattering property)
- good image contrast and no background noise (concentration)
- good particle dispersion

Standard PIV system

Tracer particles

Seed Particle Specifications

TSI Model	Particle Type	Nominal Mean Dia. (µm)	Size Range (µm)	Density (g/cc)	Refractive Index (real + imag.)	Quantity
900805	Dye-impregnated PSL	1.0	Std. dev.<0.05	1.05	-	10 ml*
10081	Silicon carbide	1.5	Std. dev. = 1.4	3.2	2.65	100 cc
10084	Nylon	4	Std. dev. = 1.5	1.14	1.53	400 cc
10085A	PSL	0.54	Std. dev. = 1.05	1.05	1.55 to 1.6	15 ml**
10086A	Titanium dioxide	3 to 5	-	4.2	2.6	0.45kg (1 lb)
10087	Metallic coated	9	4 to 12	2.6	0.21 + 2.62*i*	30 cc
10089	Hollow-glass spheres	8 to 12	10%<3 to 5 90%<14 to 17	1.05 to 1.15	1.5	1000 cc
10089-SLVR	Metallic-coated hollow-glass spheres	14	10%<7 90%<21	1.65	0.21 + 2.62*i*	100 cc

* Aqueous suspension, 1% solids by weight ** Aqueous suspension, 10% solids by weight
Particles highlighted in blue are spherical, particles in gold are irregularly shaped.

For liquid flow problems solid particles, metallic and glass particles of few tens of microns, are adequate

Standard PIV system

Light source and optics

Light Amplification by Stimulated Emission of Radiation: because its ability to emit monochromatic light with high energy density, which can easily be bundled into thin light sheets.

- light pulses can be obtained with pulsed lasers or with continuous wave (CW) lasers, combined with a chopping system for producing light pulses and/or a shuttered recording camera.
- a variety of lasers were proposed, like helium-neon, copper-vapor, argon-ion, which are gas lasers, and ruby and Neodym-Yag, which are solid-state lasers.

Standard PIV system

Light source and optics

Optics generate from laser beam a light sheet in the desired position

Mirrors reflect beam in the desired position

Cylindrical lens expand the beam into a plane

Spherical lens compress the plane into a thin sheet

Standard PIV system

Light source and optics

Exposure time: duration of the illumination pulse

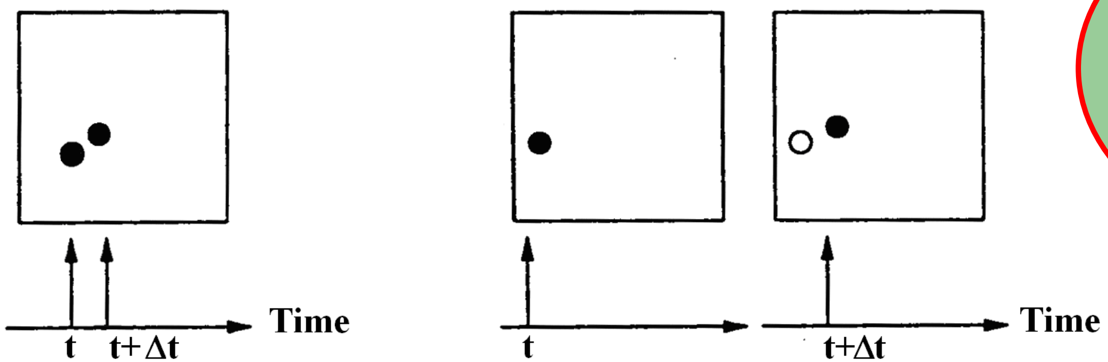
- it has to be short so that particles motion is “frozen” without “streaks”
- not too short in order to guaranty a good illumination of seeds

Delay time: time interval between to consecutive pulses

It influences the maximum and the minimum velocity that can be measured.

Recording modes

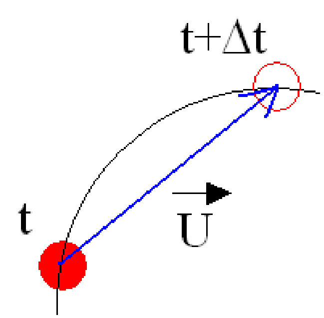
Single frame- double exposure - Double frames-single exposure



No ambiguity on the direction of the velocity vector

Delay time

- long enough to be able to determine the displacement of the same particle in two consecutive images without overlapping
- small enough because the velocity vectors, considered a good approximation of the “instantaneous” flow values, are “mean” values in Δt
- not to large because particles can go out of the light sheet or out of the plane



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Standard PIV system

Camera

- Distance between the camera and the plane of view characterizes the pixel size.

- High speed CCD cameras are now available.

- The camera and the laser are connected through a syncronizer, which is controlled by a computer and dictates the timing of the camera sequence in conjunction with the firing of the laser.

- More than one camera can be used.

Elaborating Phase

Image Analysis, Pre-processing, Post-processing

The algorithm for image analysis is related to the recording procedure and the image density

High: particles overlap and form speckles

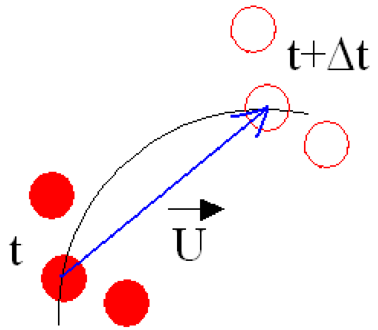
Medium: the images of individual particles can be still individuate, but it is not possible to identify image pairs

Low: images corresponding to the same particle can be recognized

Image analysis

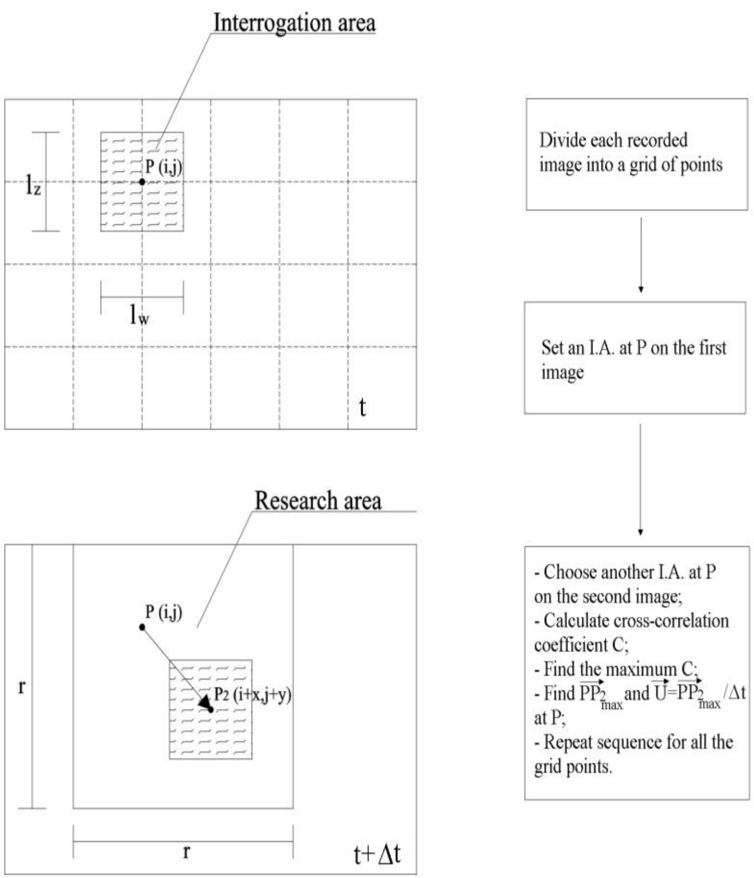
PIV mode: velocity is evaluated considering the displacement of small group of particles (patterns), assuming that they do not change their relative position in the group during the delay time

Pattern displacements are evaluated by statistical means, computing two dimensional correlations on pairs of images (cross-correlation technique)



The cross-correlation technique individuate the corresponding particles patterns in the two images of the pair using a cross correlation coefficient.

Image analysis



A grey-level intensity for each pixel

The distance , which furnishes the best correspondence, represents the particles movement in the time interval Δt and it is used for computing the velocity vector.

$$C(x,y)=\frac{\sum_{i=1}^{l_w}\sum_{j=1}^{l_z}\left(I_1(i,j)-\mu_1\right)\left(I_2(i+x,j+y)-\mu_2\right)}{\sqrt{\sigma_1\sigma_2}}$$

being *I1(i,j)* and *I2(i,j)* the pixel values in images 1 and 2; $\mu1,\mu2$ and $\sigma1,\sigma2$ the mean and variance values of the intensity in the interrogation areas *A1* and *A2*, respectively

The correlation coefficient can be also calculated via the Fourier transform.

Image analysis

Important parameters:

- **delay time**
- **the sizes of the interrogation area (*l*)**
- **the size of the research area** (*r*)
- **the grid spacing**
- **pixel size**

Decreasing *l*, the computational requirements, but also the statistical reliability decrease

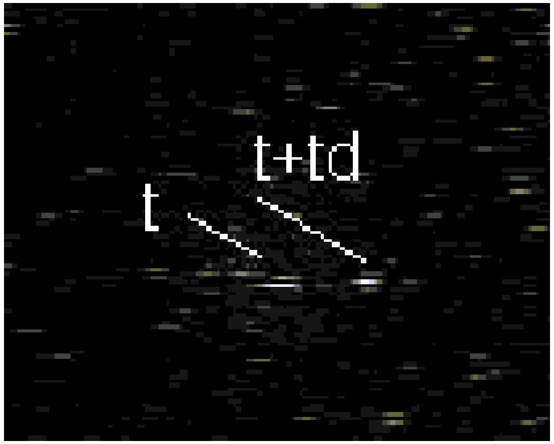
The ratios $r/\Delta t$ and $1/\Delta t$, multiplied for the pixel width, give the maximum and minimum velocity that the technique may resolve.

To improve the accuracy of the analysis: techniques for determining with sub-pixel accuracy the location of the maximum c-correlation coefficients

Particle Tracking Velocimetry

Image density is low and particles are tracked individually

- similar cross-correlation techniques have been developed for PTV mode.
- velocity vectors are evaluated in the centre of each particle with an unstructured distribution across the image plane.



Pre and Post-processing procedures

Pre-processing: may be applied to the images in order to remove non-ideal aspects and enhance image quality befor to apply the processing algorithm.

histograming-equalization, smoothing, hedge detection, background subtraction, thresholding, binarization

The use and the effects of such procedures should be carefully considered, since a not appropriate application could degrade, rather then to improve the processing results

Post-processing: they validate the correct velocity vectors, removing the incorrect ones.

Applications in hydraulics

Starting from the measurements of instantaneous velocities:

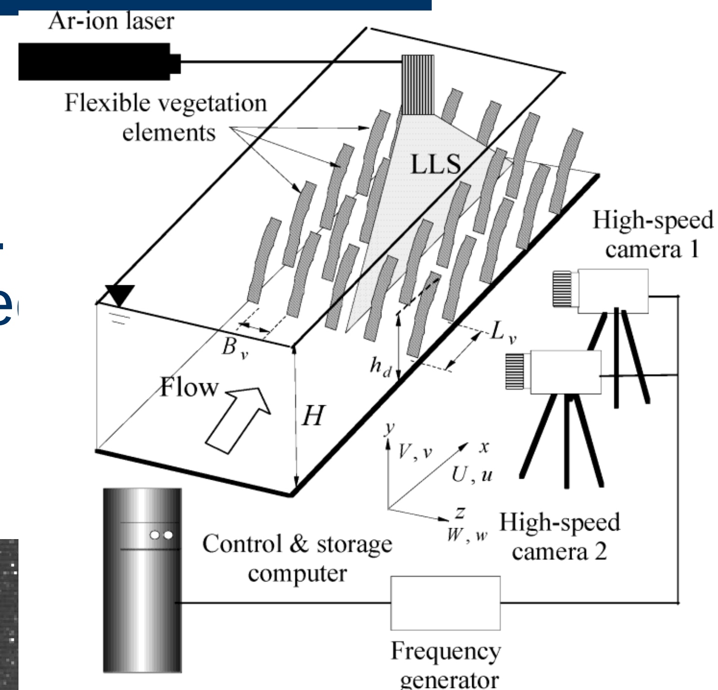
- mean velocities
- turbulence intensities
- Reynolds stresses
- production term in transport equation for turbulence kinetic energy
- and more…..

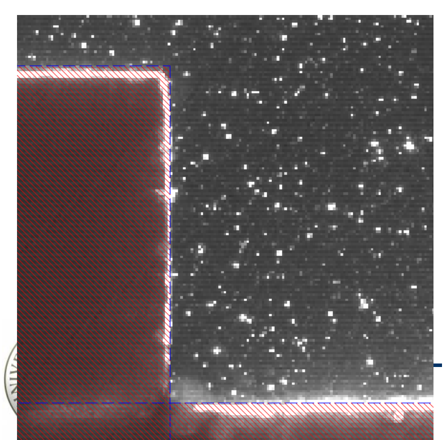
PIV and PTV are consolidated techniques to measure velocity fields for studying hydraulic phenomena.

Laboratory and field applications.

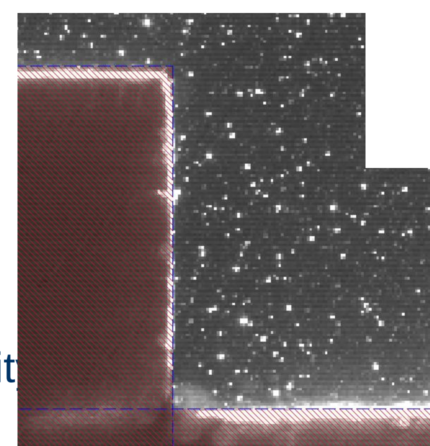
Applications in hydraulics

- hydrodynamics aspects in presence of rough (e.g. Campbell 2005, Campbell et al. 2005, Manes et al. 2007, Ferreira et al. 2010) or vegetate beds (e.g. Okamoto & Nezu 2009)



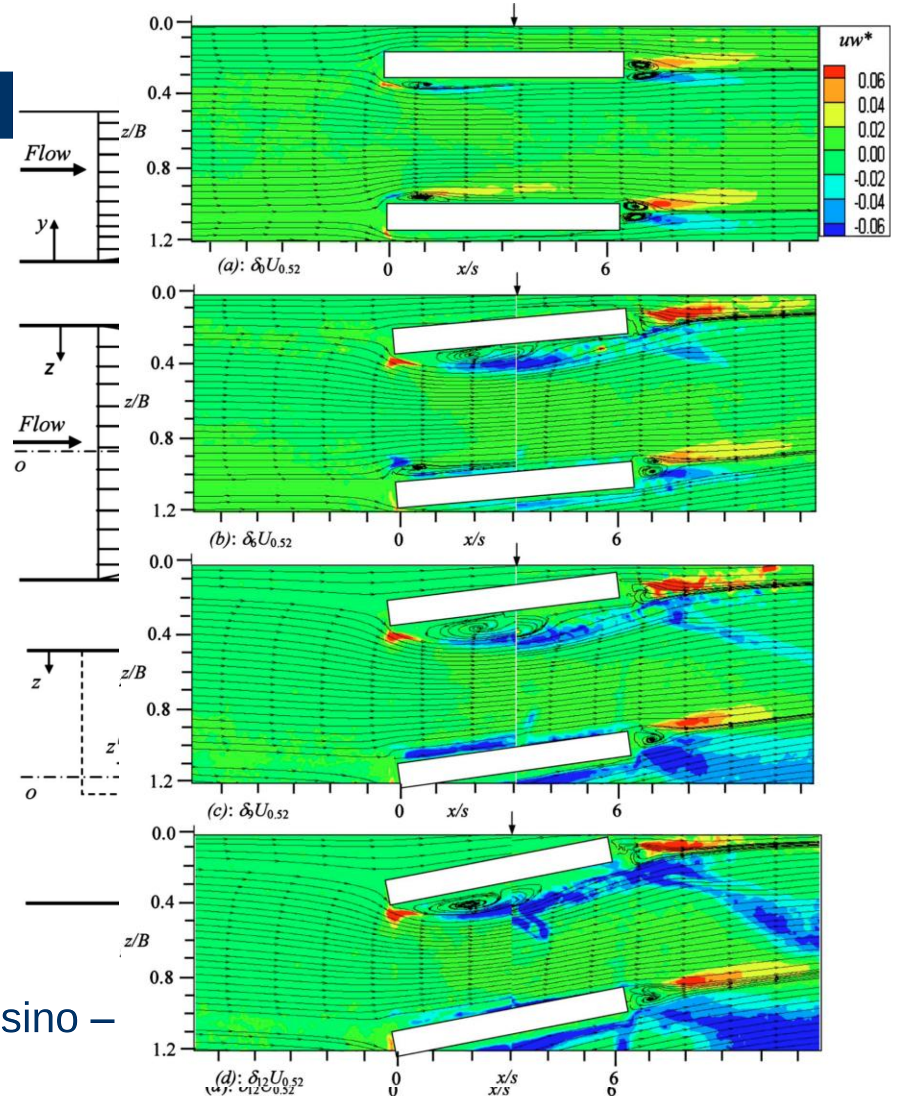


Δt



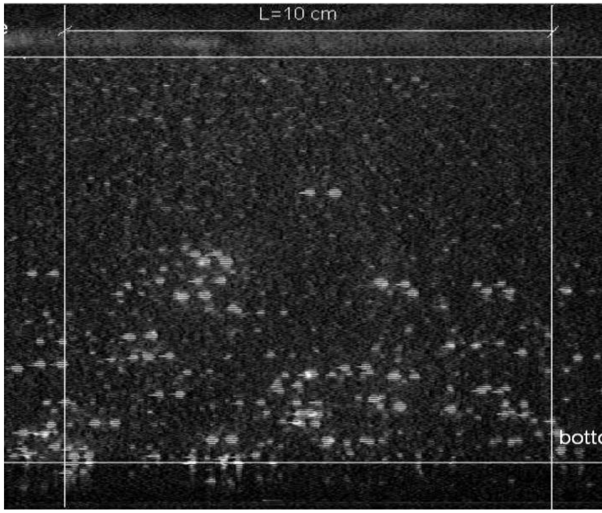
Applications in hydraulics

- near hydraulic structures (e.g. Tsikata et al. 2009)
- in complex phenomena also combined with other measurement techniques (e.g. Zweifel et al. 2006)
- many others



PIV and PTV in two phase flows

Bubbly and sediment laden flows



- the possibility of discriminating between the two fractions, separating the particles seeding the liquid phase from the dispersed particles, bubbles or sediments
- measurements of the velocities of both fractions simultaneously

Discriminating methods:

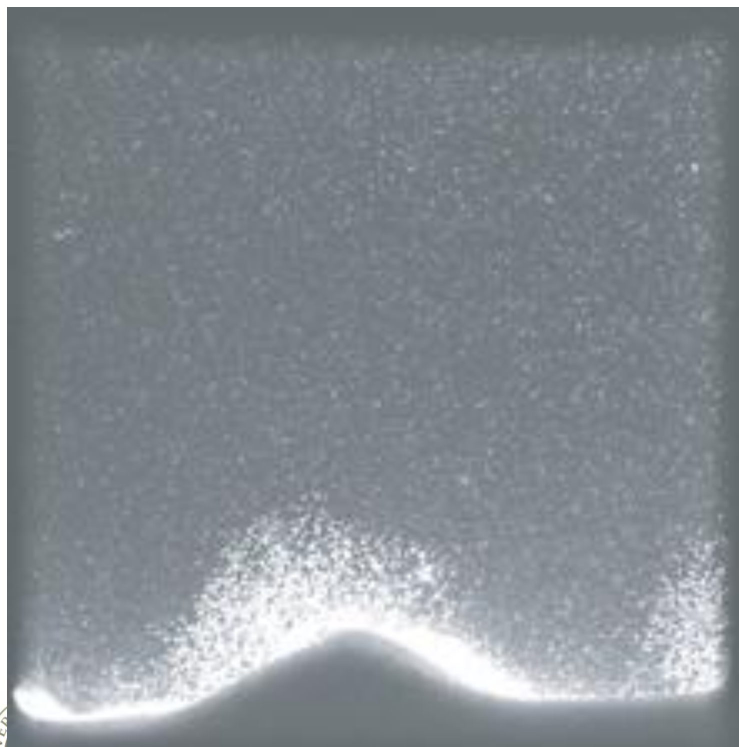
- Optical separation criteria (recording phase)
- Different criteria in the a pre-processing phase, starting from a single image with both phases

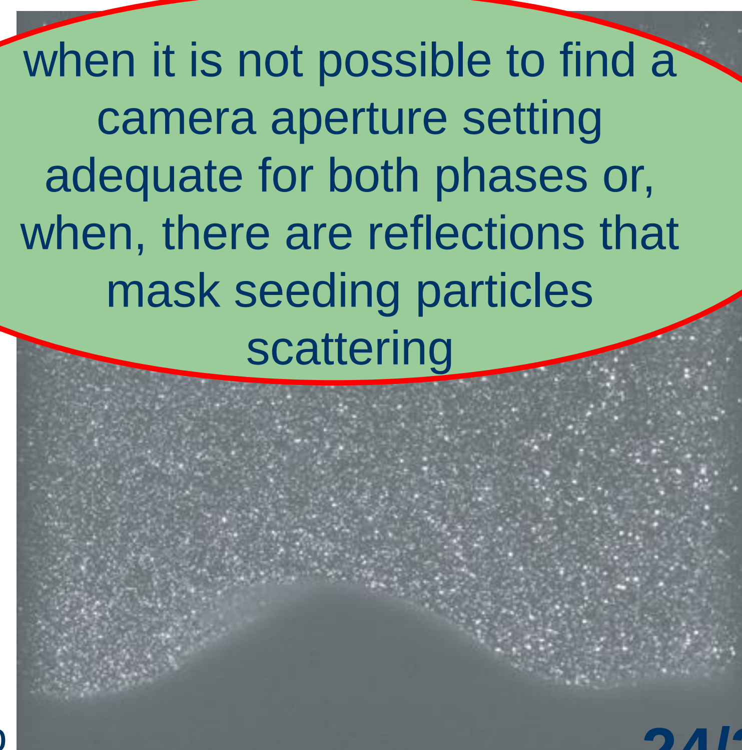
PIV and PTV in two phase flows

Optical separation criteria

Fluorescent tracers are used in conjunction with a camera equipped with on optical filter to ensure that only seeding particles are imaged

Admiral et al. 2006





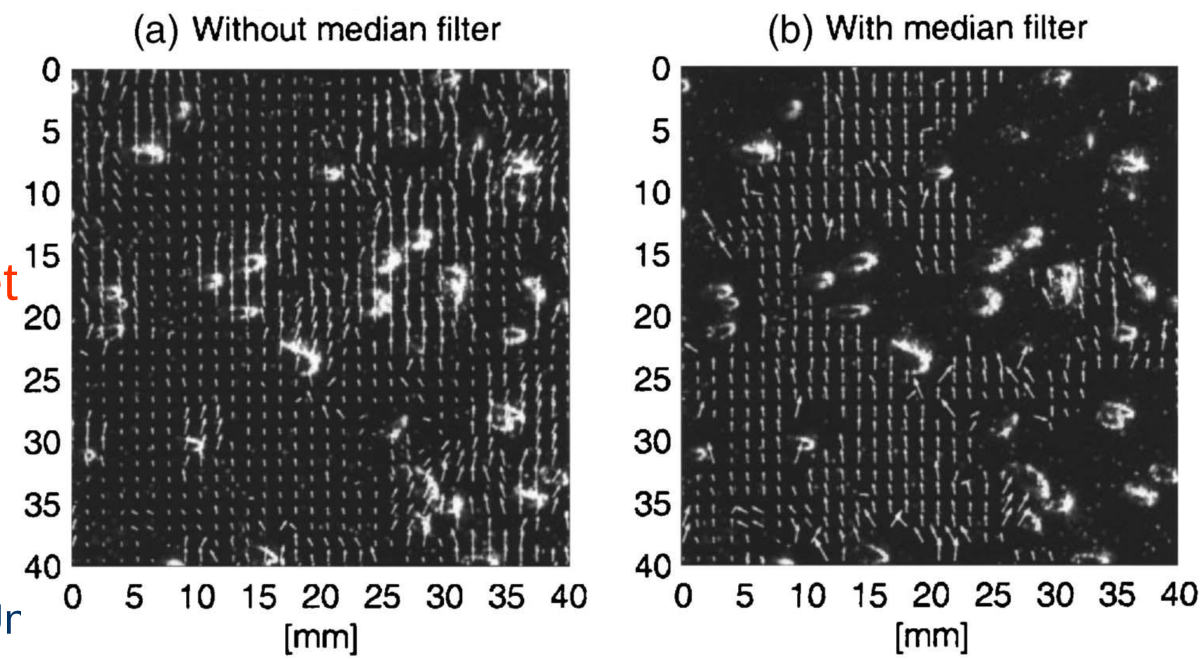
when it is not possible to find a camera aperture setting adequate for both phases or, when, there are reflections that mask seeding particles scattering

PIV and PTV in two phase flows

Criteria in the processing phase

A single image with both phases is recorded, then a criterion for discriminating between the images of the two phases is applied. Different criteria have proposed based on:

- size
- image intensity
- particle velocities
- others (e.g. Seol et al. 2007)



PIV and PTV in two phase flows

The selection of the discriminating method depends on:

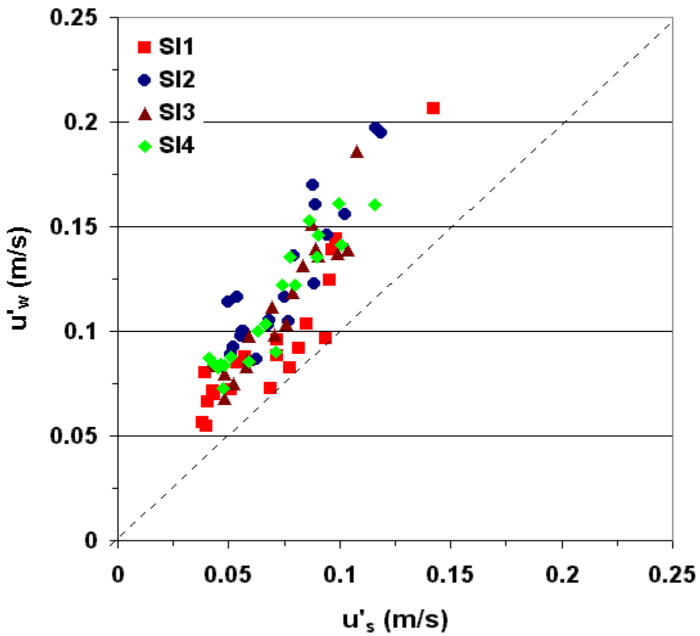
- **research objectives**
  - measurement of the liquid phase velocity
  - measurement of both phases velocities simultaneously
  - effect the dispersed phase on the liquid
- **characteristics of the two phases**
  - relative size
  - scattering characteristics
  - slip velocity
- **costs and available instrumentation**

PTV in sediment laden flows

An example

(Di Cristo and Muste 2002)

- To distinguish between sediment and tracer velocity vectors, a phase-discrimination criterion based on the size of the particles was used.
- Choosing a relatively large difference between the two size ranges (buffer) the erroneous attribution of particle velocity to water tracer was minimized.

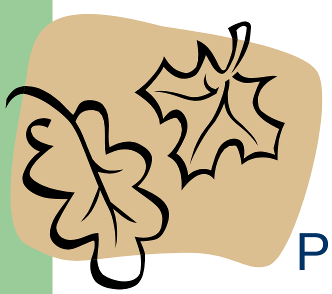


Instantaneous velocity of liquid and sediments simultaneously, mean slip velocity, liquid and sediment turbulent intensities, turbulence modulation.

Large scale PIV

Evaluation of the free surface velocity fields

(e.g. Fuijta et al 1998)



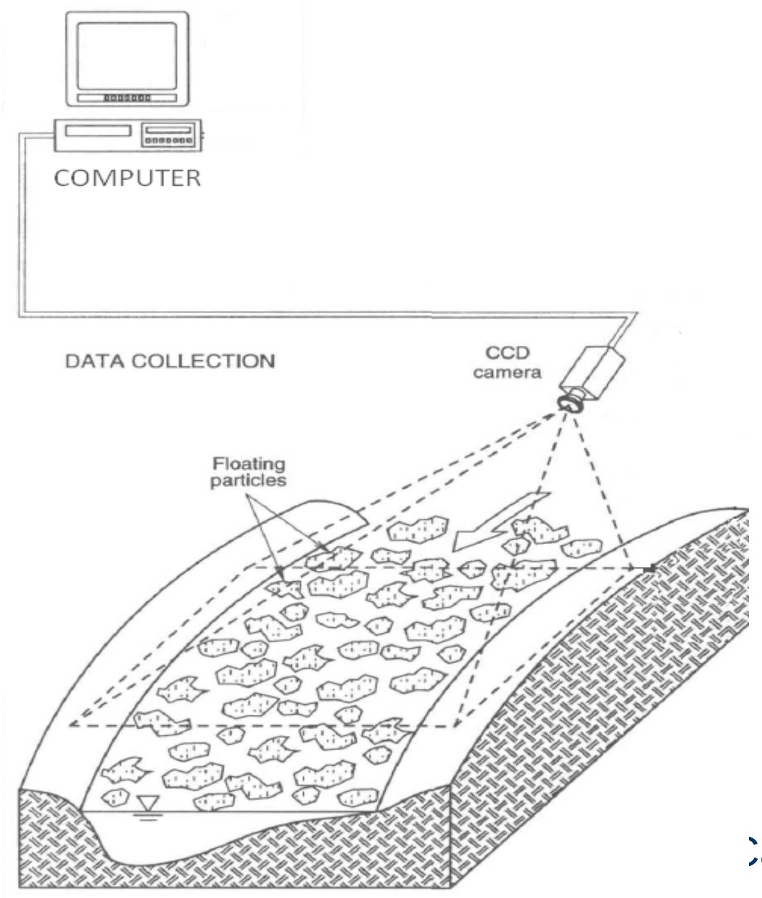
Field of view

PIV: several square centimetres ⟷ LSPIV: several square meters

LSPIV is now a suitable non-intrusive technique to measure free surface velocity field in an entire physical model or in rivers.

Large Scale PIV

Main characteristics



Differences respect to PIV

- seedings
- illumination
- the large distance between the camera and the image plane can introduce (lens) and geometrical distorsion ➡ correction procedure in the pre-processing
- more then one camera can be used
- the elaborating phase is similar

Large Scale PIV

Seedings

Characteristics

- well distributed
- lighter then water density
- big enough comparing with pixel size
- travel with the flow velocity
- good contrast between tracers and background color
- enviromental-friendly material
- low cost

Foam

- Styrofoam disks used in packaging industry
- Eco-Foam peanuts: a combination of over 95% cornstarch with synthetic additive

Straw

Grain straw or other plant residues

Large Scale PIV

Seedings

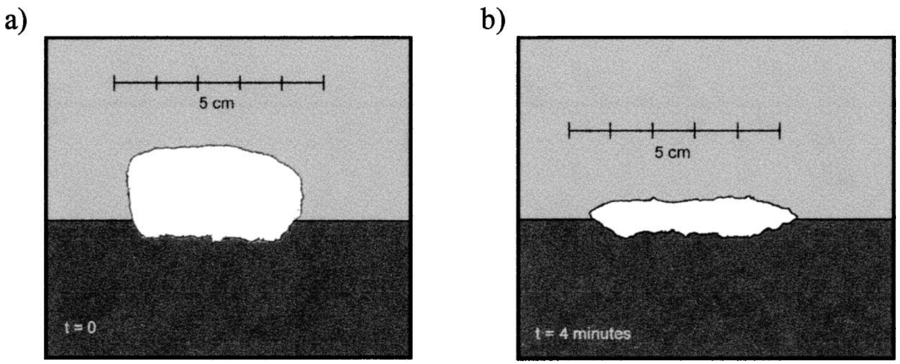
Foam vs. Straw

• the eco-foam changes geometry: after about 30 s become flat, but they continue to float on the water surface

→ advantage in field with wind

• the eco-foam completely dissolves in water, while straw needs to be remove

•the surface tension of the water surface can cause foam to coalesce. Their velocity can be inconsistent with the true flow velocity.



seeding procedures (general or local) and concentration

Large Scale PIV

Illumination

Indoor measurements

strong illumination is required (alogen, sodium-vapor or other kind of lamps)

Field measurements

natural light

Uniform distribution of the light intensity over the imaged area
No light reflections on the flow free surface

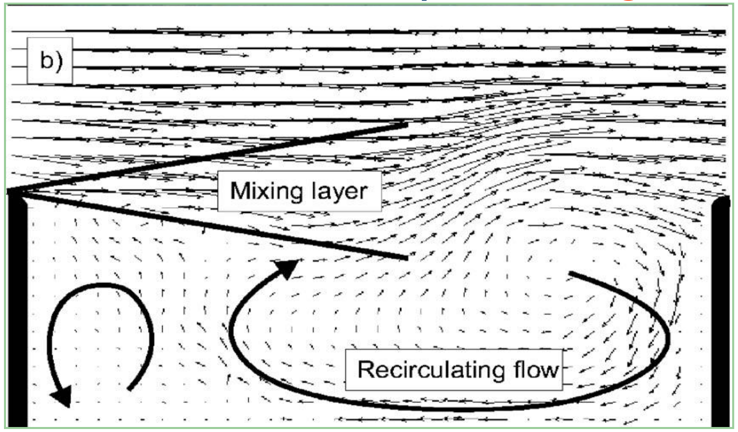
Large Scale PIV

Applications

The main products of LSPIV is the free surface instantaneous velocity field

Given the large size of LSPIV imaged area and of the pixel size, the spatial resolution of velocity measurements is limited. LSPIV cannot measure small-scale turbulence, but it is intended to capture large-scale flow structures.

- time-evolving flow processes
- global flow analysis (large coherent structures, mixing processes, sediment and ice transport, …..)

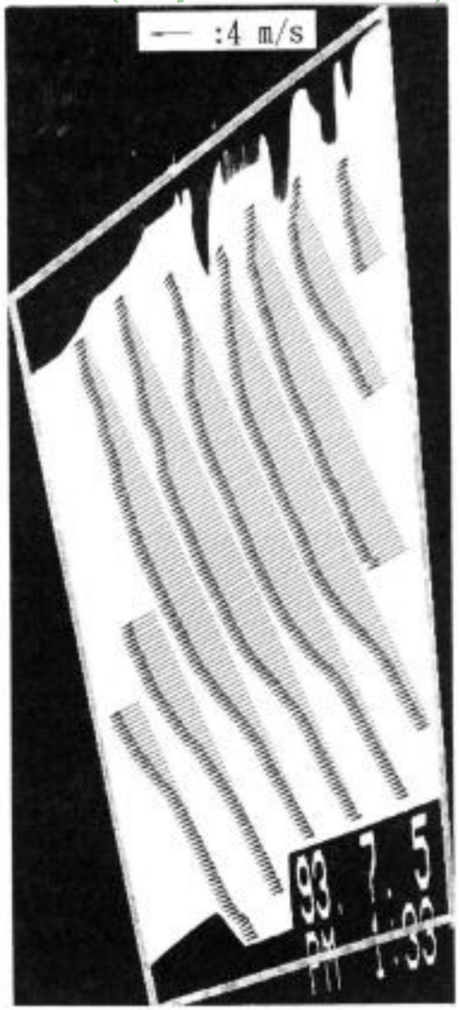


Instantaneous velocity field in a groin field experiment (Weibrecht et al. 2007)

Large Scale PIV

Field applications

Mean velocity cross-sections for the Yodo River during the flood (Fuijta et al. 1998)



Different equipments: fixed or mobile (Kim et al. 2008) field equipments, video from helicopters (Fuijta, 2007b), continuous operation systems (Hauret et al. 2008), measurement with poor or not seedings that takes advantage of the reflection on the small waves present on the free surface (Fuijta et al. 2007a).

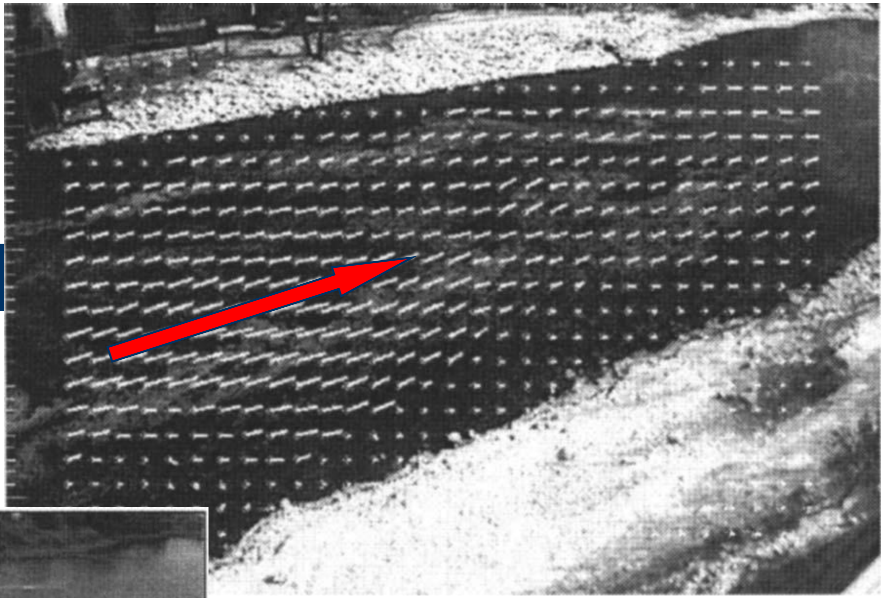
Measurements:

• surface velocities evolution in rivers also during extreme events

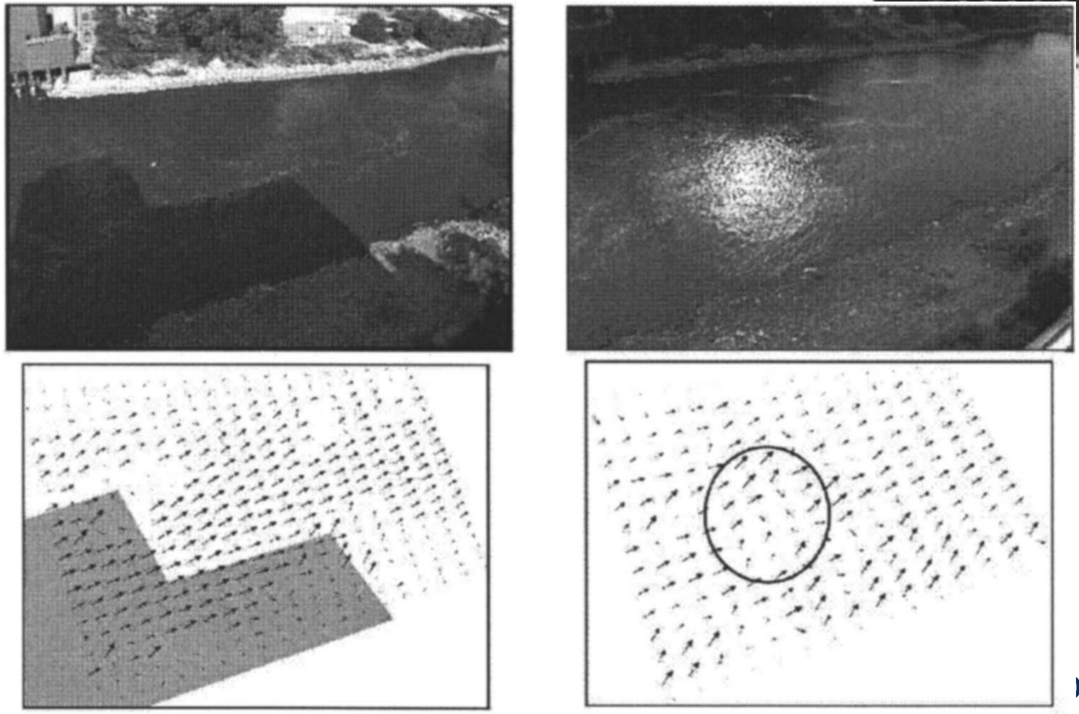
• indirect estimate of discharge

Large Scale PIV

Field applications



Vectors field computed with a continuous operation system (Hauret et al. 2008- Iowa river)



Problems:

- wind and rain
- illumination (shadows, reflections)

Different PIV setups

3D Flows

- stereoscopic PIV: uses the principles of the stereoscopic vision
- multi-layers PIV: more light sheets are generated by splitting the laser beam
- holographic PIV

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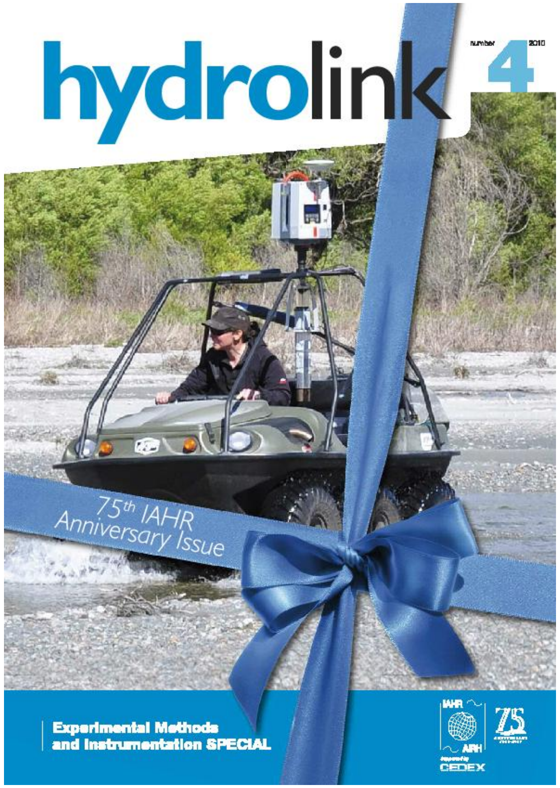

Special issue on Experimental Methods and Instrumentation

•10 **QUESTIONS TO…***Prof. Iehisa Nezu*

• **3D Optical Diagnostics from aerodynamics to Hydraulics** (by Fulvio Scarano)

The capability to measure simultaneously the velocity and vorticity field in a three-dimensional domain makes the Tomo-PIV approach effective for the understanding of complex unsteady flows.

Thank you for your attention !

Montecassino Abbey - Cassino