COST - Fiber suspension flow modeling
Martin Sommerfeld & Cristian Marchioli

Regular and irregular non-spherical particles in laminar and turbulent flows

Martin Luther University, Halle-Wittenberg
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Experimental techniques for two phase flows

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References

- Handbook of Experimental Fluid Mechanics, Springer, 2008

- Romano & Zincone, Journal of Vizualization, 2000
- Righetti & Romano, Journal Fluid Mechanics, 2004
- Lavoie *et al*., Experiments in Fluids, 2007
- Cagnoli & Romano, Journal of Volcanology & Geot. Res., 2010
- Lacagnina *et al*., Experiments in Fluids, 2011
- Capone, Soldati & Romano, Experiments in Fluids, 2014
- Capone & Romano, Physics of Fluids, 2015

Overview

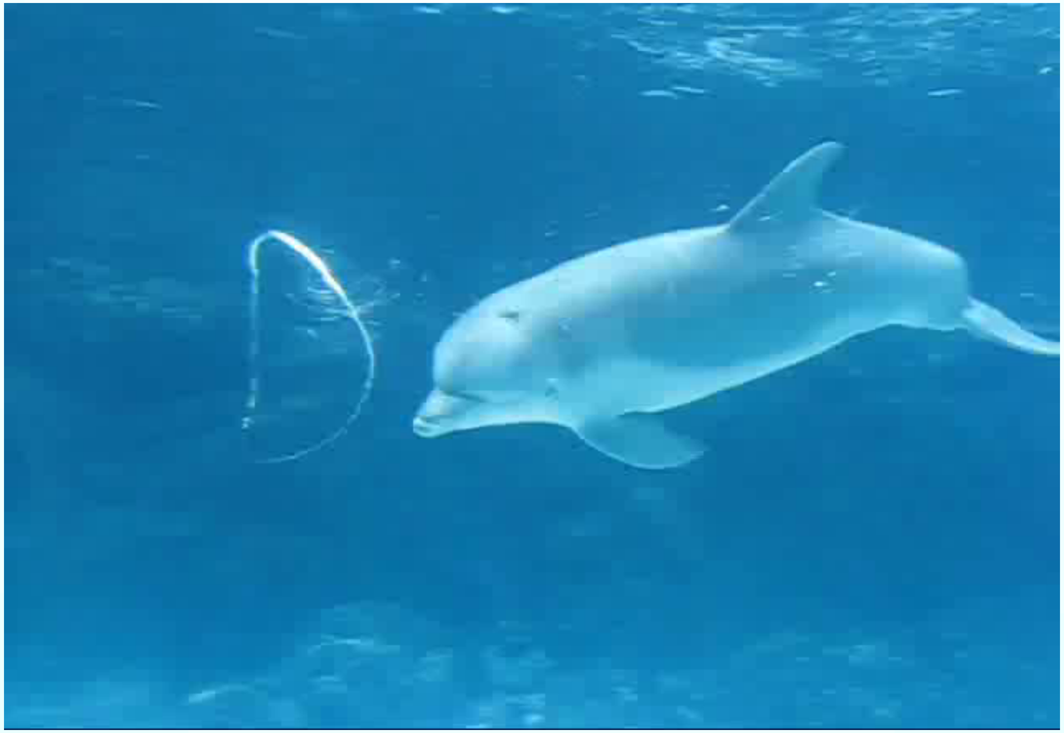
3 Lectures:

- **Two phase flows, optical techniques & flow tracers**
- **Single & multi-point measurements**
- **Measurements for non spherical particles**

Use of optical techniques: the problem of tracers
Light scattering by particles
Single point and multipoint techniques
Laser and Phase Doppler Anemometry
Imaging techniques: Particle Image Velocimetry & Global Phase Doppler
Discrimination and phase separation in acquired images
Two-phase flow measurements in shear layers

Why to measure in two-phase flows

<u>Why</u>: drag reduction, noise control, sedimentation, pollution and environmental phenomena, fiber suspension, sprays and other industrial applications, …… and Dolphins play with bubbles !!!



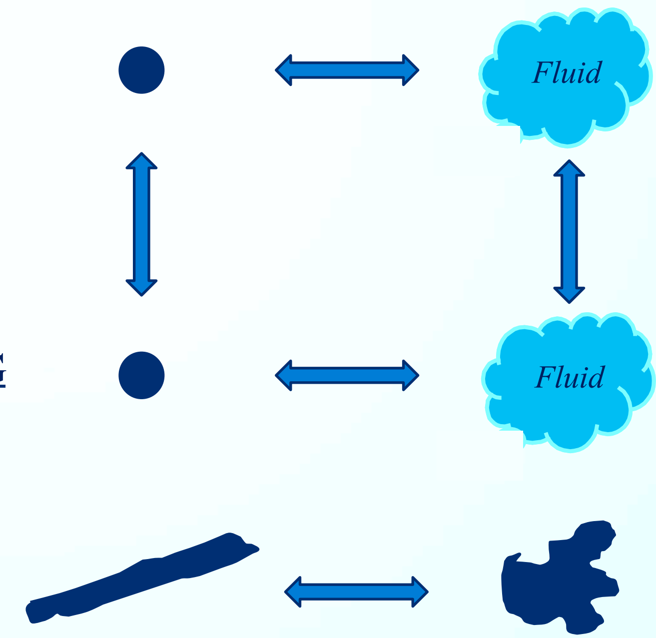
What to measure in two-phase flows

What: velocity components, concentration, size, cross-correlation among them
SIMULTANEOUSLY FOR EACH PHASE !!!

FLUID-PARTICLE COUPLING

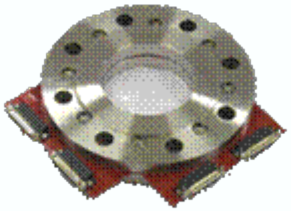
PARTICLE-PARTICLE COUPLING

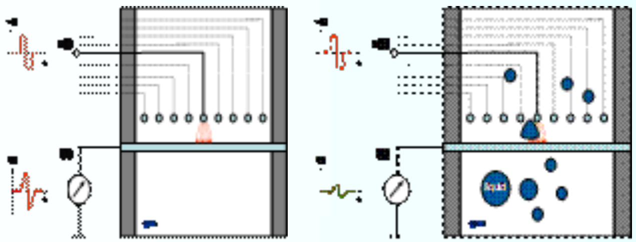
ADDITIONAL EFFECTS
(rotation, stretching, shear)



Intrusive *vs* non-intrusive methods

<u>INTRUSIVE</u>: Grids, WMS (Wire Mesh Sensors), …. = good temporal resolution, very low spatial resolution, …… OK for industrial applications





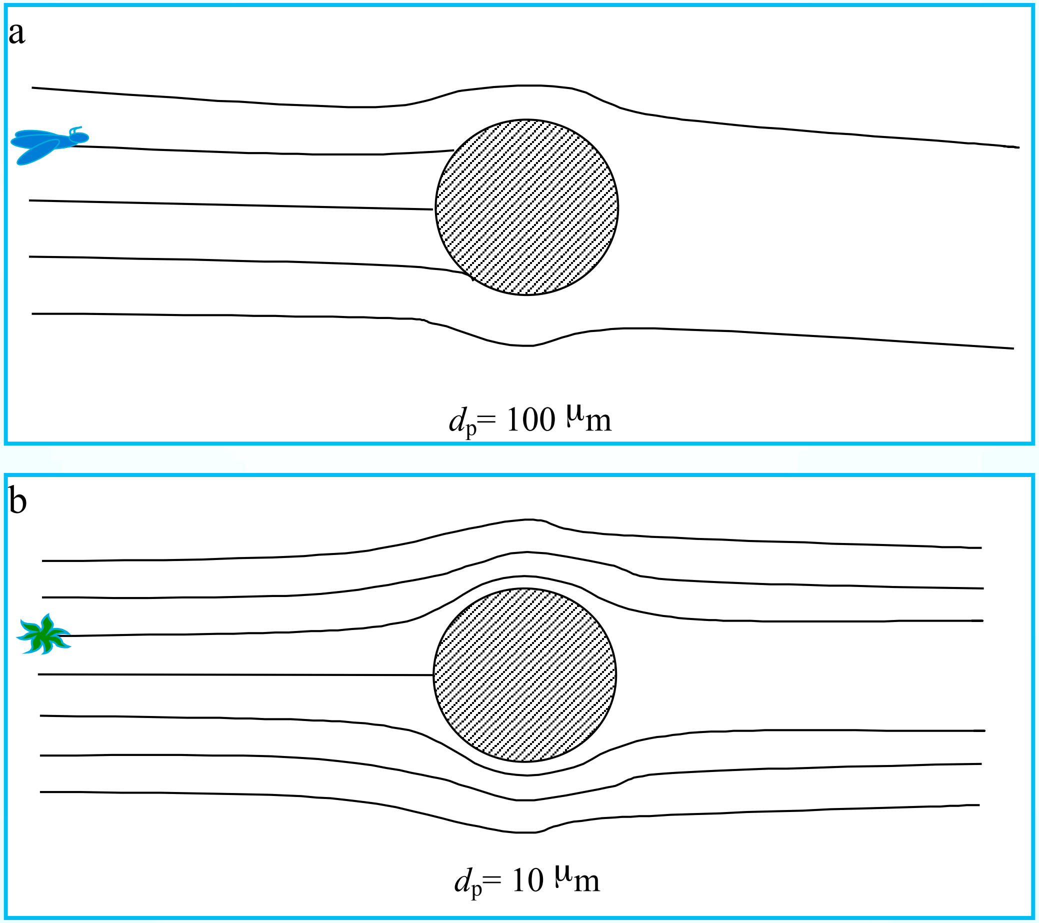
Grunewald, 2012

<u>NON-INTRUSIVE</u>: capacitive and magnetic sensors, ultrasound sensors, … = sufficient temporal resolution, low spatial resolution ⇒ <u>OPTICAL TECHNIQUES</u>

the problem of tracers and light scattering

Do we really measure single-phase flows in optical techniques?

Flow Tracers



Tracer particles

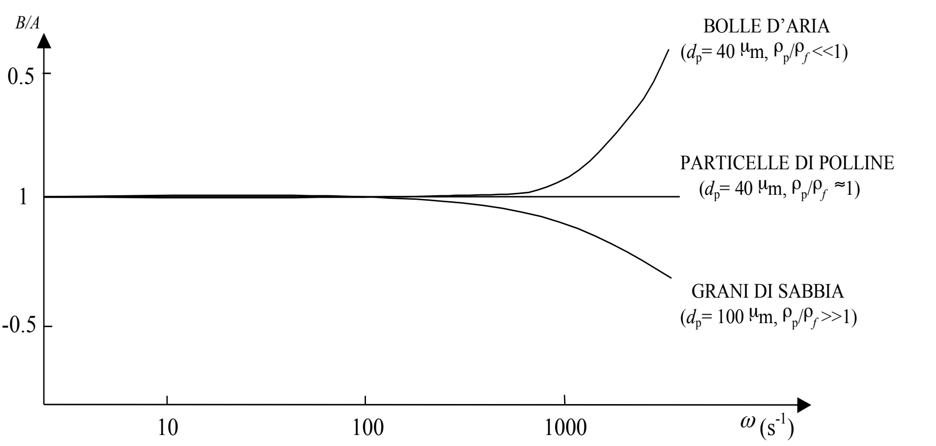
Basset, Boussinesque, Oseen (BBO) equation

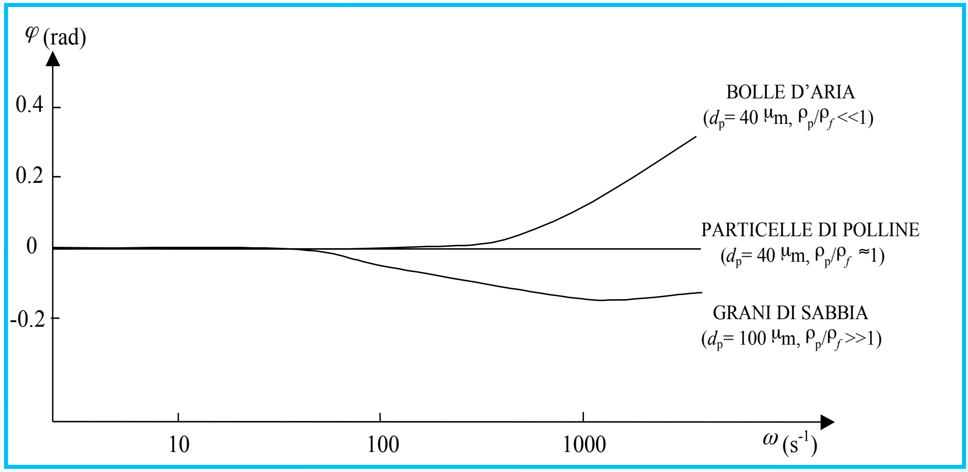
$$m_P\left(\frac{D\underline{u}_p}{Dt}\right)=\left(m_P-m_f\right)g\underline{k}+m_f\frac{D\underline{u}_f}{Dt}-\frac{1}{2}m_f\left[\left(\frac{D\underline{u}_p}{Dt}-\frac{D\underline{u}_f}{Dt}\right)-\frac{1}{10}\left(\frac{d}{2}\right)^2\nabla^2\underline{u}_f\right]-$$

$$-6\pi\mu\left(\frac{d}{2}\right)\left[\left(\underline{u}_p-\underline{u}_f\right)-\frac{1}{6}\left(\frac{d}{2}\right)^2\nabla^2\underline{u}_f\right]-\frac{3}{2}d^2\sqrt{\pi\rho_f\mu}\int_{t_0}^{t}\frac{1}{(t-\tau)^{1/2}}\frac{d}{d\tau}\left(\underline{u}_p-\underline{u}_f\right)d\tau$$

$u_f = Ae^{i\omega t}$

$u_p = BAe^{i\omega t+\varphi}$





Tracer particles

if $\rho_p >> \rho_f$

$$\boxed{\frac{du_p}{dt} = a'\left(u_f - u_p\right)}$$

$$\boxed{a' = \frac{18\mu}{\rho_p d^2}}$$

Stokes frequency

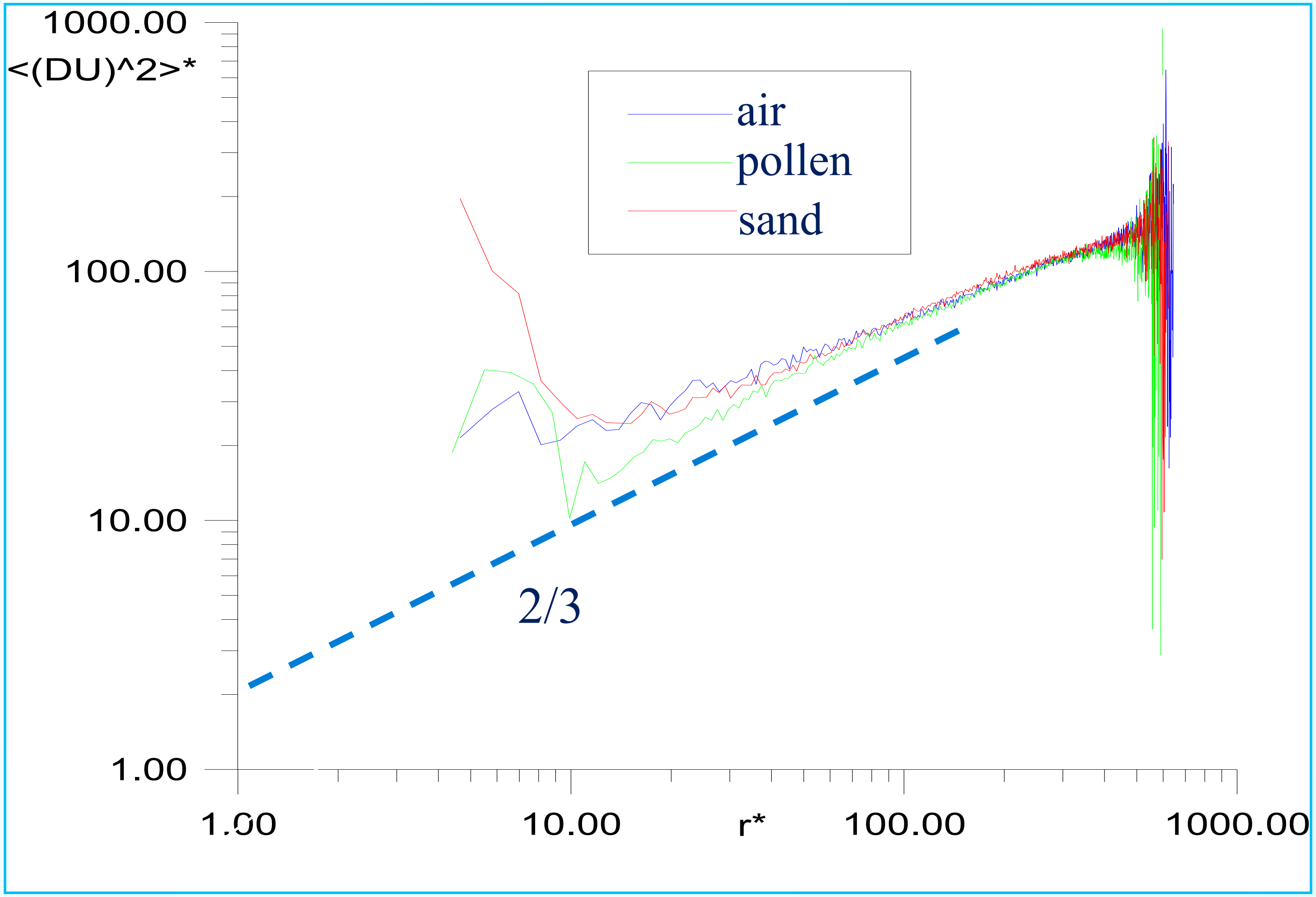
$$\varphi = \mathrm{arctg}\left(\frac{\left(\frac{-\omega a'}{a'^2 + \omega^2}\right)}{1 - \left(\frac{\omega^2}{a'^2 + \omega^2}\right)}\right) = \mathrm{arctg}\left(\frac{-\omega a'}{a'^2}\right) = \mathrm{arctg}\left(\frac{-\omega}{a'}\right) = \begin{cases} \omega << a' & \varphi = 0 \quad \text{no effect} \\ \omega >> a' & \varphi = -\pi/2 \end{cases}$$

$$B = \left[1 + \frac{\omega^4}{\left(a'^2 + \omega^2\right)^2} - \frac{2\omega^2}{\left(a'^2 + \omega^2\right)} + \frac{\omega^2 a'^2}{\left(a'^2 + \omega^2\right)}\right]^{1/2} = \left[\frac{\left(a'^2 + \omega^2\right) + \omega^4 - 2\omega^2 a'^2 - 2\omega^4 + \omega^2 a'^2}{\left(a'^2 + \omega^2\right)}\right]^{1/2} =$$

$$= \frac{a'\left(a'^2 + \omega^2\right)^{1/2}}{\left(a'^2 + \omega^2\right)} = \frac{a'}{\left(a'^2 + \omega^2\right)^{1/2}} \begin{cases} \omega << a' & \mathrm{B} = 1 \quad \text{no effect} \\ \omega >> a' & \mathrm{B} = \frac{a'}{\omega} \quad \text{low-pass filter} \end{cases}$$

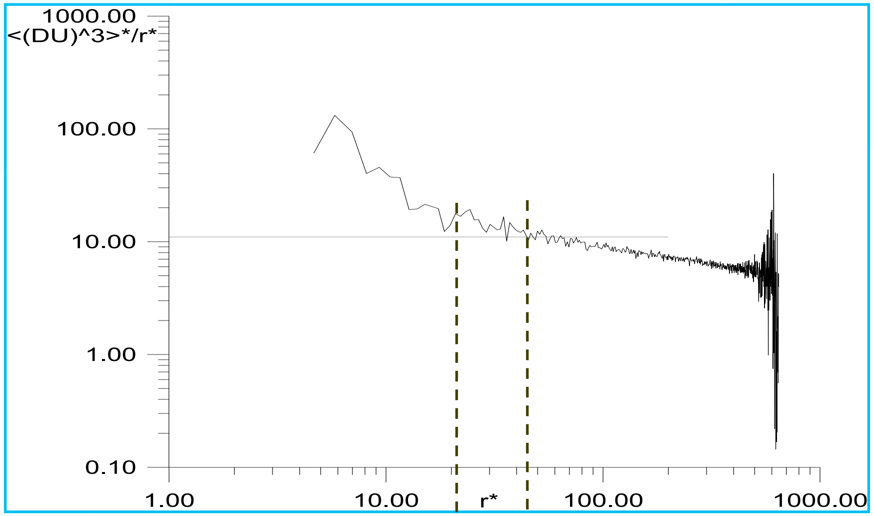
Effect of tracers in PIV

2^{nd}-order structure function



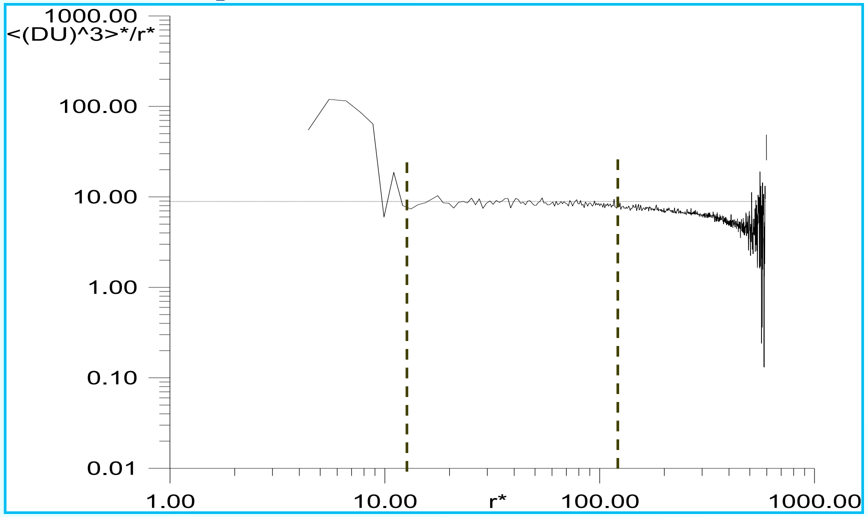
Effect of tracers in PIV

compensated
3nd-order
structure function

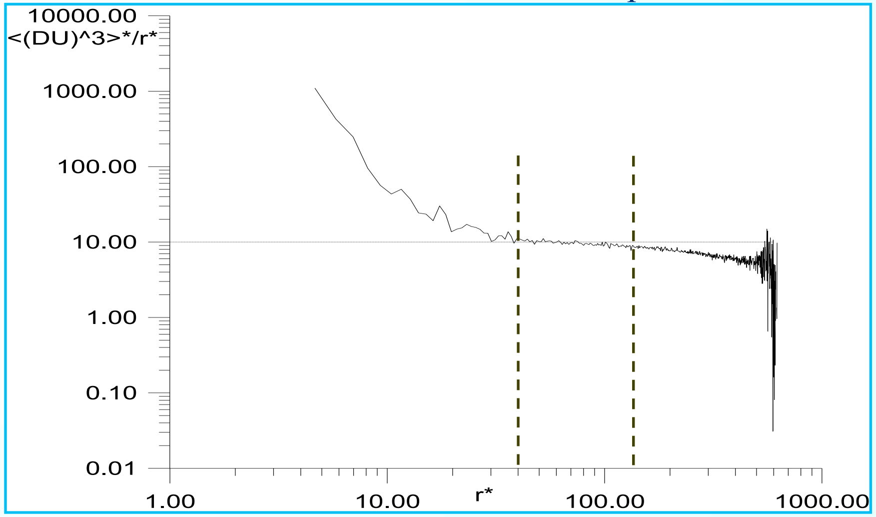


air bubbles
(ρ_p/ρ_f=10^{-3})

pollen (ρ_p/ρ_f=1.01)



sand (ρ_p/ρ_f=2.01)



Non-intrusive optical methods for measuring <u>particle size</u> (in addition to flow tracers)

Spherical *vs* non spherical particles

spherical

<u>Single-point methods:</u> Phase Doppler Anemometry (PDA)

<u>Multi-point methods</u>: Global Phase Doppler (GPS) or Interferometric Laser Imaging Droplet Sizing (ILIDS), Image Analysis Methods

Durst et al. 1976, Konig et al. 1986, Kiger & Pan 2000

non-spherical

<u>Single-point methods:</u> PDA: not working

<u>Multi-point methods</u>: ILIDS: not working, Image Analysis Methods: OK

Parsa et al. 2011, Dearing et al. 2013

light scattering by particles

Light scattering

Complex for spherical particles

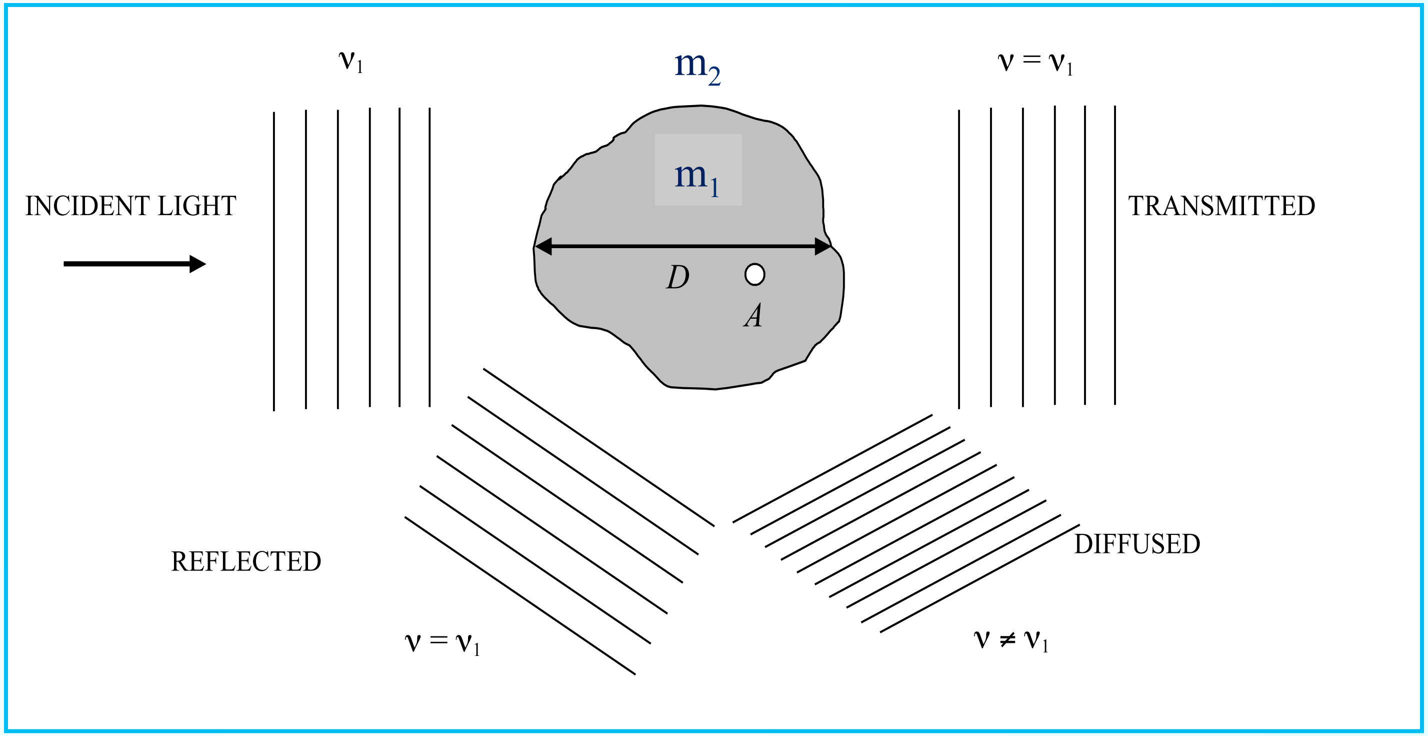
Very complex for non-spherical particles

$$\frac{\lambda}{\lambda_n} = \frac{c}{c_n} = \frac{m_1}{m_2} = m$$

$$c = \frac{1}{(\varepsilon_0 \mu_0)^{1/2}}$$

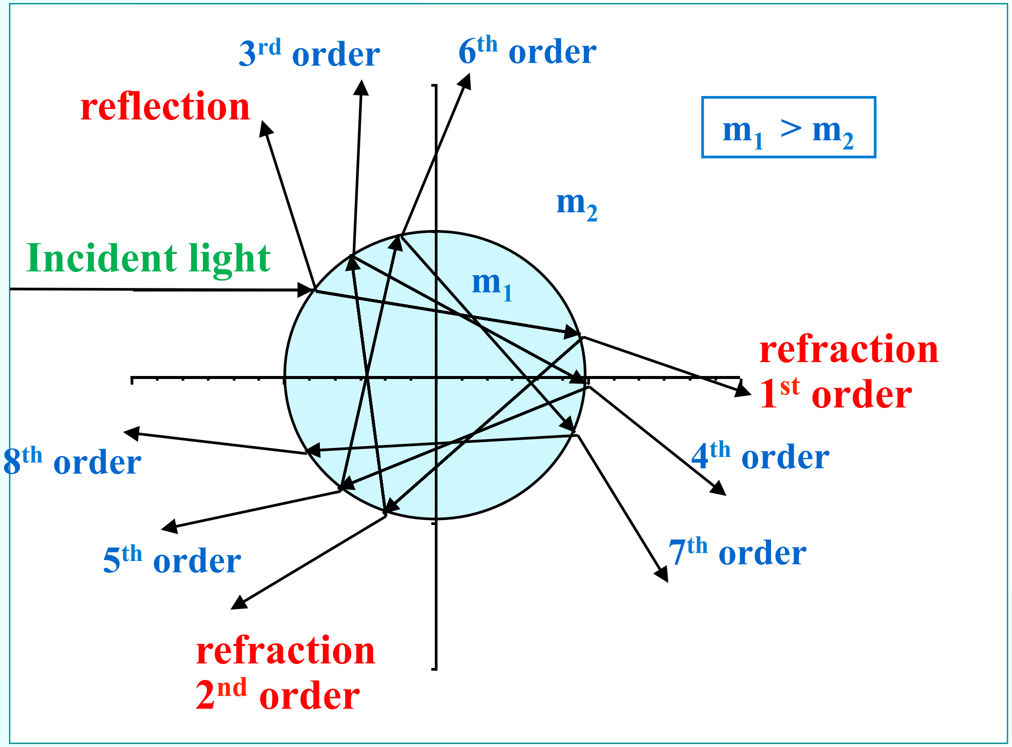
$$c_n = \frac{1}{(\varepsilon_n \mu_n)^{1/2}}$$

$$m = \left(\frac{\varepsilon_n \mu_n}{\varepsilon_0 \mu_0}\right)^{1/2} = \sqrt{\varepsilon_{n_r} \mu_{n_r}} \approx \sqrt{\varepsilon_{n_r}}$$



Light scattering

Analytical solution of Maxwell equations - Lorenz-Mie theory, 1908



$x = \pi d/\lambda$

d = particle diameter
λ = light wavelength

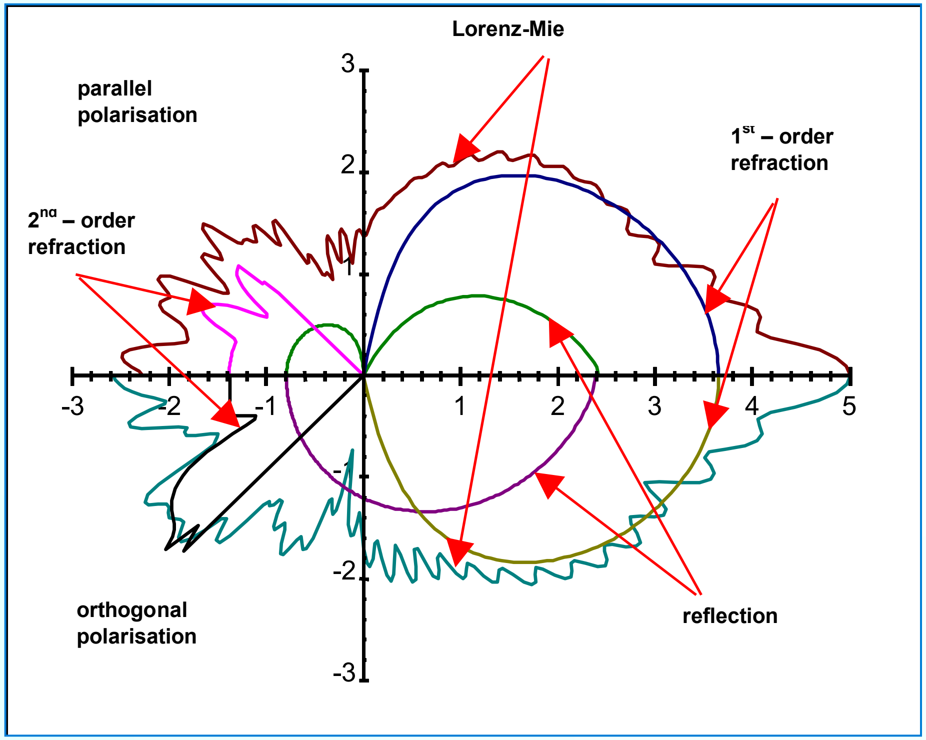
if $x >> 1$, then only reflection and 1^{st} + 2^{nd} order refractions

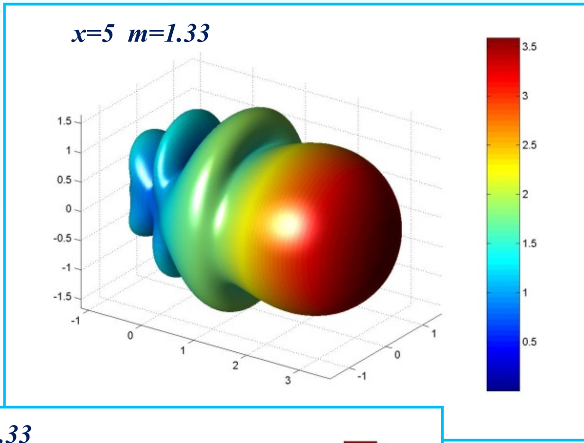
Van de Hulst, 1956

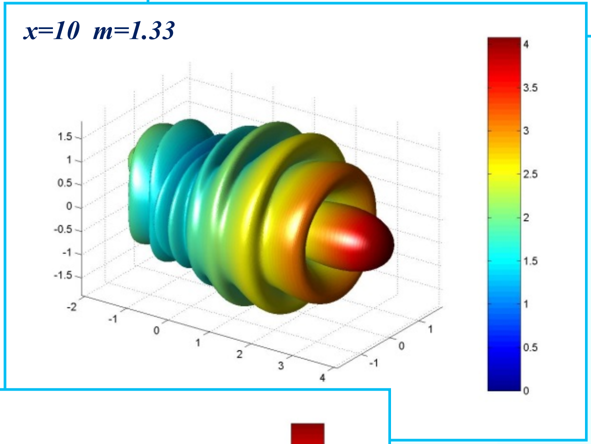
Light scattering

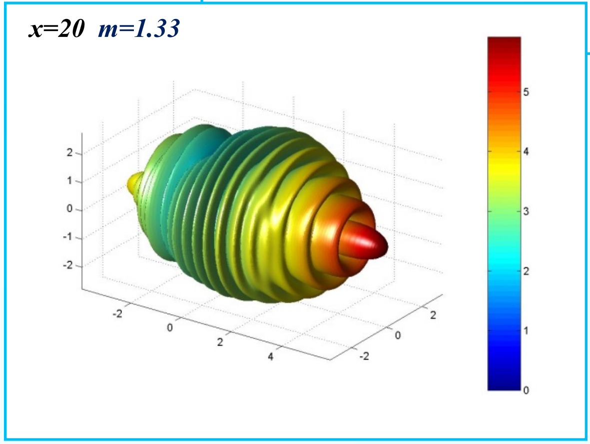
majority of light in forward scattering

Lorenz-Mie and Geometrical Optics









$x = \pi d/\lambda >> 1$

Single-point size measurements

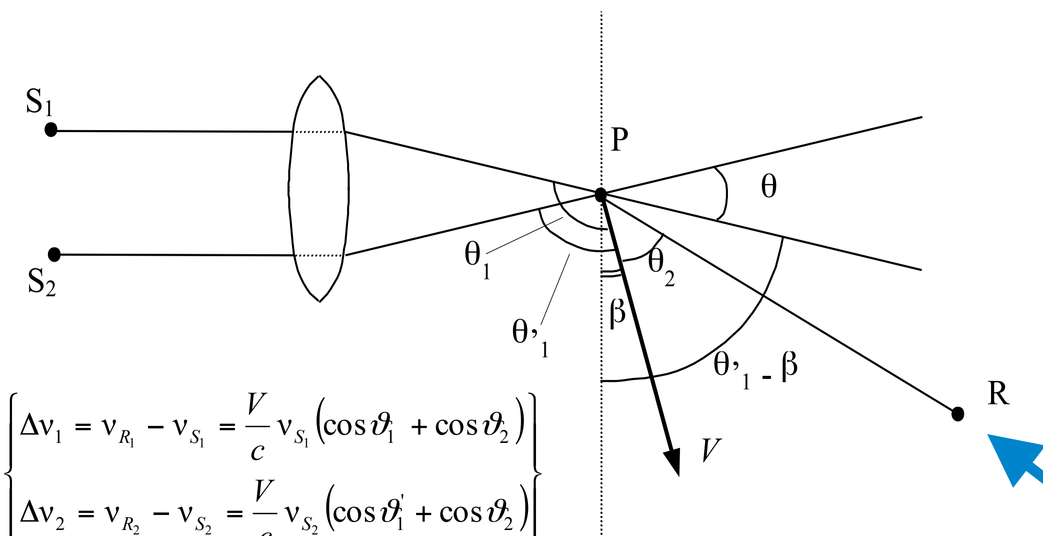
Phase Doppler Anemometry (PDA)

Laser Doppler Anemometry (LDA)

Laser Doppler Anemometry

$$\nu_S = \frac{c}{\lambda}$$

MEASUREMENT PRINCIPLE:
Doppler effect among incident and scattered light



$$\begin{cases} \Delta\nu_1 = \nu_{R_1} - \nu_{S_1} = \dfrac{V}{c}\nu_{S_1}\left(\cos\vartheta_1 + \cos\vartheta_2\right) \\ \Delta\nu_2 = \nu_{R_2} - \nu_{S_2} = \dfrac{V}{c}\nu_{S_2}\left(\cos\vartheta_1' + \cos\vartheta_2\right) \end{cases}$$

$$\Delta\upsilon = \frac{2V\cos\beta}{\lambda} sen\left(\frac{\theta}{2}\right) = \frac{2V\cos\beta}{s}$$

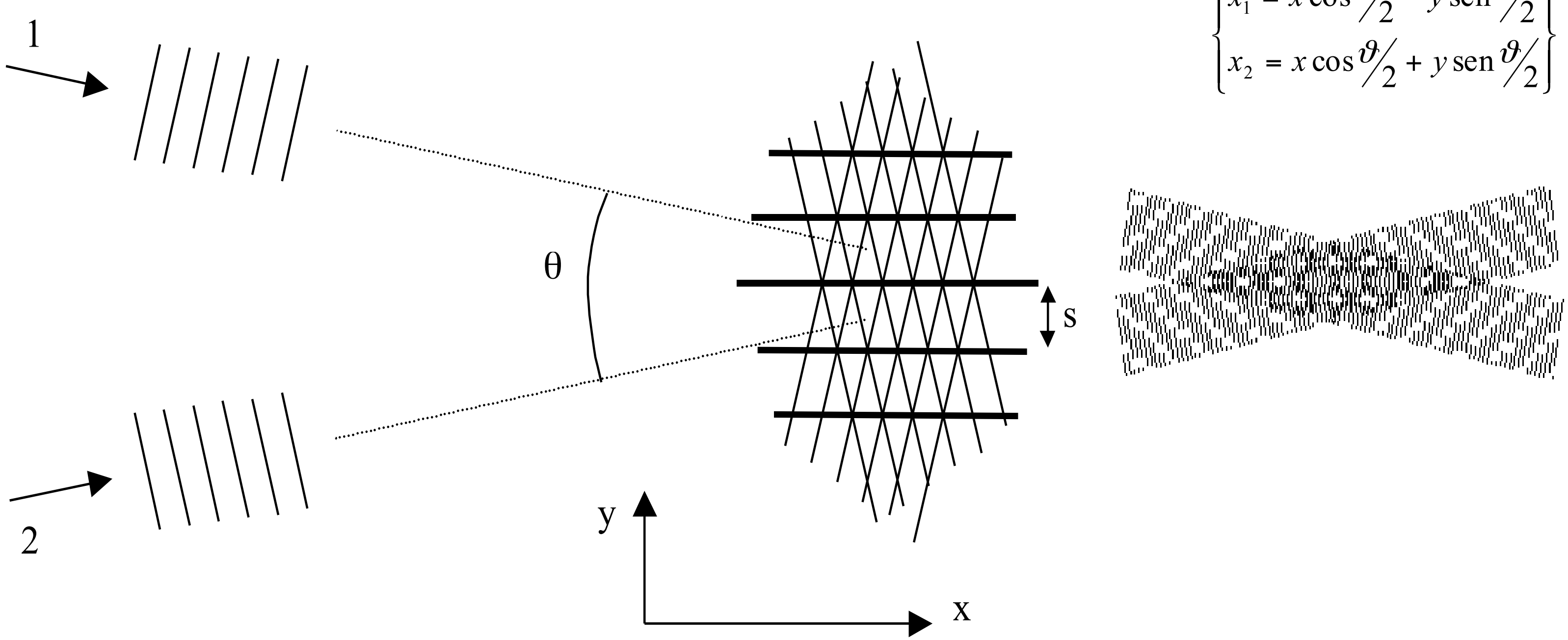
$$s = \frac{\lambda}{2\mathrm{sen}\left(\vartheta/2\right)}$$

to be measured

known

Laser Doppler Anemometry

interference fringes



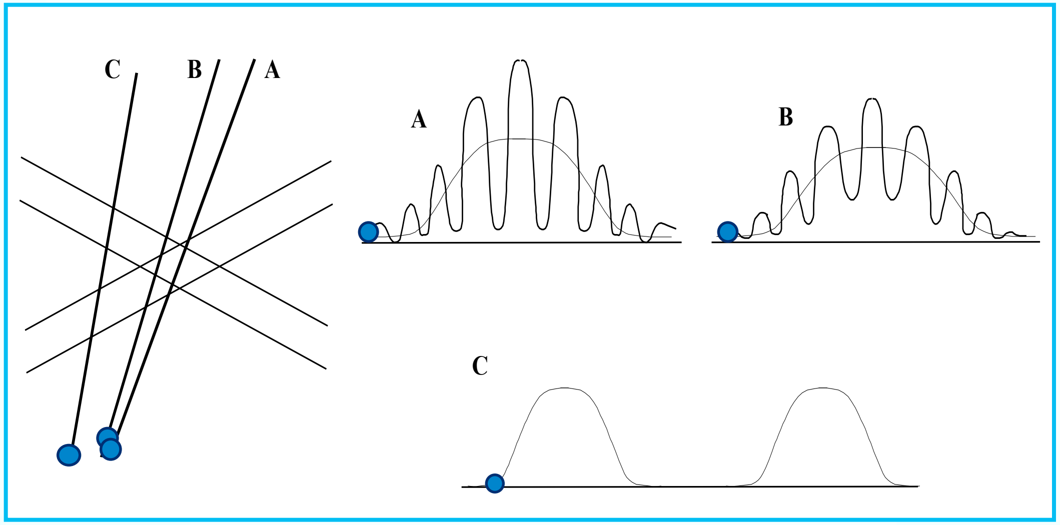
$$\begin{cases} x_1 = x\cos\vartheta/2 - y\,\mathrm{sen}\,\vartheta/2 \\ x_2 = x\cos\vartheta/2 + y\,\mathrm{sen}\,\vartheta/2 \end{cases}$$

$$\boxed{\Delta l = 2y\,\mathrm{sen}\,\vartheta/2}$$

$$\boxed{\Delta\varphi = 2\pi\frac{\Delta l}{\lambda} = 2\pi\frac{2y\,\mathrm{sen}\,\vartheta/2}{\lambda}}$$

Laser Doppler Anemometry

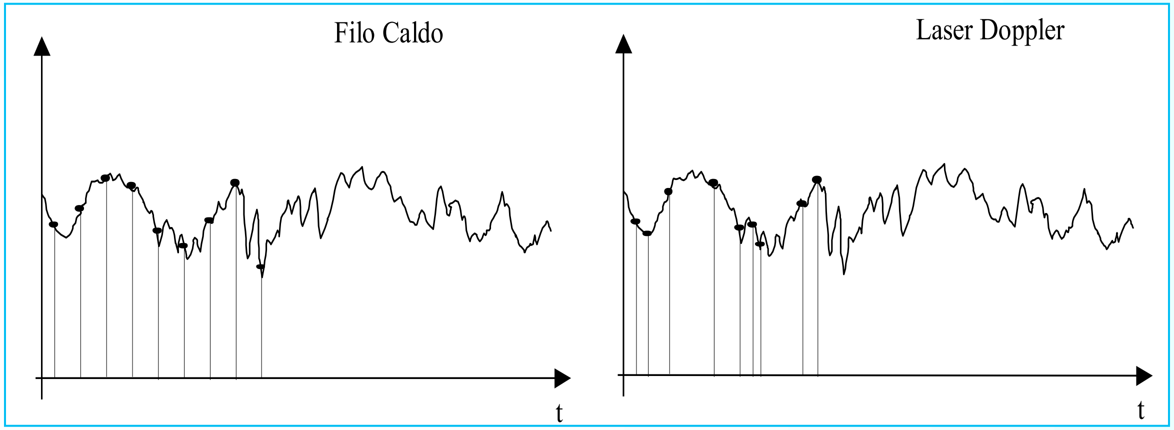
Doppler signals from tracer particles (1-5 μm)



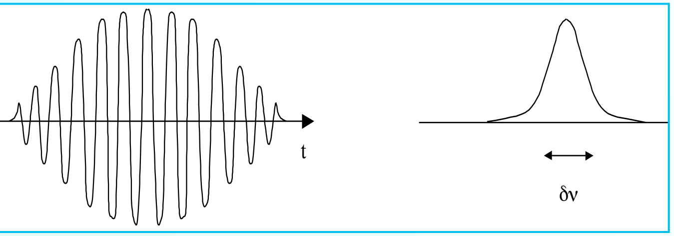
Laser Doppler Anemometry

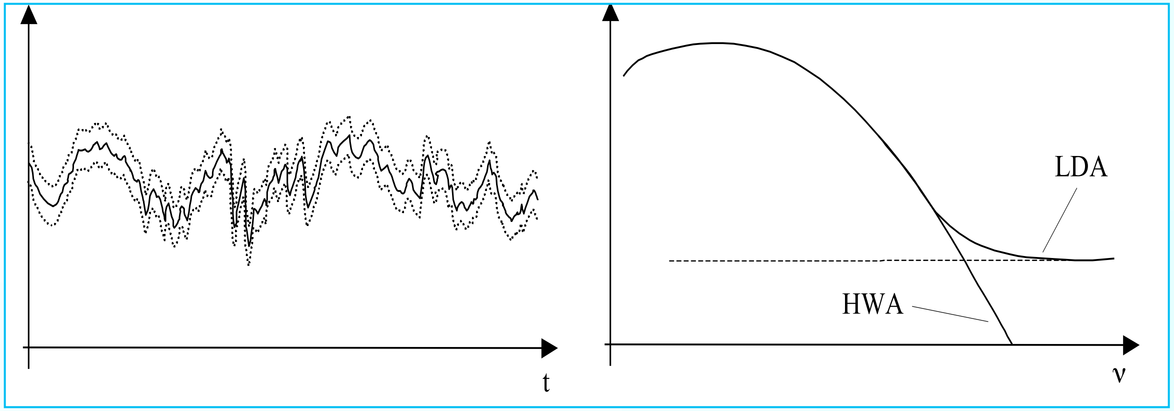
drawbacks

random sampling



finite time
broadening noise

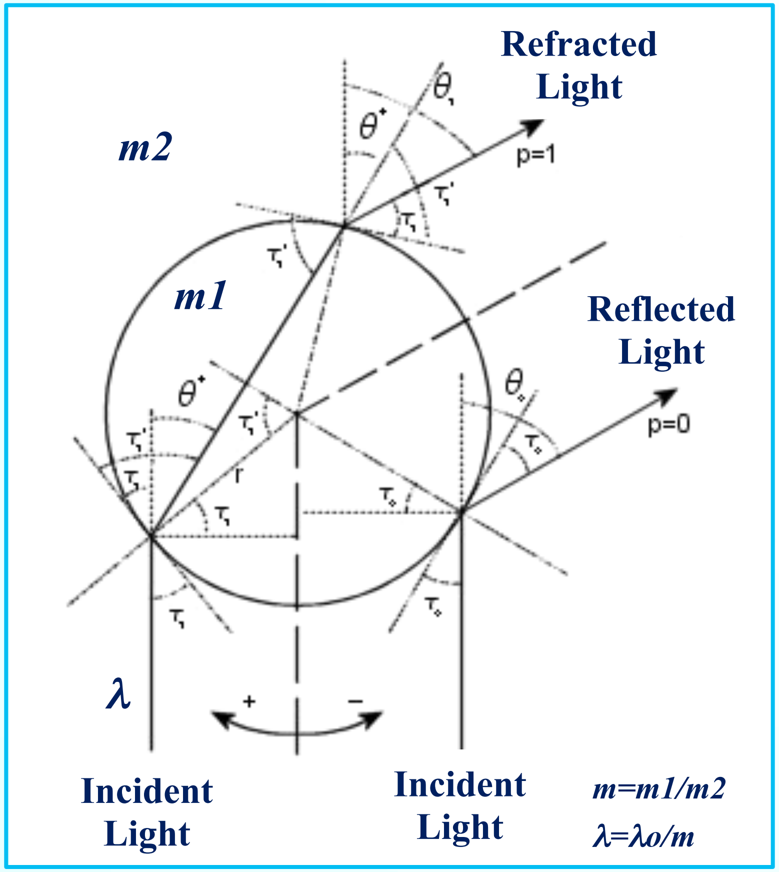




Phase Doppler Anemometry

Spherical particles – single-point measurements

Relation Particle Size - Phase Difference

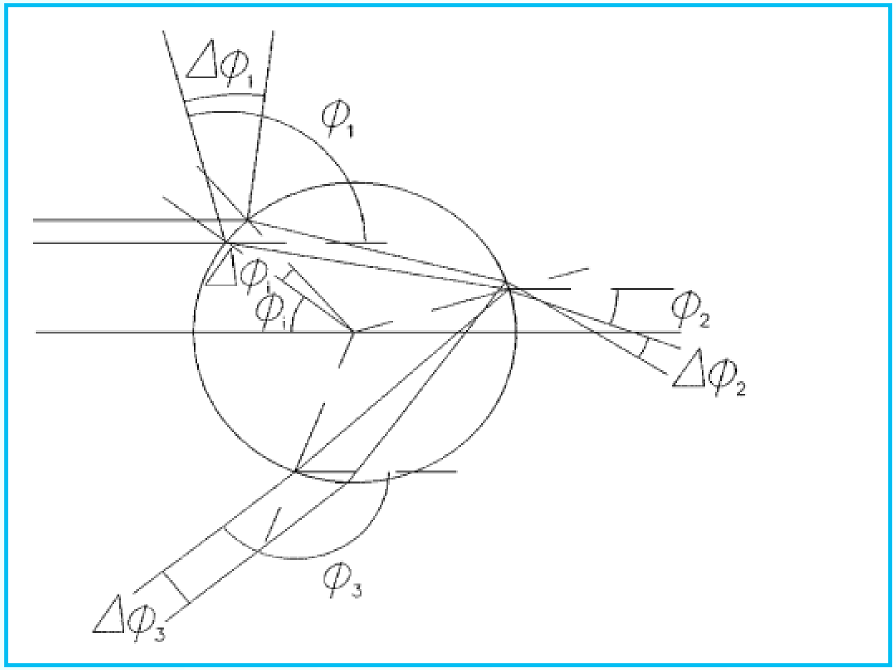


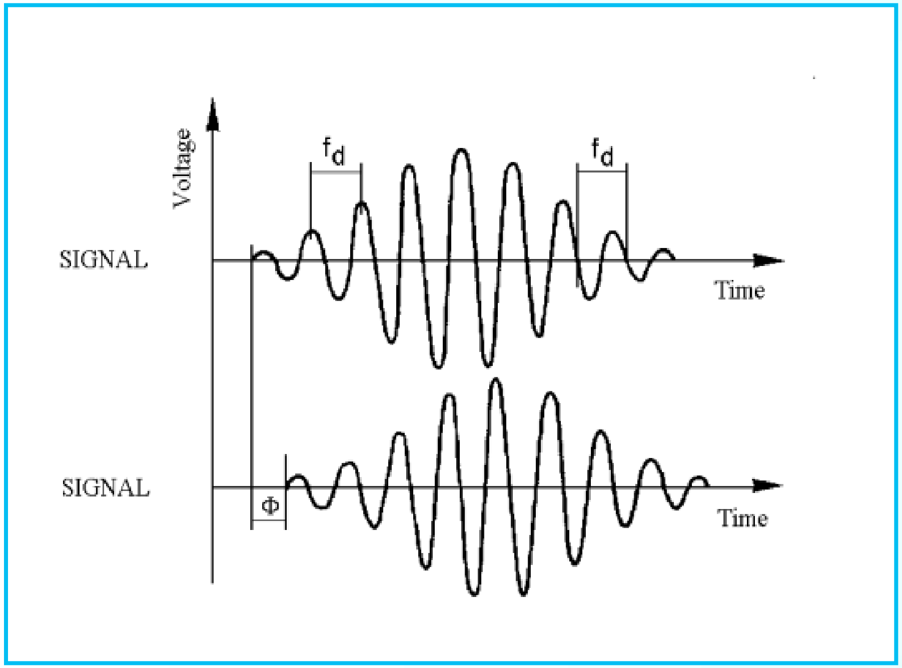
Different optical path
Geometrical Optics: Snell Law

$$\left(\delta_1 - \delta_0\right) = \frac{2\pi d}{\lambda}\left(\sin\frac{\theta}{2} + \sqrt{m^2 + 1 - 2m\cos\frac{\theta}{2}}\right)$$

d = particle diameter
δ_1-δ_2 = $\Delta\Phi$ = phase difference
θ = scattering angle

Phase Doppler Anemometry





$$\boxed{\Delta\Phi = \beta \cdot p}$$

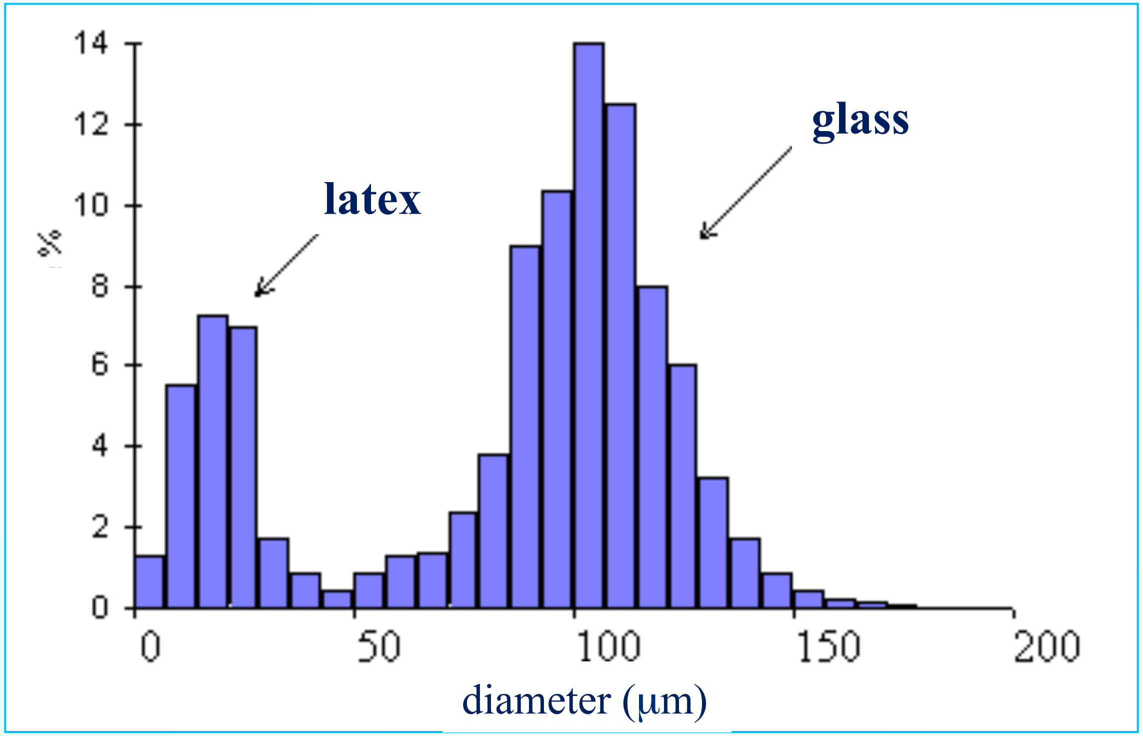
$$\boxed{\beta = xm = \pi \cdot d_p \cdot m / \lambda}$$

p=f(scattering angles)

Phase Doppler Anemometry

An example: near wall turbulence + solid particles

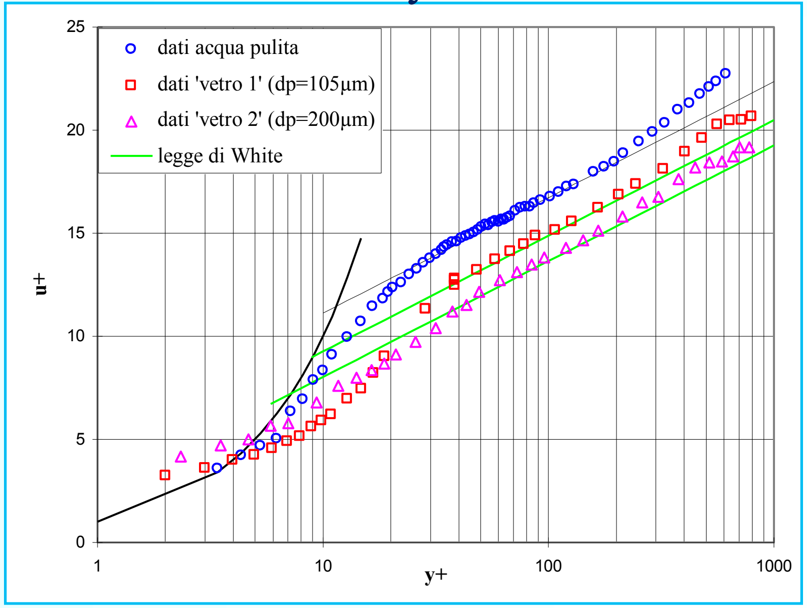
Righetti & Romano, 2004



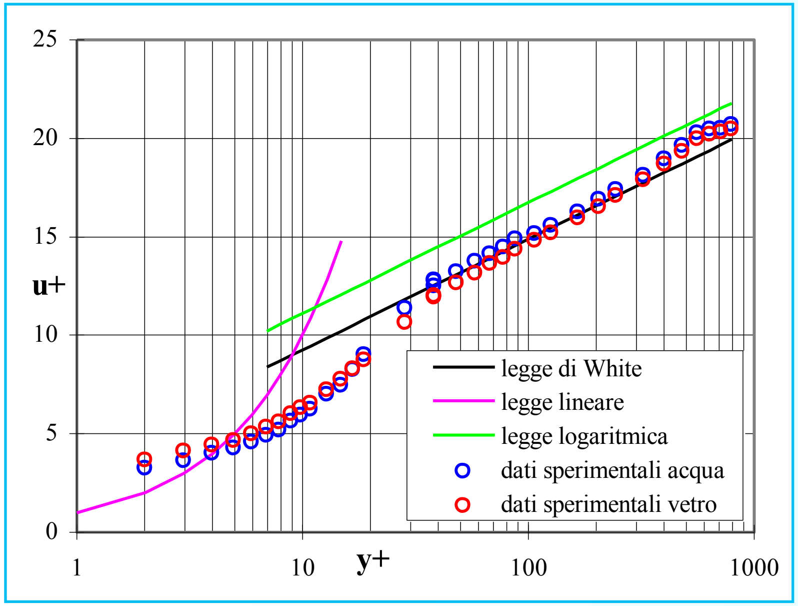
Particles	*100 μm*
Tracers	*20 μm*

Phase Doppler Anemometry

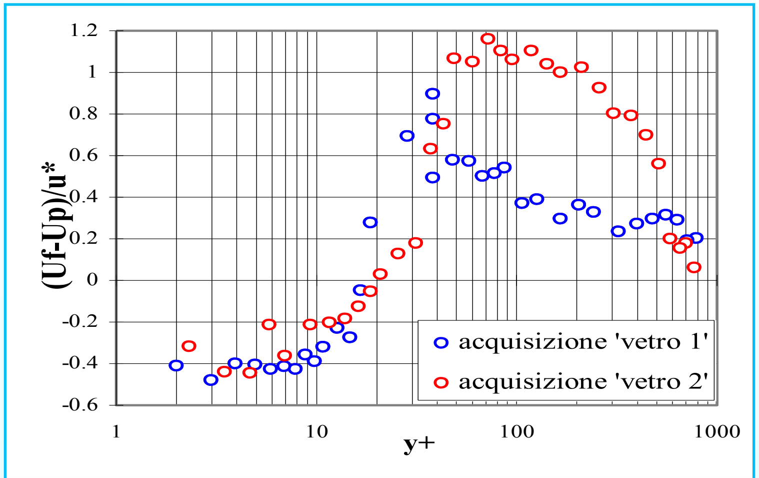
overall mean velocity



phase separated mean velocity

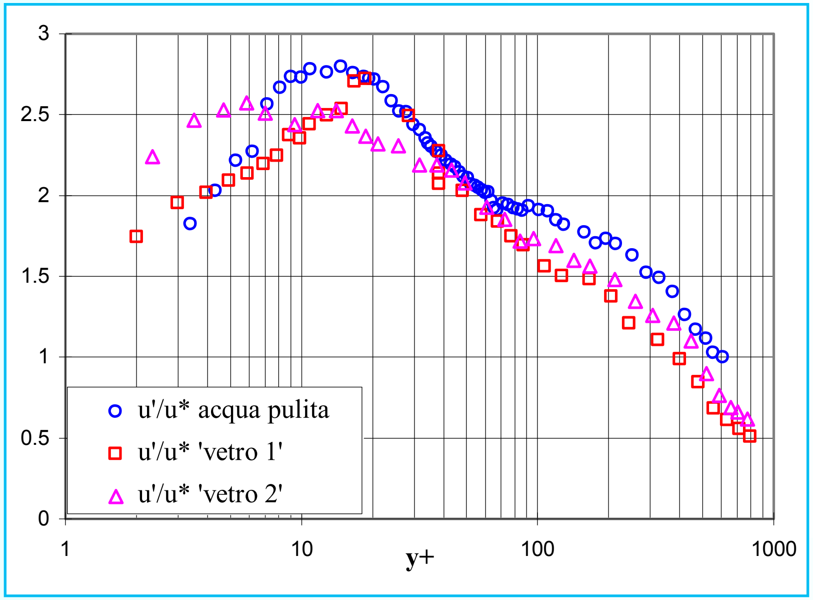


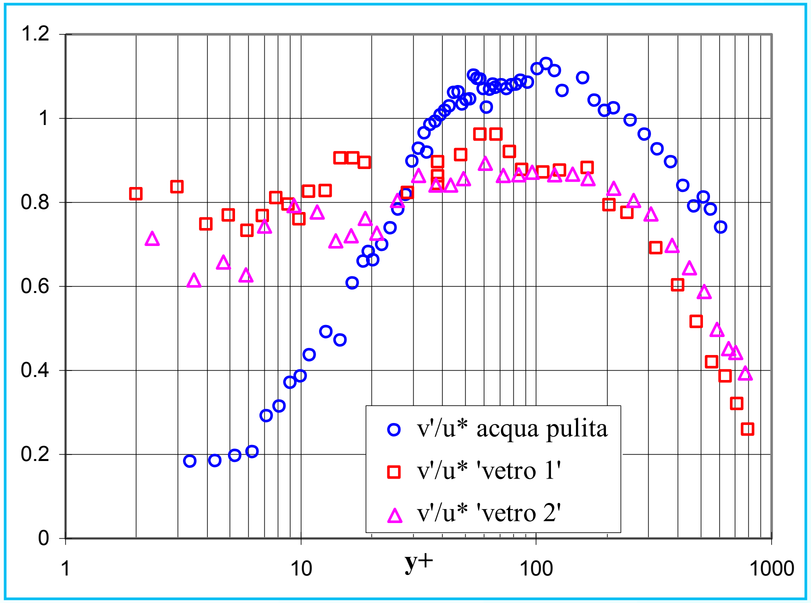
velocity difference



Phase Doppler Anemometry

turbulence intensity





Multi-point size measurements

Global Phase Doppler (GPS)

Interferometric Laser Imaging Droplet Sizing (ILIDS)

Image Analysis Methods

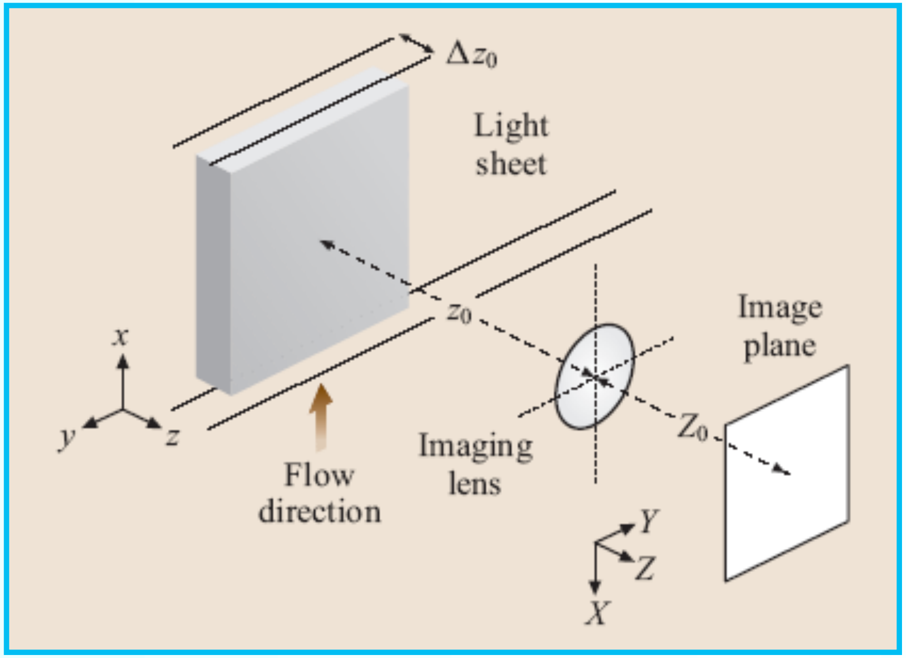
Particle Image Velocimetry (PIV)

Particle Image Velocimetry

IMAGE ACQUISITION	Light Source, Optics, Camera, Storage
IMAGE PROCESSING	Cross-correlation Tracking Optical Flow
IMAGE PRE-PROCESSING	Noise replace & Filters Reflections replace Mask determination
IMAGE POST-PROCESSING	Vector Validation
DATA POST-PROCESSING	Vortex Detection

Particle Image Velocimetry

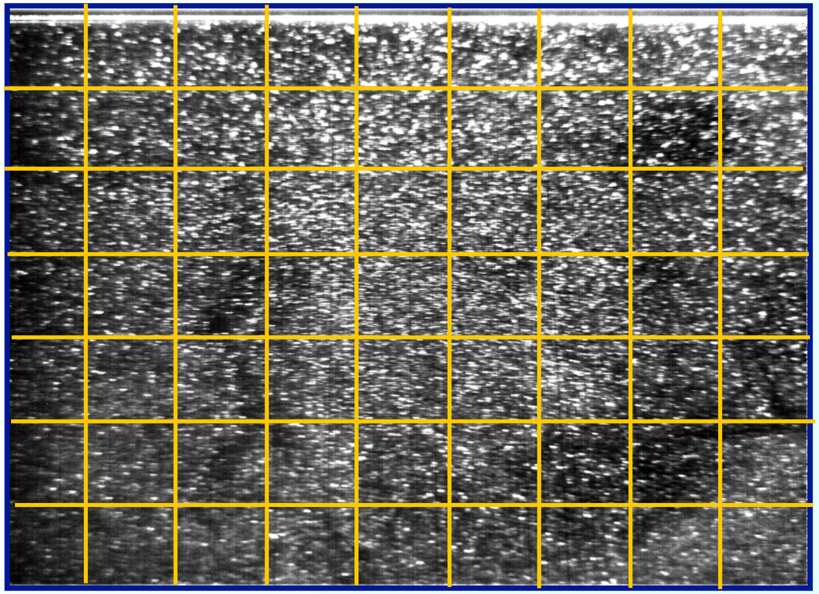
IMAGING ON A VIDEOCAMERA



Magnification factor

$$M = \frac{Z_0}{z_0}$$

Particle ≡ Intensity level (0-255)

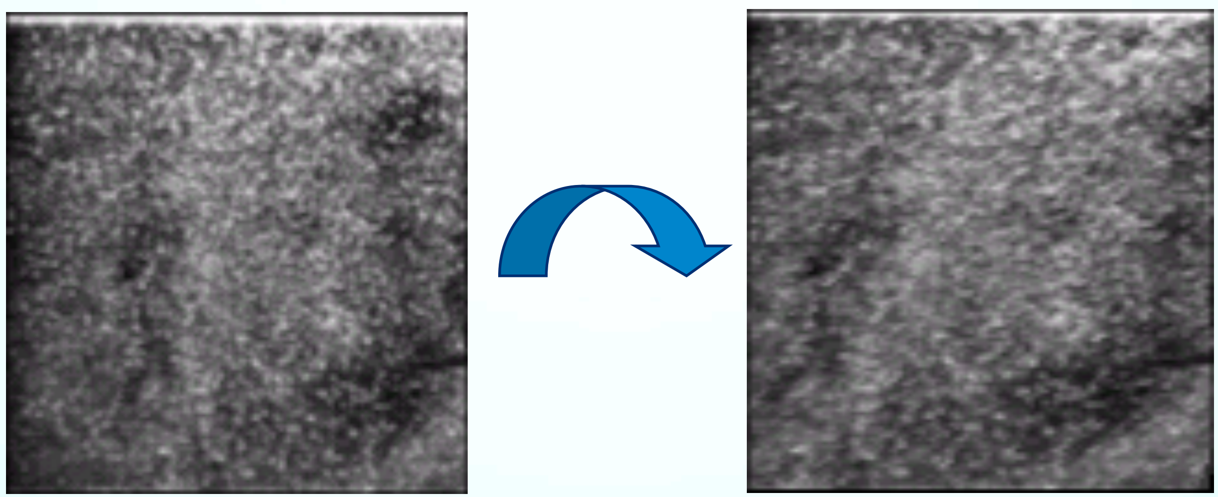


Particle Image Velocimetry

<u>**Cross-correlation function (of light intensity levels)**</u>

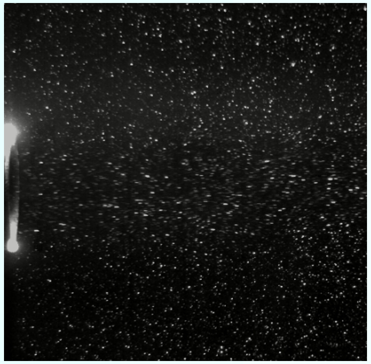
$$R_{ij}\left(r_1, r_2\right) = \iint F_i(x, y) F_j(x + r_1, y + r_2) dxdy$$

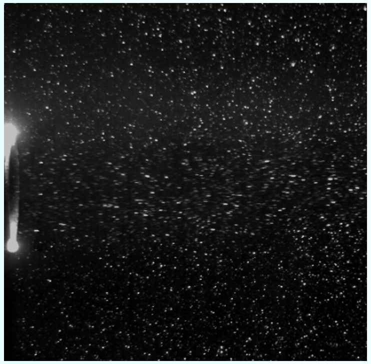
time *t*
(image *i*)

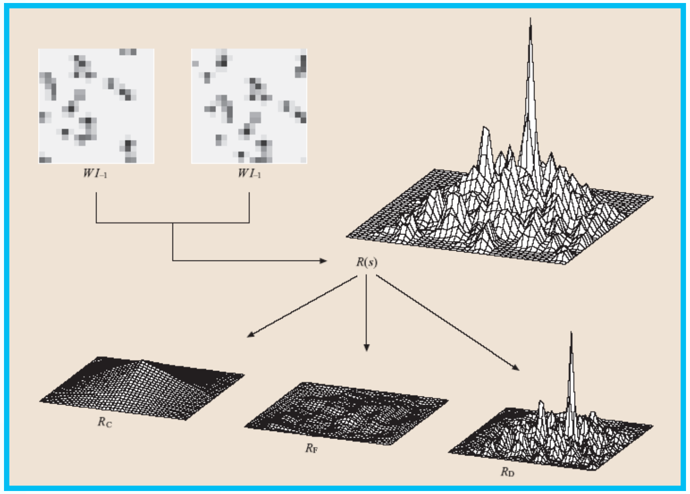


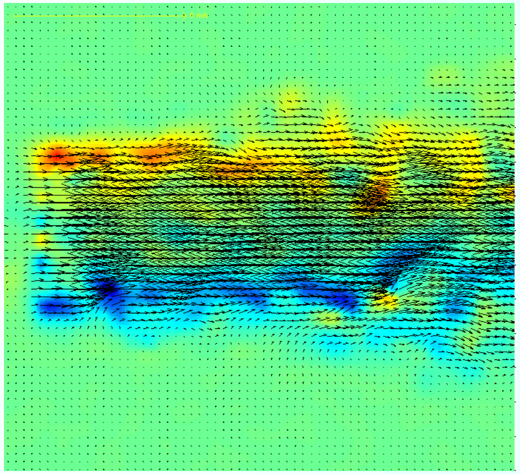
time *t*+Δ*t*
(image *j*)

Particle Image Velocimetry







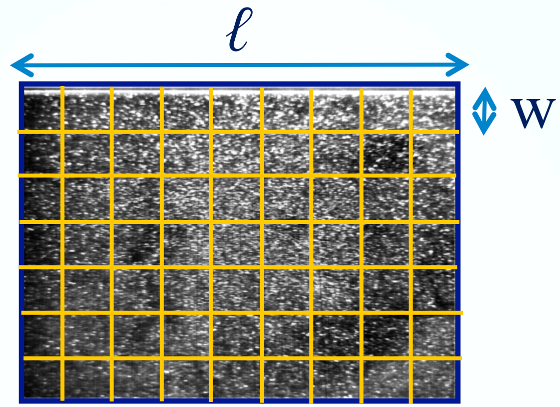


<u>**cross-correlation**</u> <u>**peak detection**</u> <u>**displacement & velocity**</u>

Particle Image Velocimetry

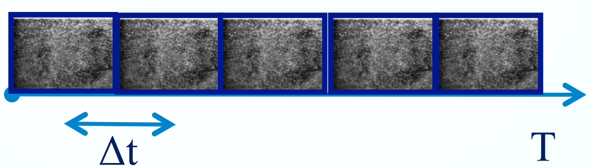
<u>**drawbacks**</u>

spatial resolution



Maximum size ≈ ℓ
Minimum size ≈ w

temporal resolution



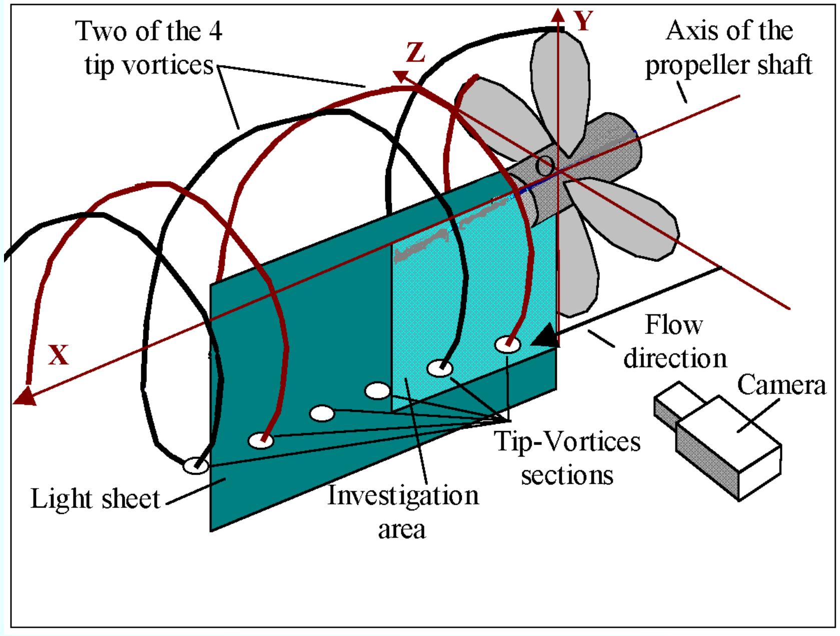
Maximum time ≈ T
Minimum time ≈ Δt

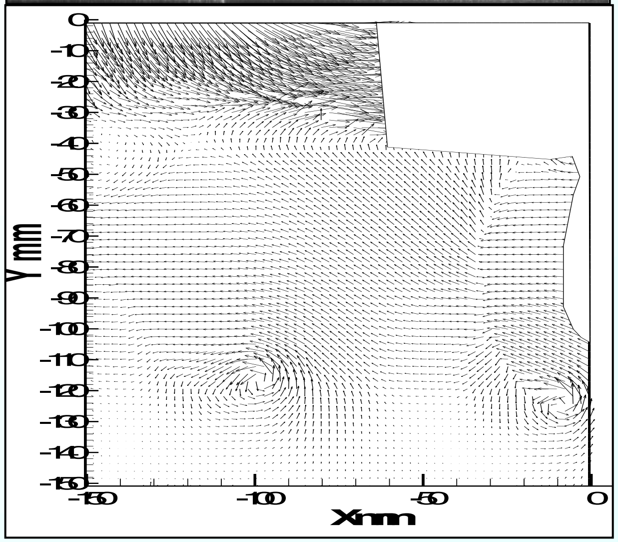
tracers & particles

no particles ……. no party !!

Particle Image Velocimetry

Propeller Wake: *Re* = 10^5-10^6





Particle Image Velocimetry

Wall Turbulence: $Re = 10^5$, $Re_\theta = 8000$

Image Acquisition

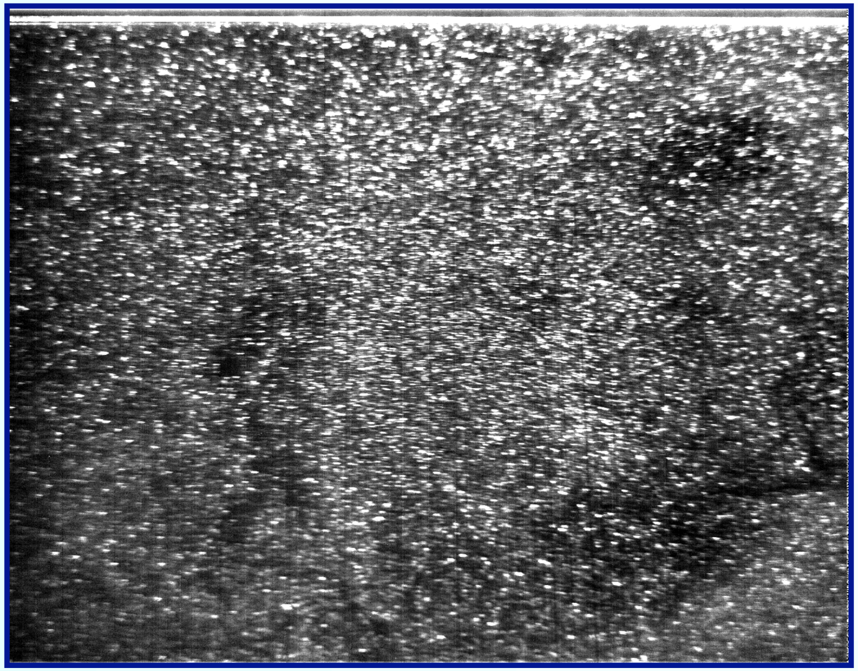
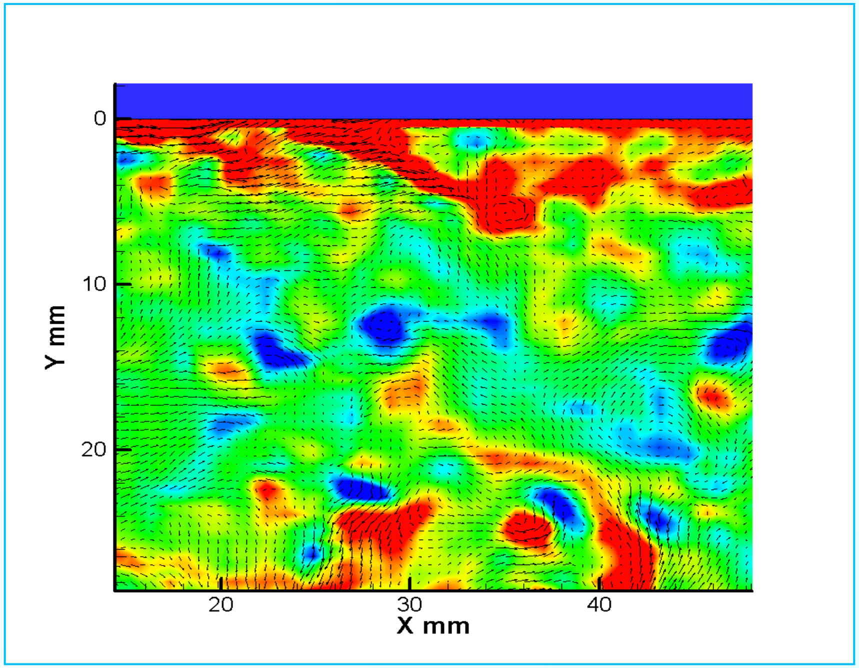


Image Processing



Multi-point size measurements

GPS & ILIDS: principle

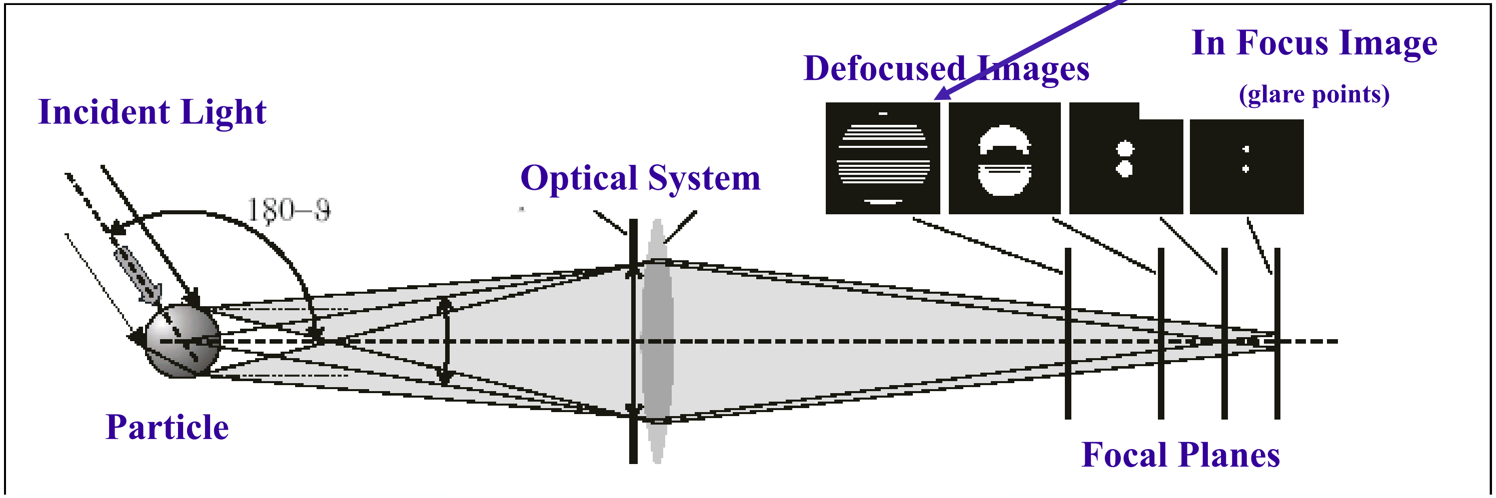
$$d = \frac{2m\lambda MD_{ef}}{\delta}\left[\cos\left(\frac{\vartheta_r}{2}\right) - \frac{m\sin\left(\frac{\vartheta_r}{2}\right)}{\sqrt{1+m^2-2m\cos\left(\frac{\vartheta_r}{2}\right)}}\right]^{-1}$$

Konig et al. 1986
Glover et al. 1995
Maeda et al. 2000
Damaschke et al. 2001, 2002
Kobayashi et al. 2001

d = particle diameter
δ = fringe spacing
θ = scattering angle

$$d = \frac{K}{\delta}$$

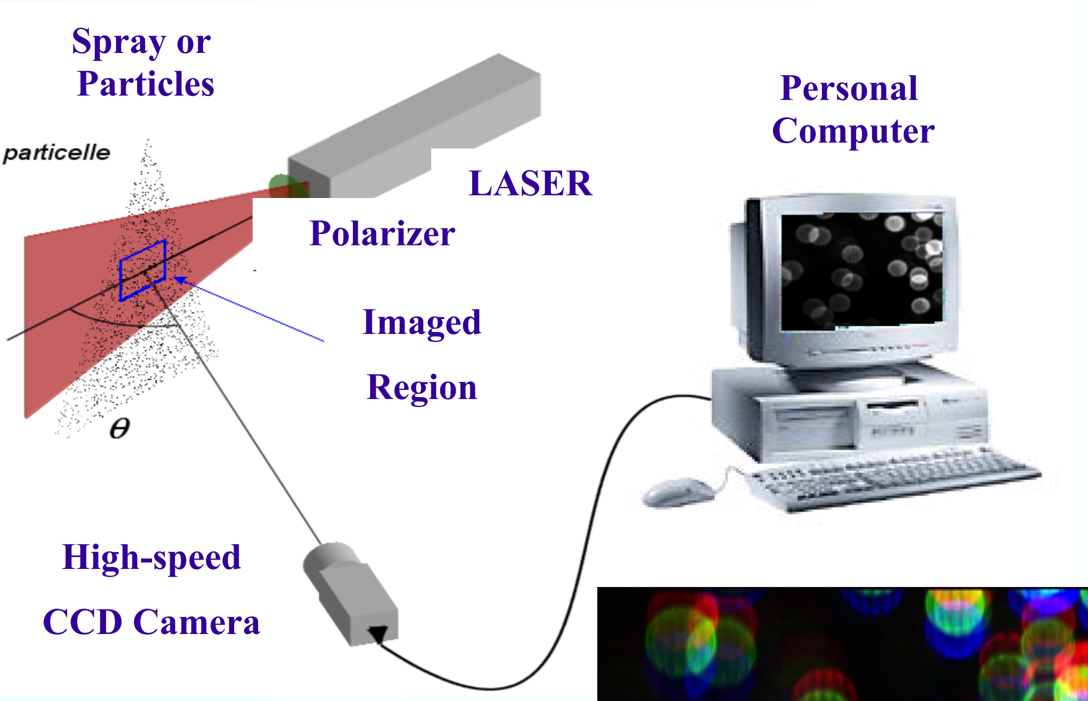
fringe system

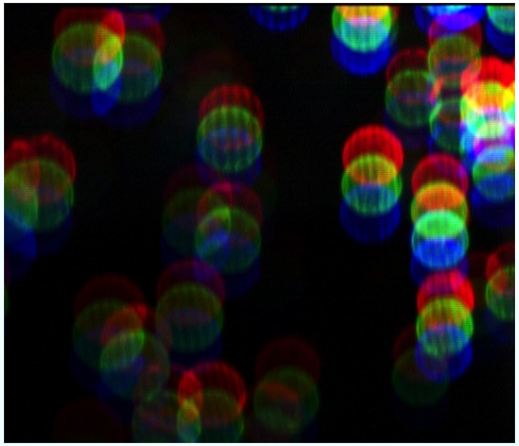


Damaschke et al. 2001)

Multi-point size measurements

GPS & ILIDS: practice



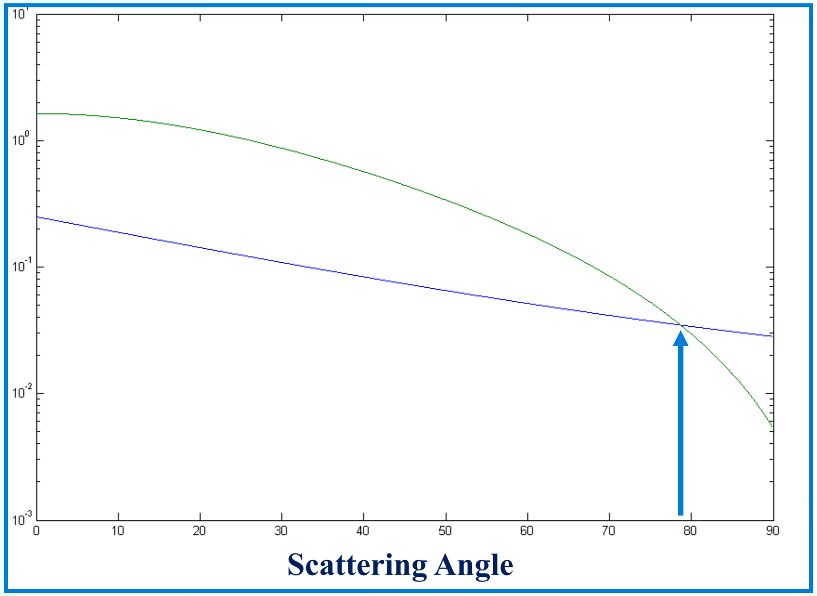


+ velocity ?

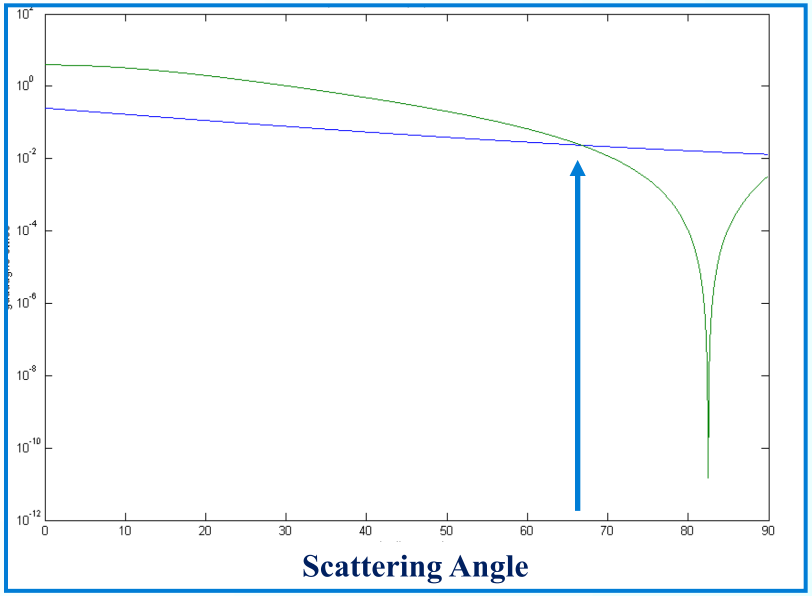
Multi-point size measurements

GPS & ILIDS: receiving optics

Optimal Fringe Contrast = Same Optical Intensity for Reflection and Refraction



Solid Particles in Air (m=1.59)



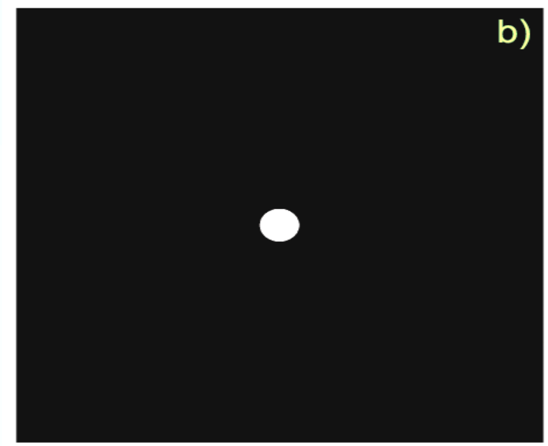
Water Droplets in Air (m=1.33)

Multi-point size measurements

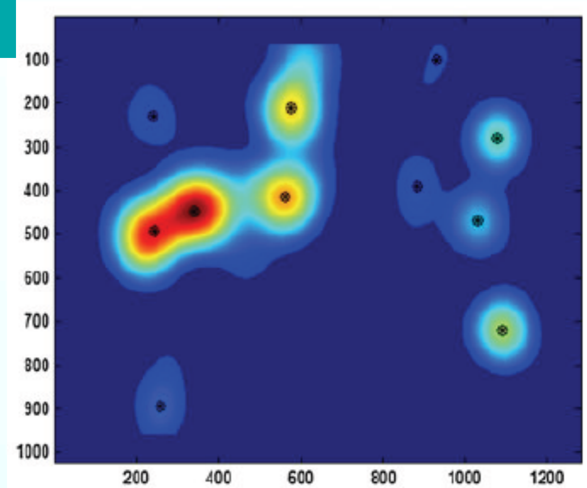
GPS & ILIDS: particle identification

original image

cross-correlation



reference image

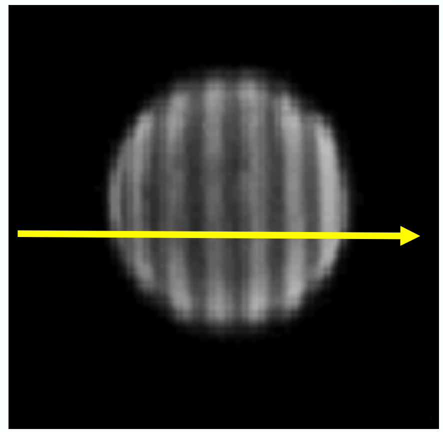


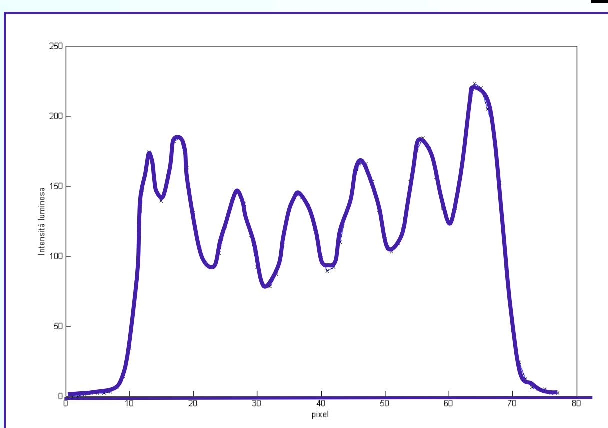
cross-correlation

Multi-point size measurements

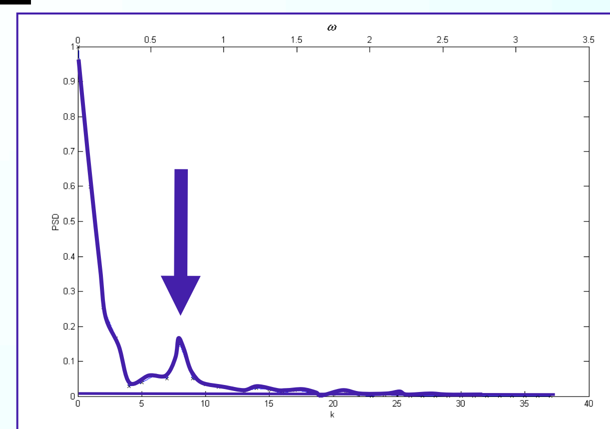
GPS & ILIDS: fringe spacing evaluation

FFT or correlation of particle defocused images





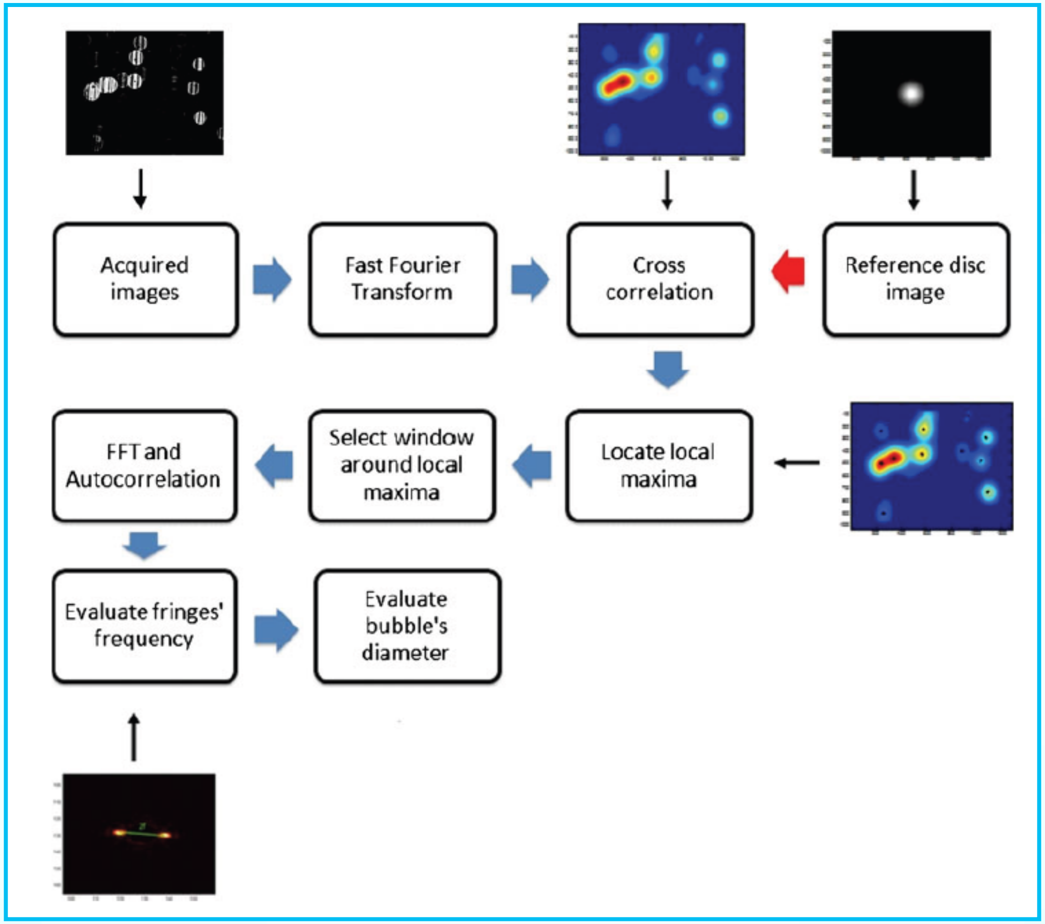
$$\frac{1}{\lambda} = \frac{k}{N}$$



k = wavenumber

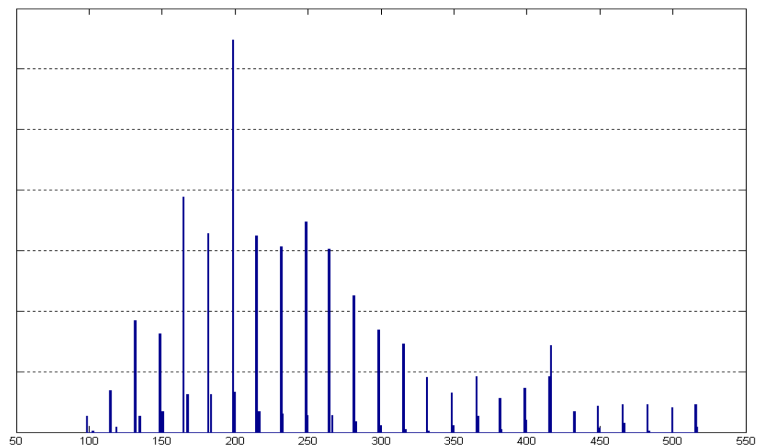
Multi-point size measurements

GPS & ILIDS: image processing algorithm

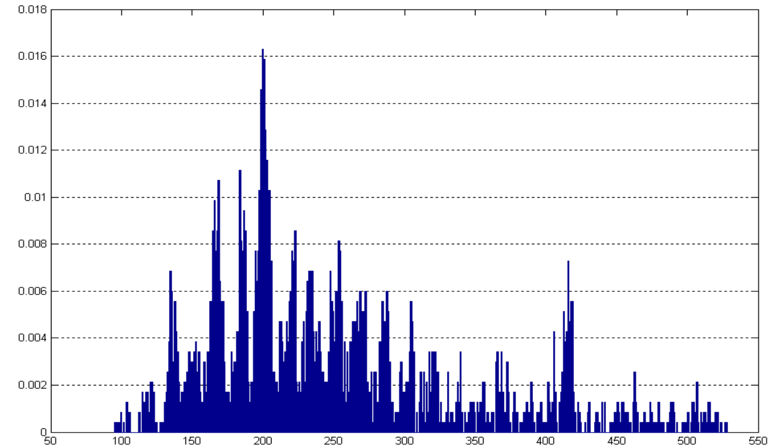


Multi-point size measurements

GPS & ILIDS: size statistics



Particle diameter

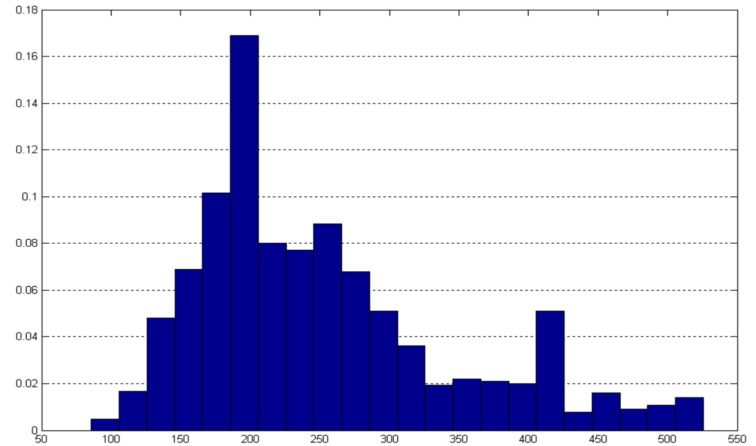


Particle diameter

Gaussian sub-pixel interpolation on PDF of particle diameter

+

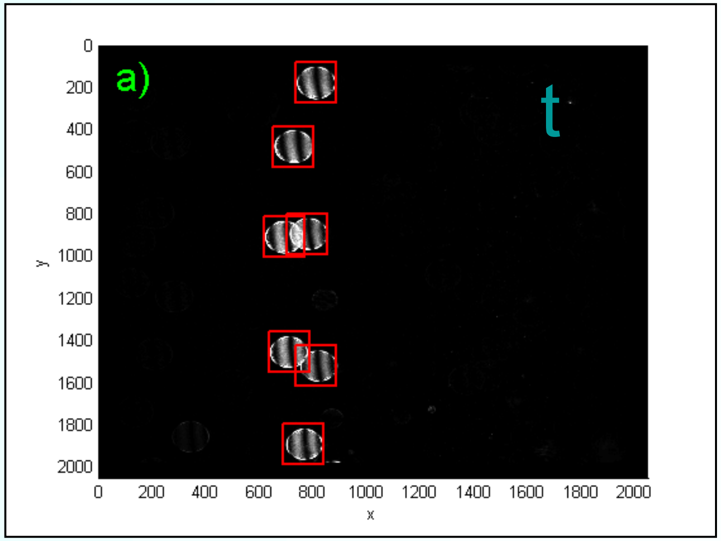
correct bin size

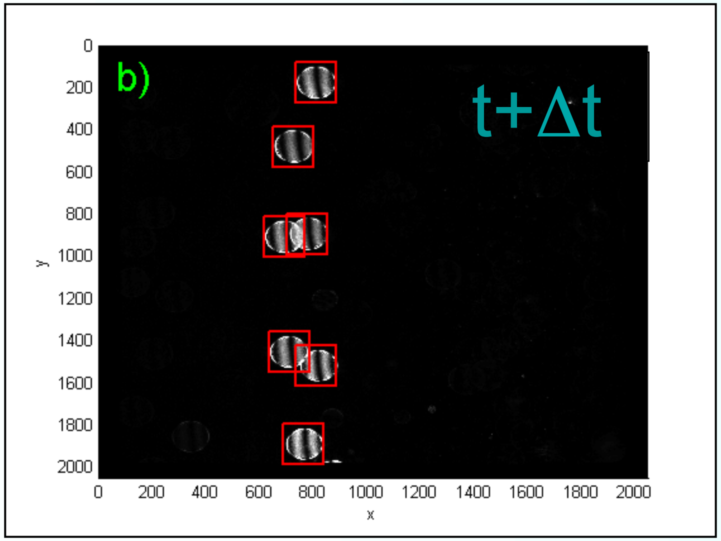


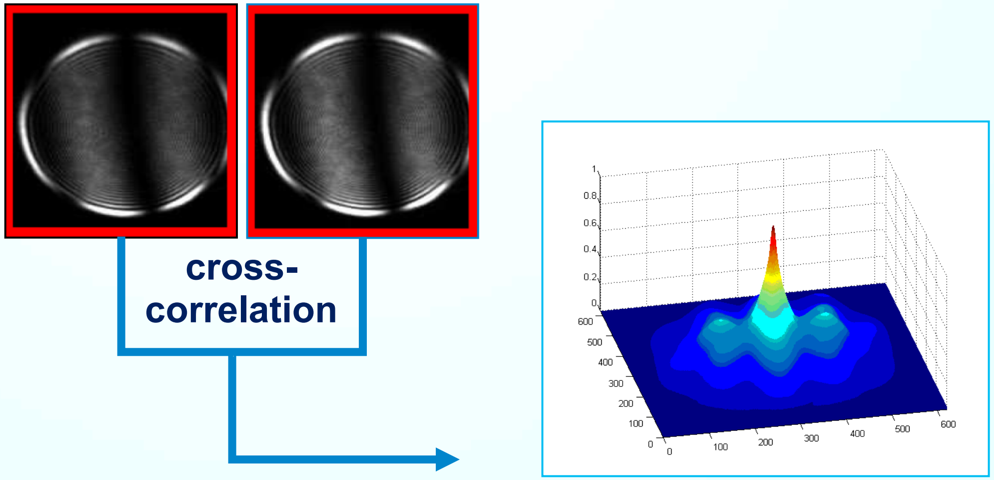
Particle diameter

Multi-point size measurements

GPS & ILIDS + velocity

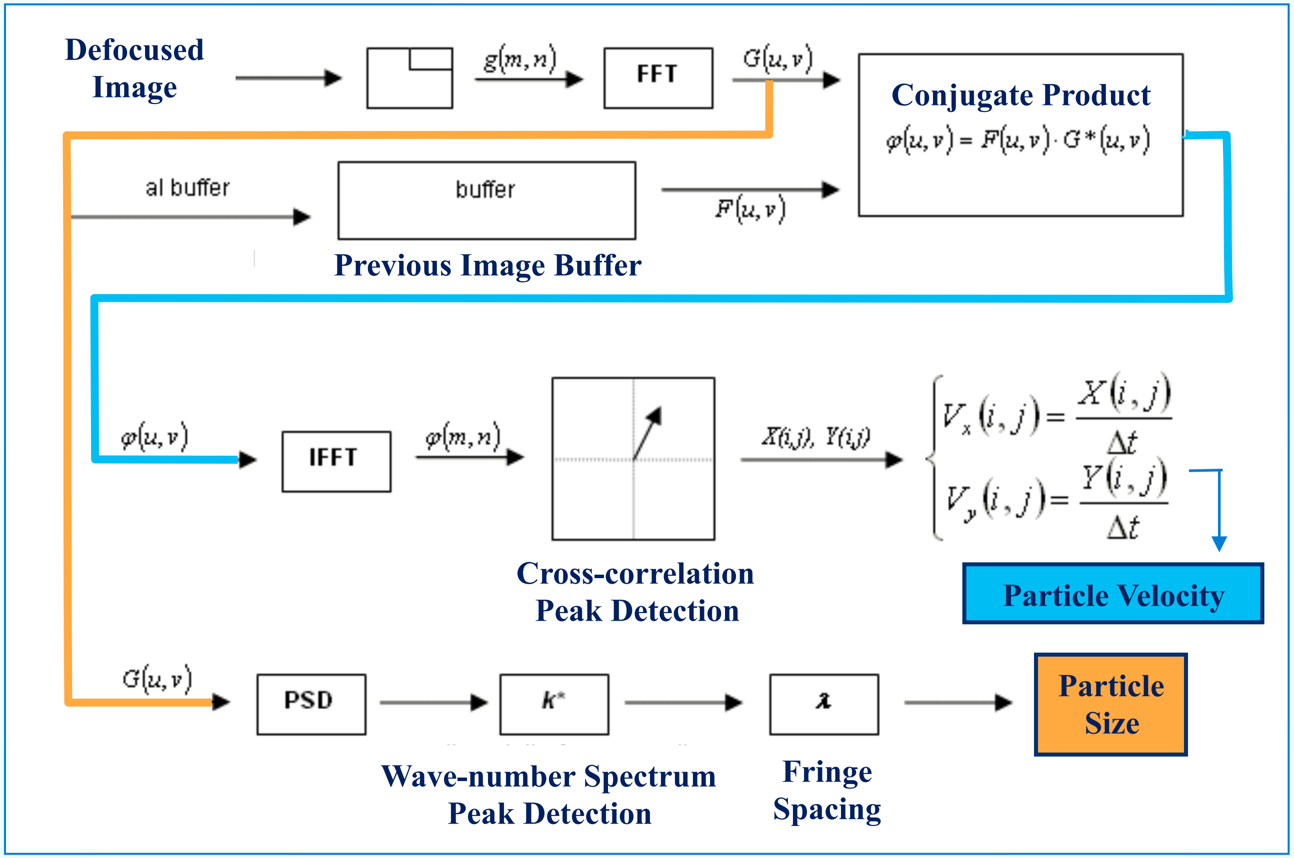






Multi-point size measurements

GPS & ILIDS + velocity



Multi-point size measurements

GPS & ILIDS: limits

LOWER LIMIT

Geometrical Optics Limit $\pi d/\lambda >> 1 \approx 20$ $d_{min} = 5\ \mu m$

At least 2 observable fringes

$$d_{min} = \frac{K}{\delta_{max}} = \frac{4\lambda \cdot L_1}{D} \frac{1}{\cos\theta/2 + \dfrac{m \sin\theta/2}{\sqrt{m^2 + 1 - 2m\cos\theta/2}}}$$

$d_{min} = 15\ \mu m$

PSD Peak in the Origin $k^* > 2$ $d_{min} = 20\ \mu m$

HIGHER LIMIT

Nyquist criterion
(to avoid aliasing over frequency N/2)
(at least 1 pixel per fringe)

$$d_{max} = \frac{K}{\delta_{min}} = \frac{K k_{x\,max}}{2\pi} = \frac{K}{2\Delta x} = \frac{K}{4}$$

$d_{max} = 600\ \mu m$

Dynamical Range for Size Measurements > 100

Multi-point sise measurements

GPS & ILIDS

Example 1: tests on calibrated solid particles

Bangs Styrene/2% VB/45-100mesh	Company	Measured
Average size	*83 μm*	*84 μm*
Std. deviation	*± 8 μm*	*± 10 μm*
Aver. ± Std.	*75 μm - 90 μm*	*74 μm - 94 μm*
Minimum size	*nd*	*58 μm*
Maximum size	*nd*	*110 μm*

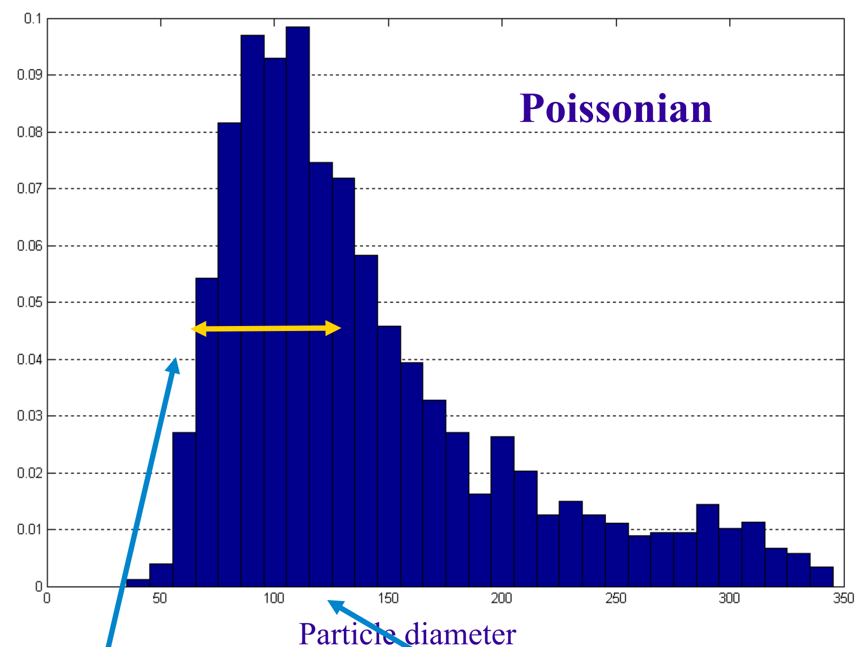
Bangs Styrene/2% VB/45-100mesh	Company	Measured
Average size	*250 μm*	*253 μm*
Std. deviation	*± 100 μm*	*± 93 μm*
Aver. ± Std.	*149 μm - 350 μm*	*160 μm - 346 μm*
Minimum size	*nd*	*96 μm*
Maximum size	*nd*	*528 μm*

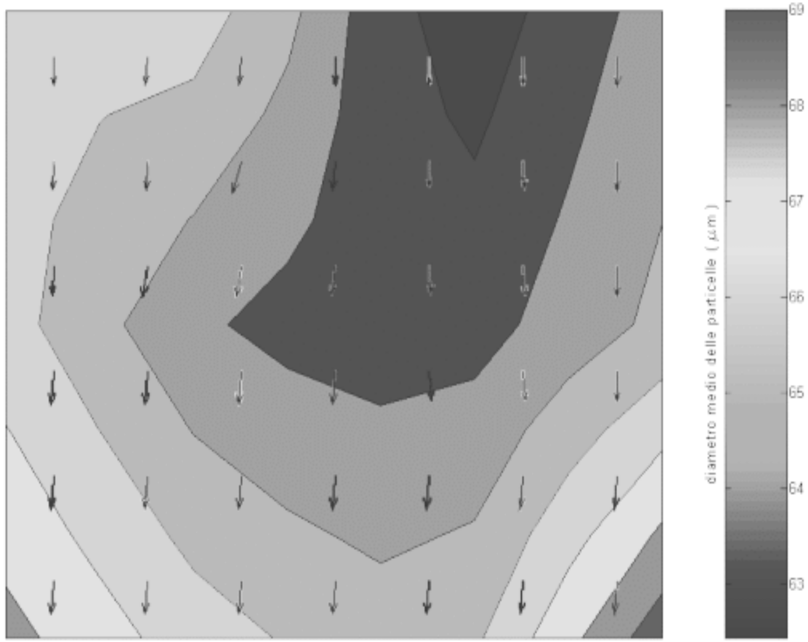
Error: 1% on mean, 3% on σ

Multi-point size measurements

GPS & ILIDS

Example 2: spray of water droplets in air





Std. Deviation = 60 μm

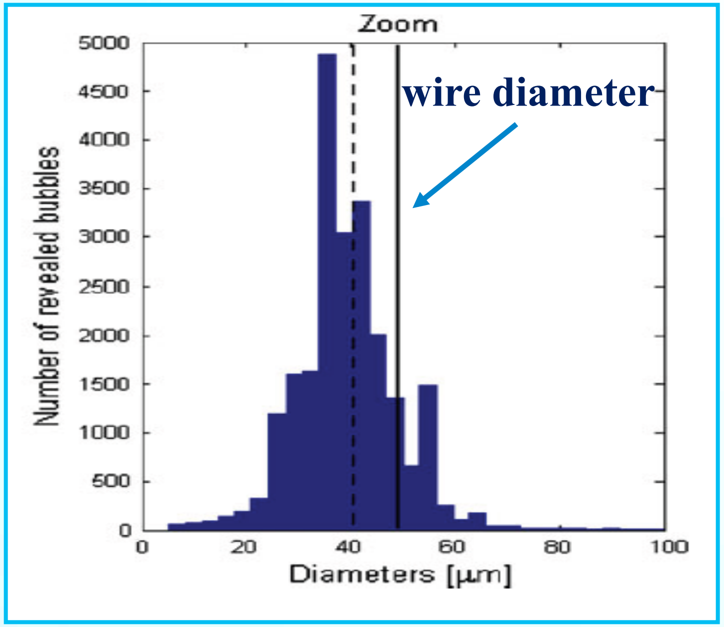
Mean Diameter = 130 μm

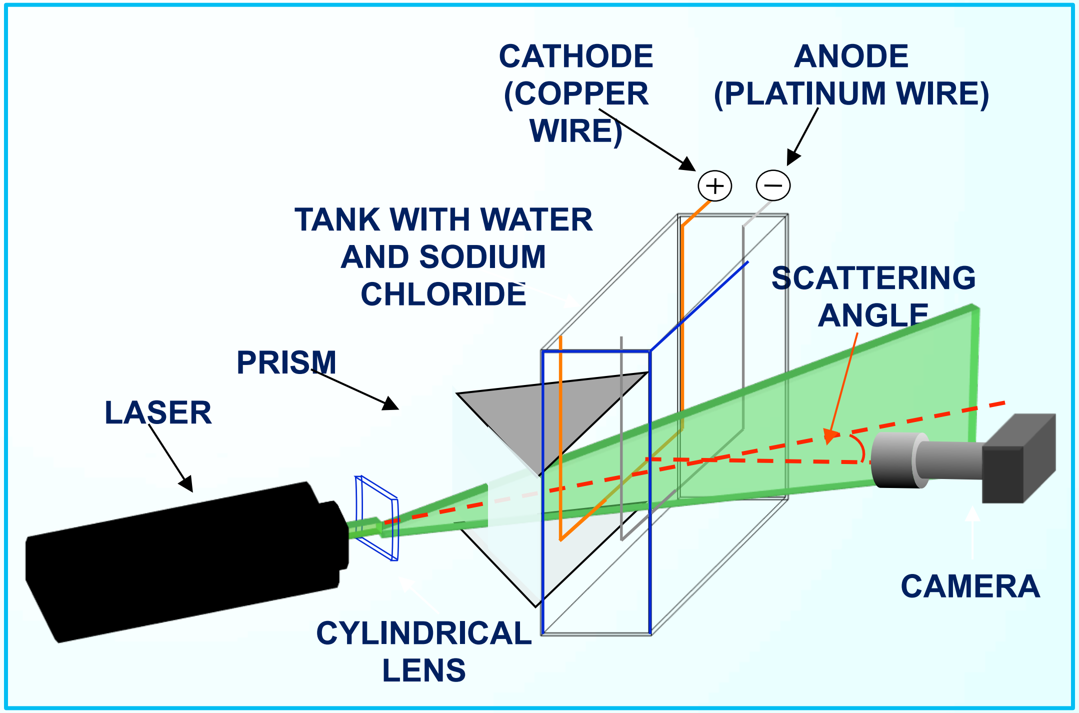
+ velocity

Multi-point size measurements

GPS & ILIDS

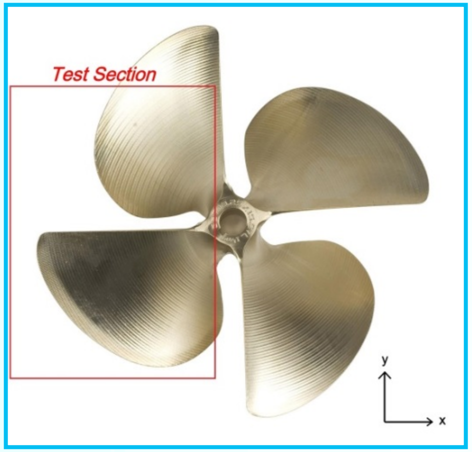
Example 3: micro air bubbles in water (wire electrolysis)





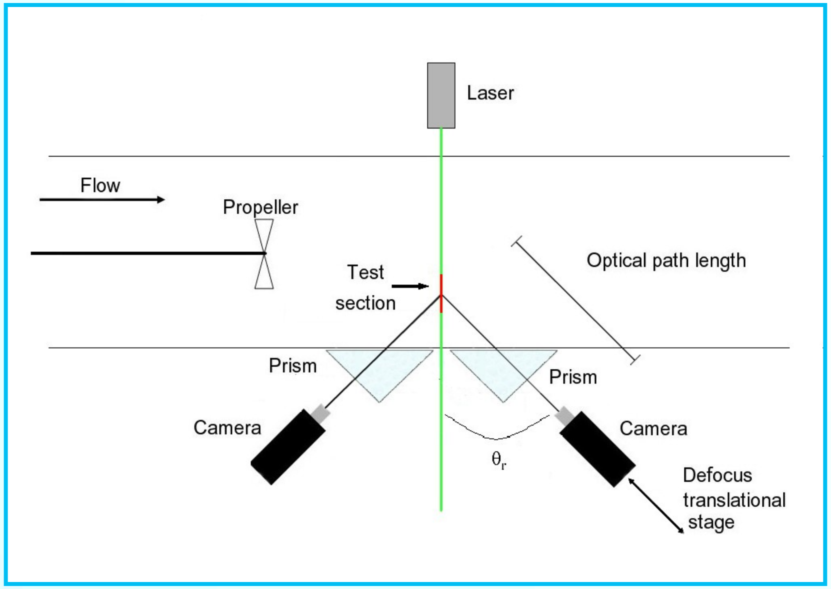
Multi-point size measurements

GPS & ILIDS

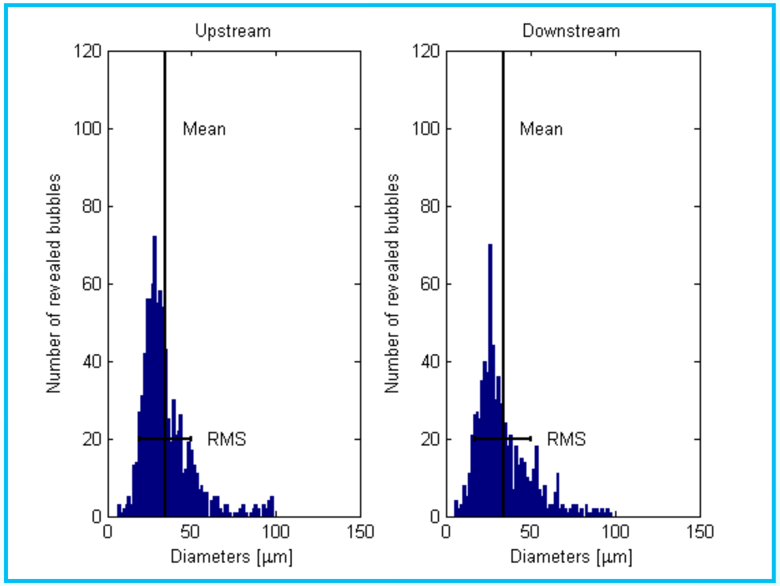


Example 4: Cavitation bubbles

Lacagnina et al., 2011, in collaboration with CNR-INSEAN,
Network of Excellence "Hydro-Testing Alliance" FP6 (2006-2010)



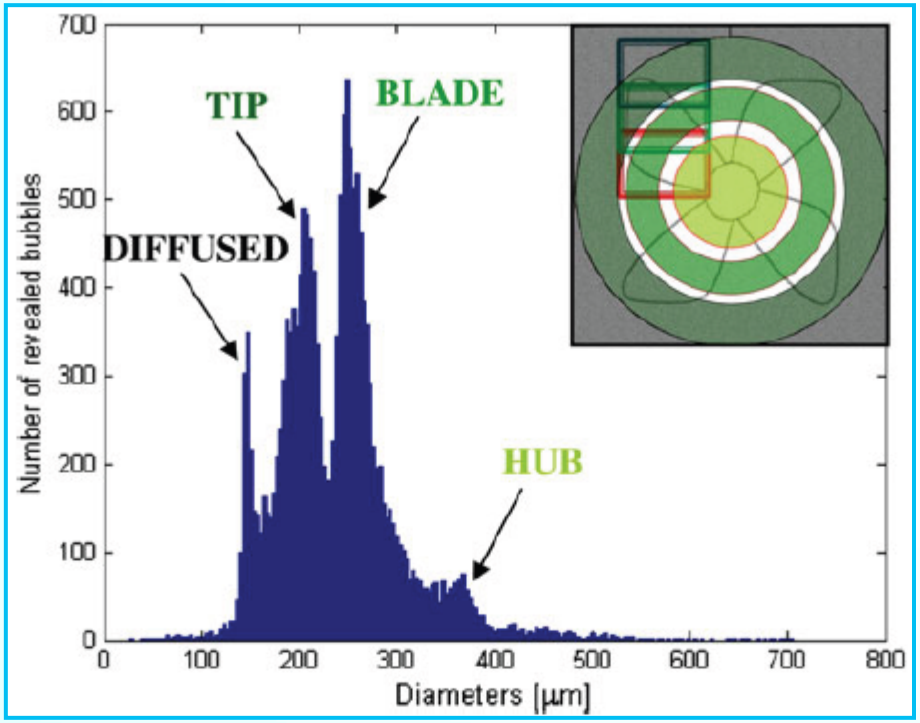
comparison of the two cameras

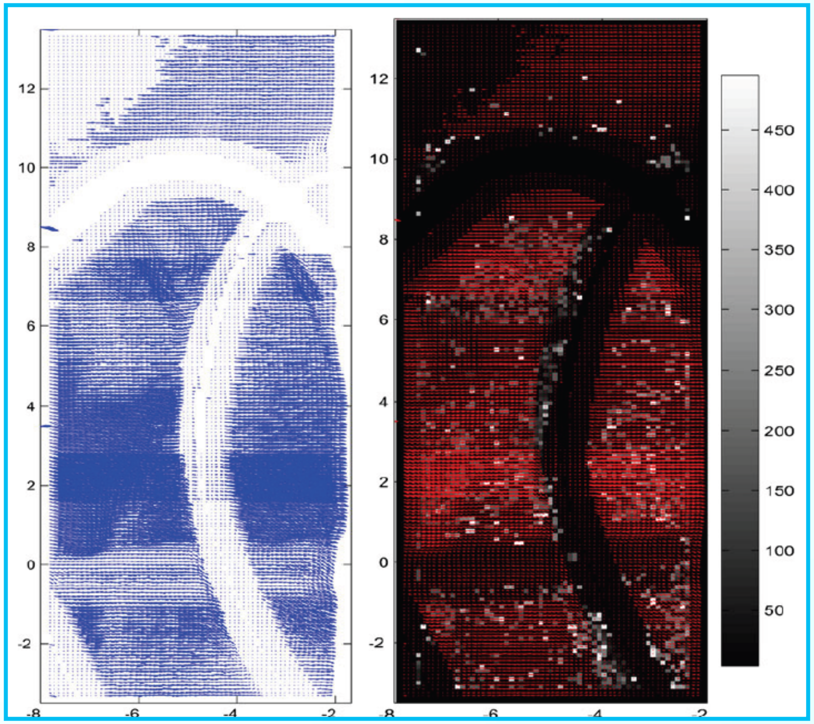


Multi-point size measurements

GPS & ILIDS

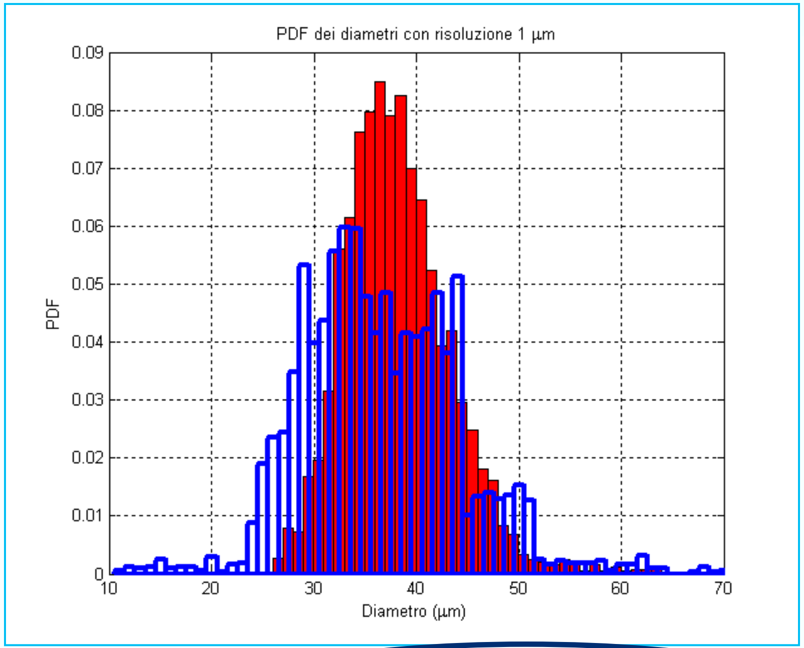
Example 4: Cavitation bubbles





Multi-point size measurements

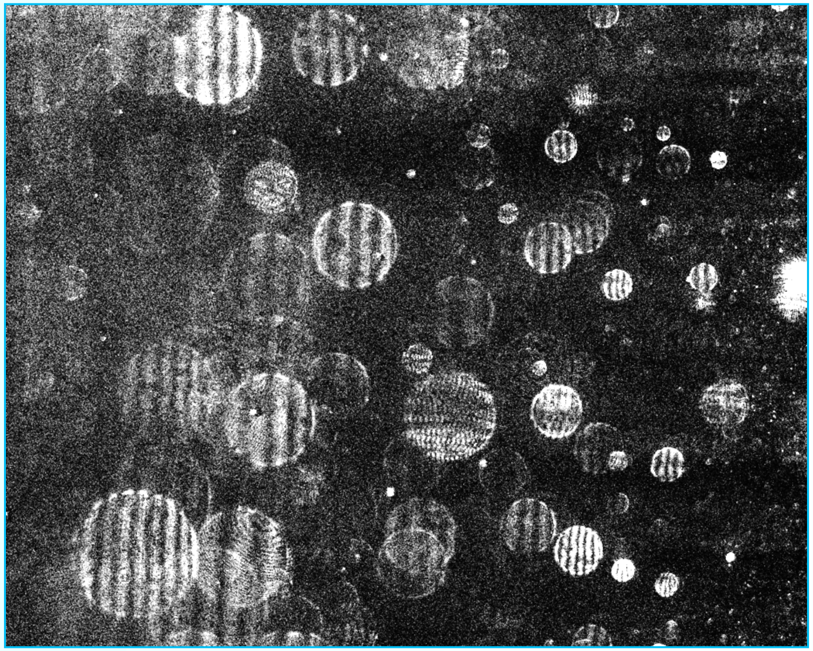
GPS & ILIDS: comparison

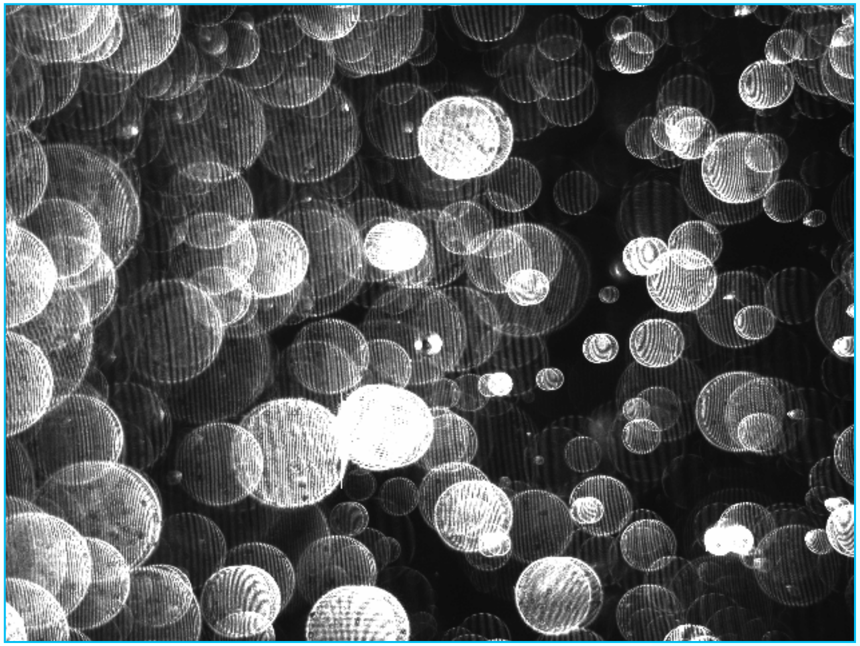


	Shadow Imaging	ILIDS
Diametro medio	38.22 μm	37.17 μm
Deviazione standard	5.25 μm	10.48 μm
Diametro più probabile	36 μm	33 μm

Multi-point size measurements

GPS & ILIDS: drawbacks





Spherical particles
Low particle density

Multi-point size measurements

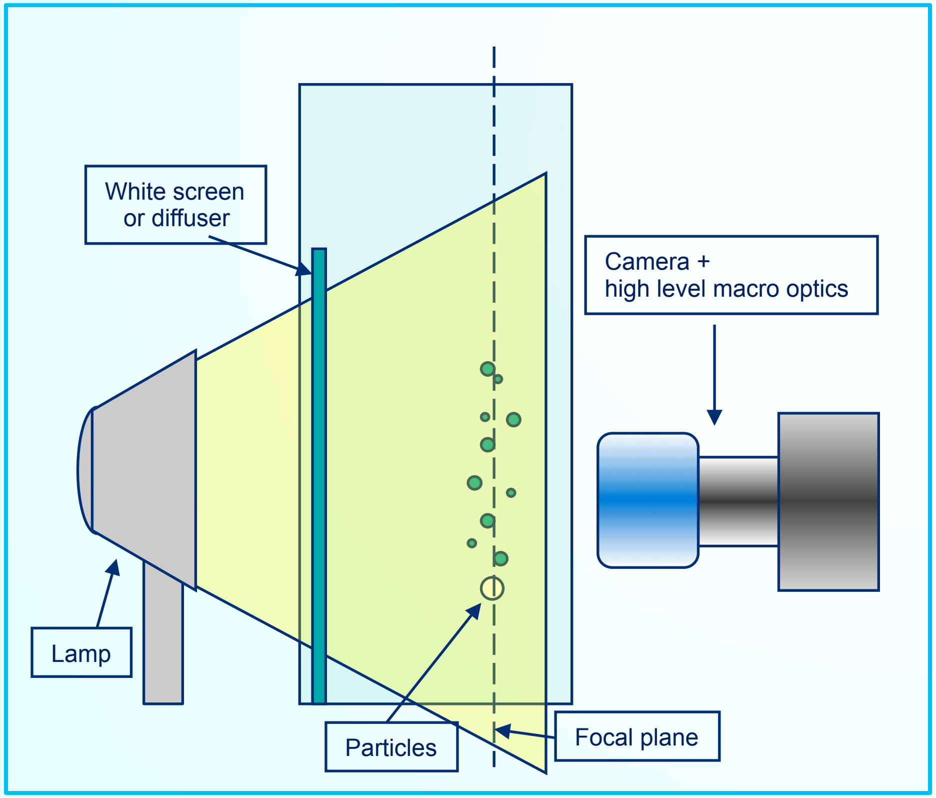
Non-spherical particles

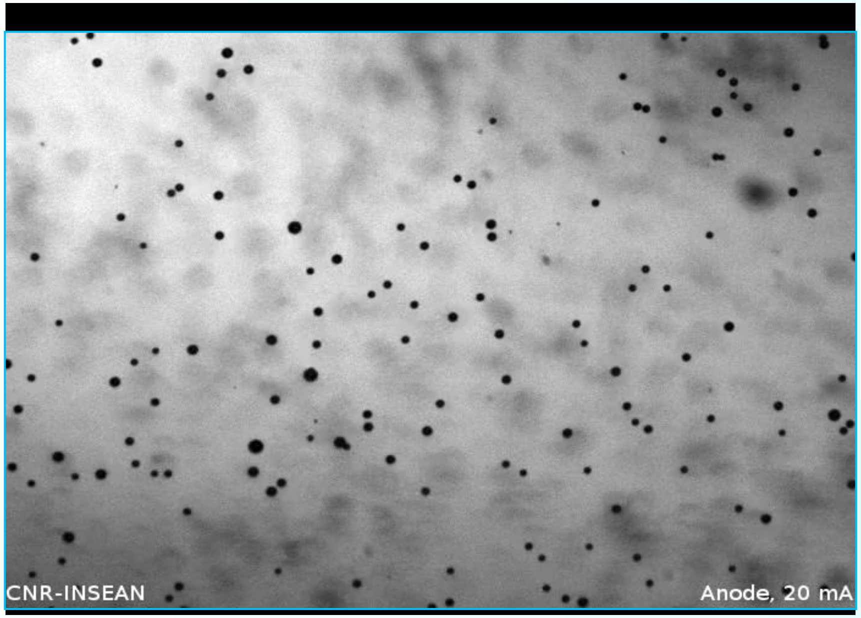
High particle density

Advanced Image Analysis Methods

Non-spherical particles – multi-point measurements

Shadow Imaging

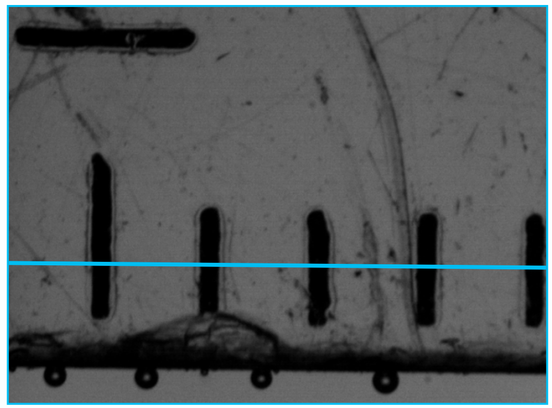




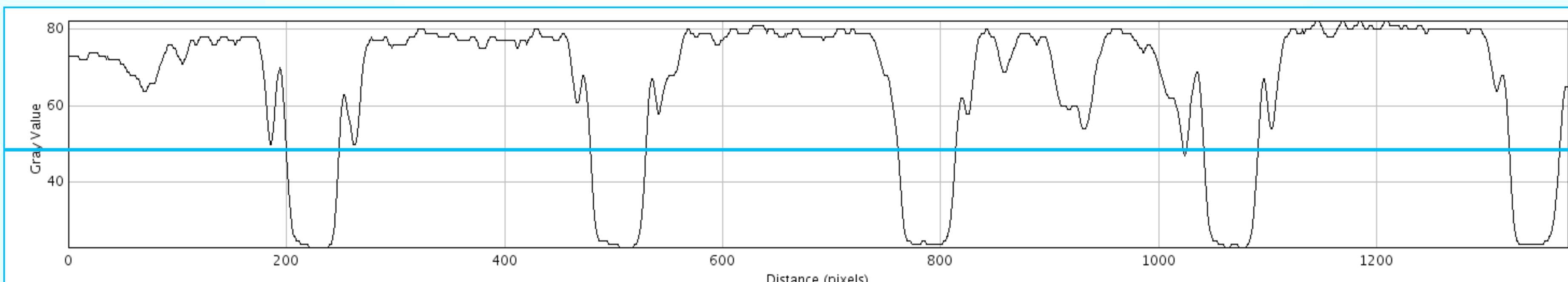
Contour → Area → Size

Non-spherical particles – multi-point measurements

Shadow Imaging: calibration



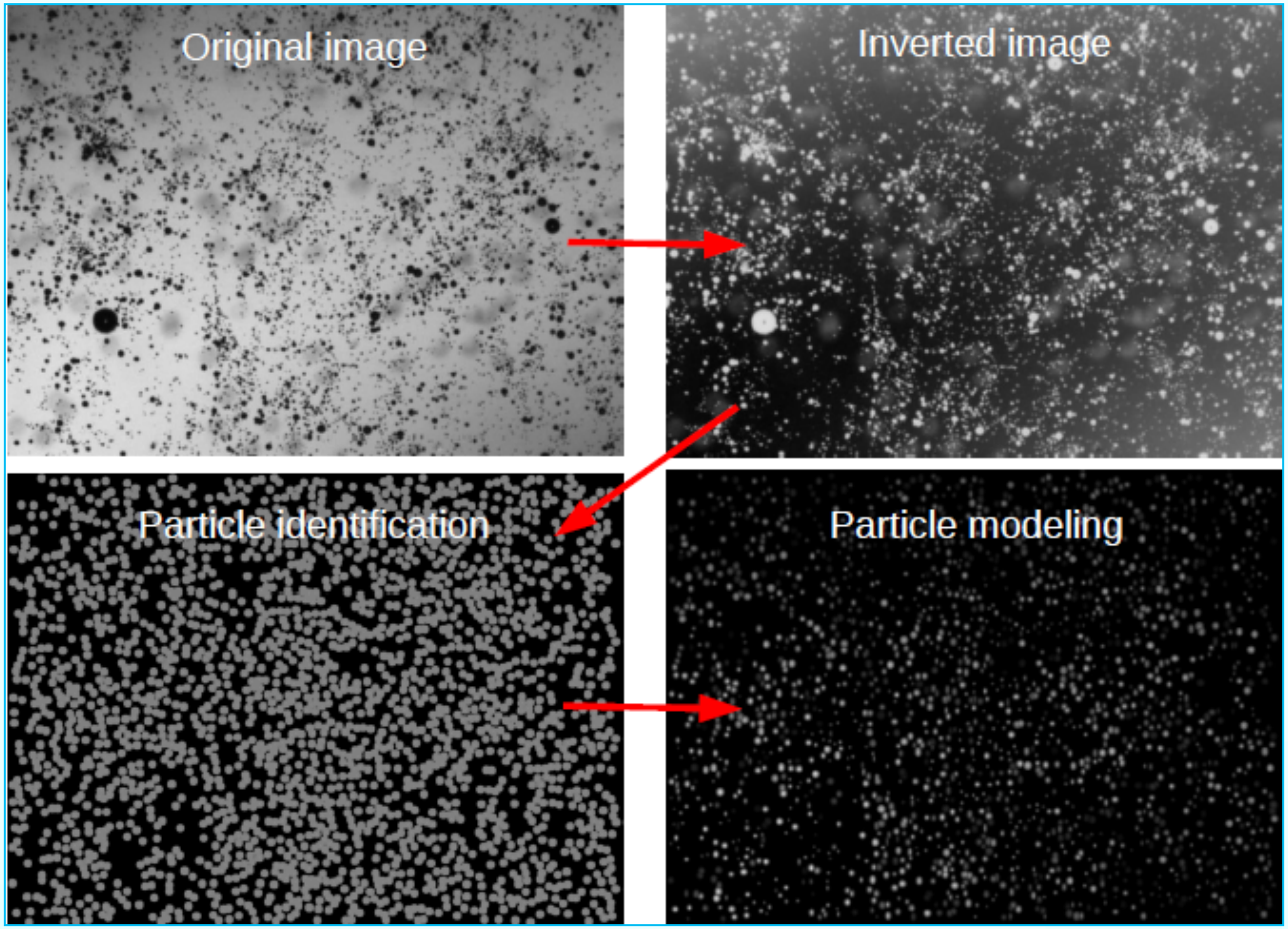
1136 pixels = 4 mm (3.52 mm/pixel)



high spatial resolution but very small region

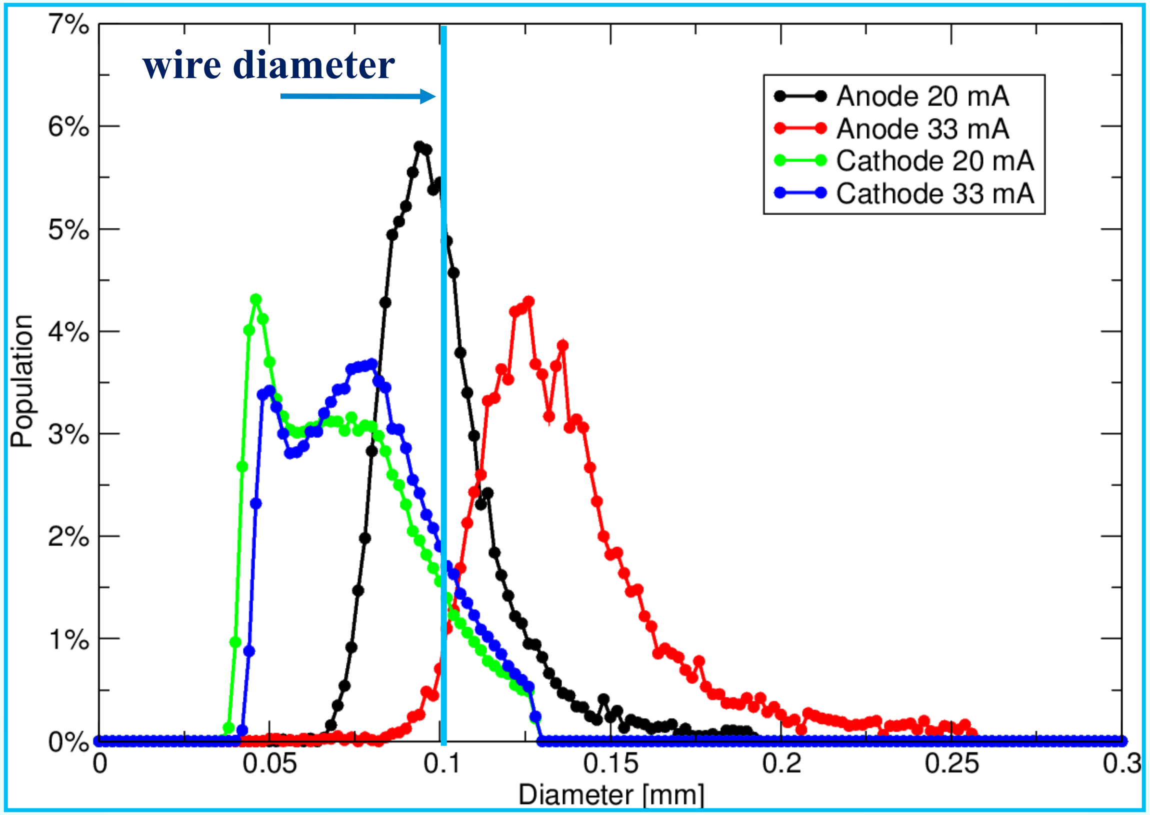
Non-spherical particles – multi-point measurements

Shadow Imaging: image processing (high density)



Non-spherical particles – multi-point measurements

Shadow Imaging: micro air bubbles in water (wire electrolysis)



Non-spherical particles – multi-point measurements

- Non-spherical particles are imaged as spherical
- Non-spherical particles are imaged as non-spherical

<u>SPATIAL RESOLUTION</u>

Non-spherical particles – multi-point measurements

Example: synthetic plastic rod fibers (nylon)

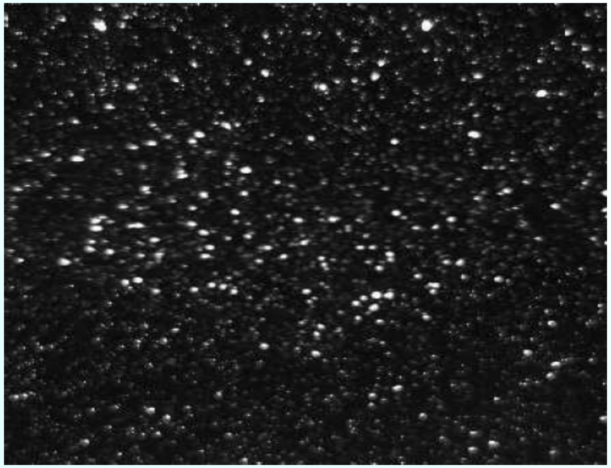
- Density 1.13-1.15 g/cm3
- Mean length L=320 μm
- Mean diameter d=24 μm
- Aspect ratio L/d=13.3

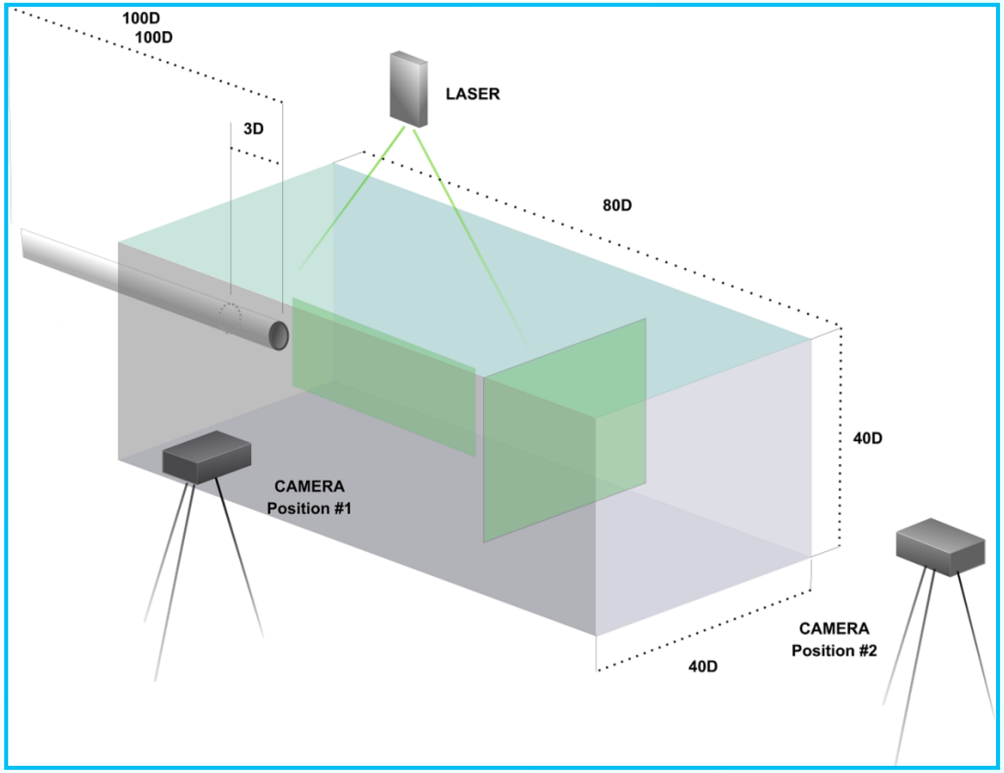
Flow tracers: hollow glass spheres
Mean diameter 12 μm, neutrally buoyant

Non-spherical particles – multi-point measurements

Low spatial resolution: fibers *eqv* to spheres

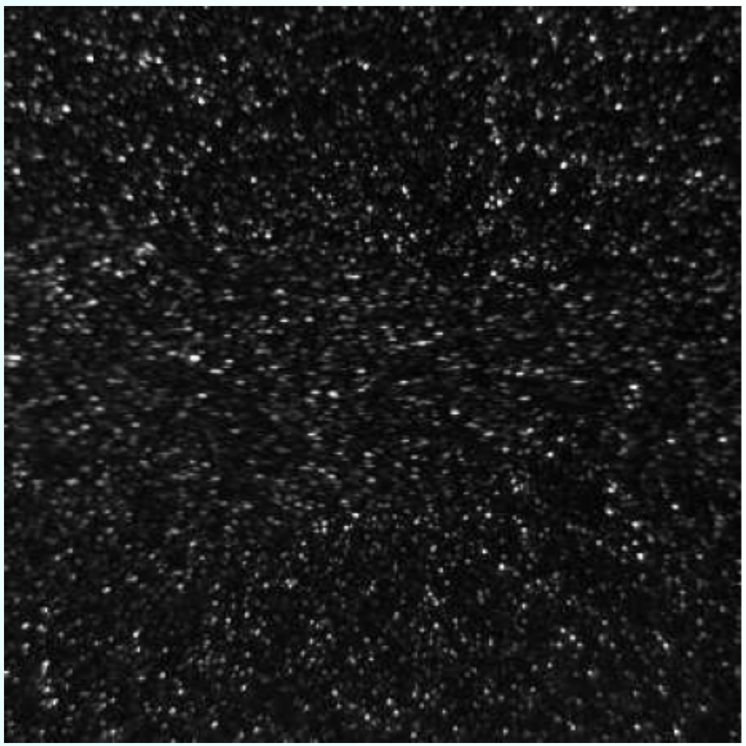
- Turbulent pipe jet
- Reynolds numbers 3000-30000
- Stokes number ≈ 0.7
- Imaged region ≈ 11 cm
- Camera sensor 1024 pixel
- Spatial resolution ≈ 8 px/mm
- 1 fiber length = 3 pixel



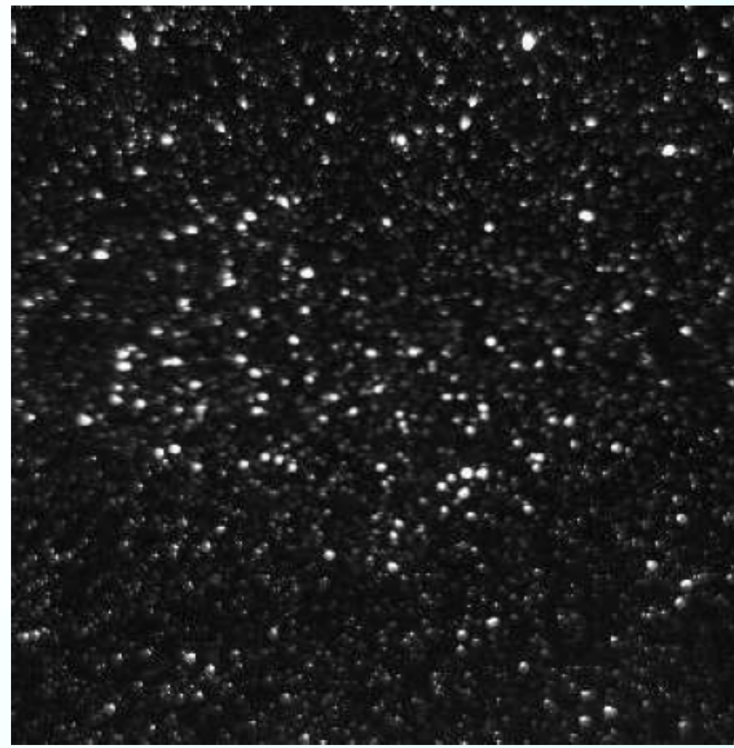


Non-spherical particles – multi-point measurements

Flow-particle phase discrimination



NO FIBERS



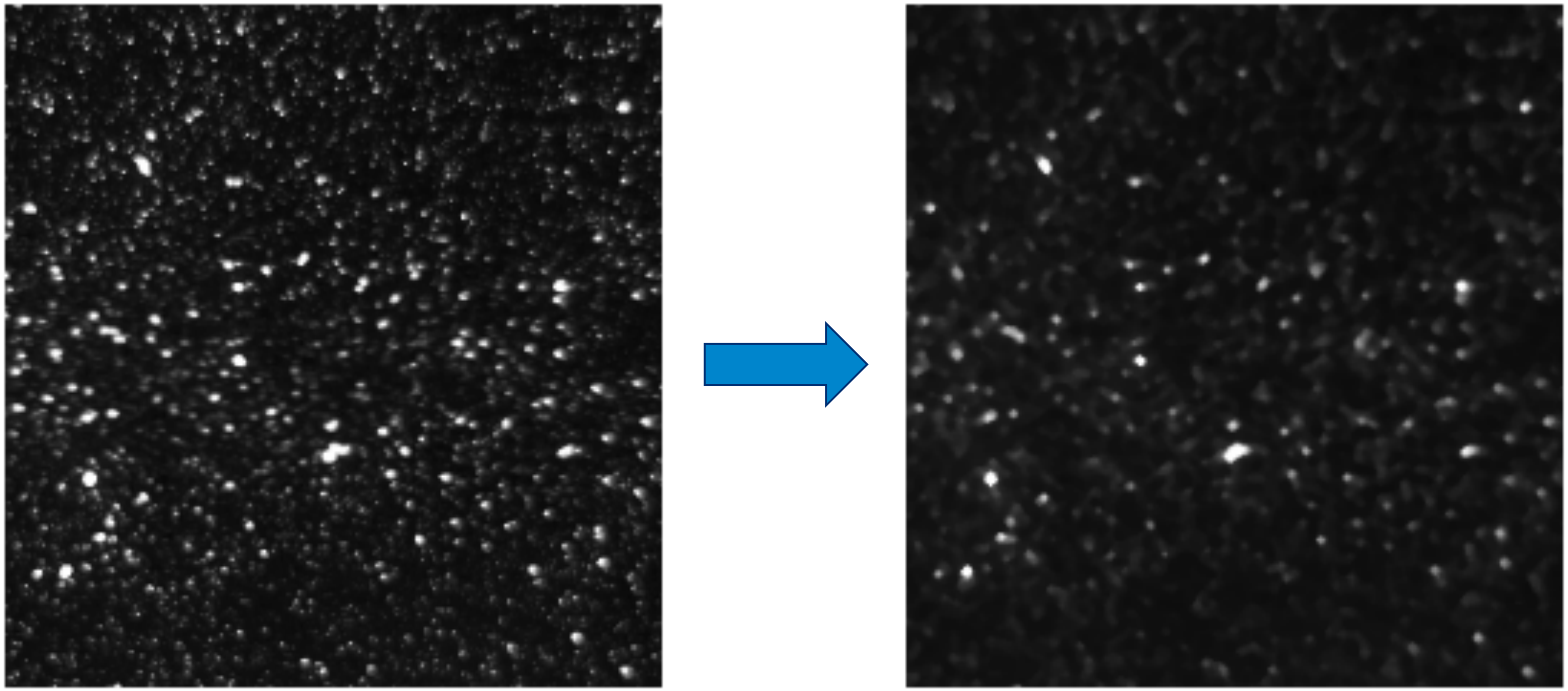
WITH FIBERS

Single or multiple cameras

Non-spherical particles – multi-point measurements

Flow-particle separation: spatial median filter

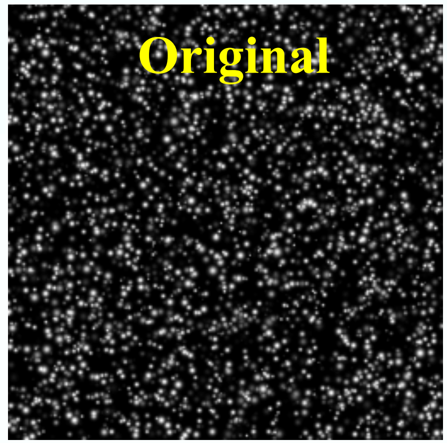
Kiger & Pan, 2001



Median filter 5x5 attenuates seeding particles

Image Pre-processing

Particle ≡ Intensity level (0-255)



-1	-1	-1
-1	8	-1
-1	-1	-1

Median Filter = ordering + medium value

"peaked" particle →

1	1	1	1	1
1	40	80	40	1
1	80	100	80	1
1	40	80	40	1
1	1	1	1	1

Median Filter = 1

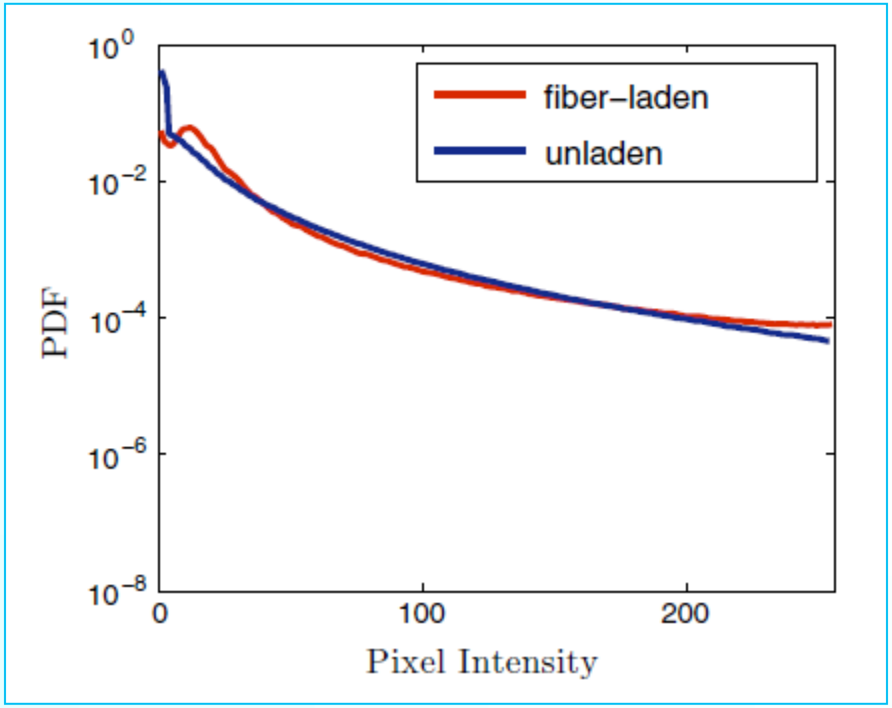
"distributed" particle →

10	20	20	20	10
20	30	30	30	20
20	30	30	30	20
20	30	30	30	20
10	20	20	20	10

Median Filter = 20

Non-spherical particles – multi-point measurements

Flow-particle separation: spatial median filter + thresholding



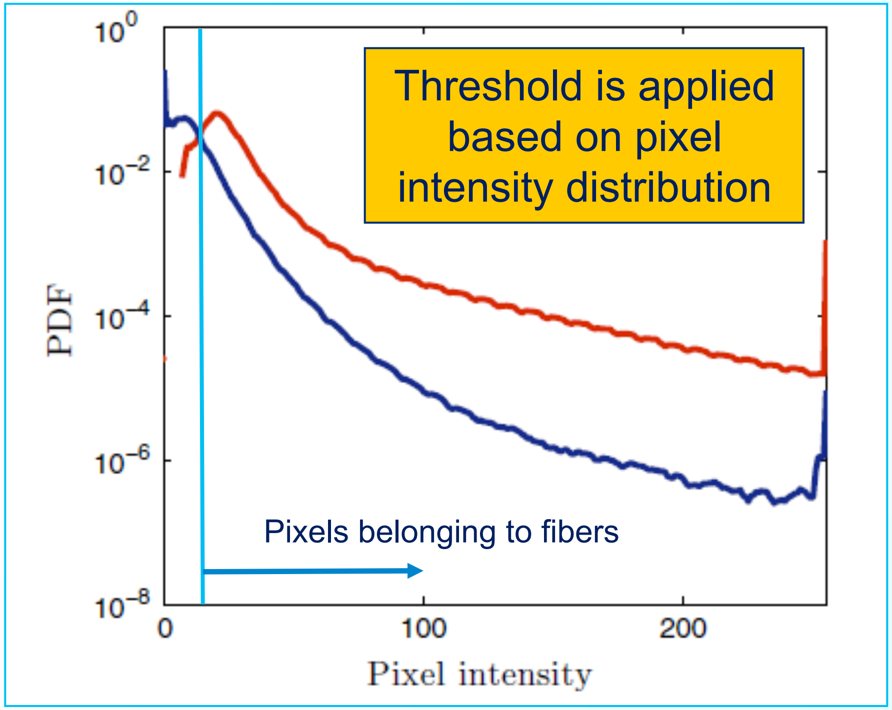


Fig. 4 PDF of light intensity at each pixel for single-phase data, compared to fiber-laden case before (at the *top*) and after (at the *bottom*) median filter

Non-spherical particles – multi-point measurements

Flow-particle separation: thresholding

which intensity threshold ?

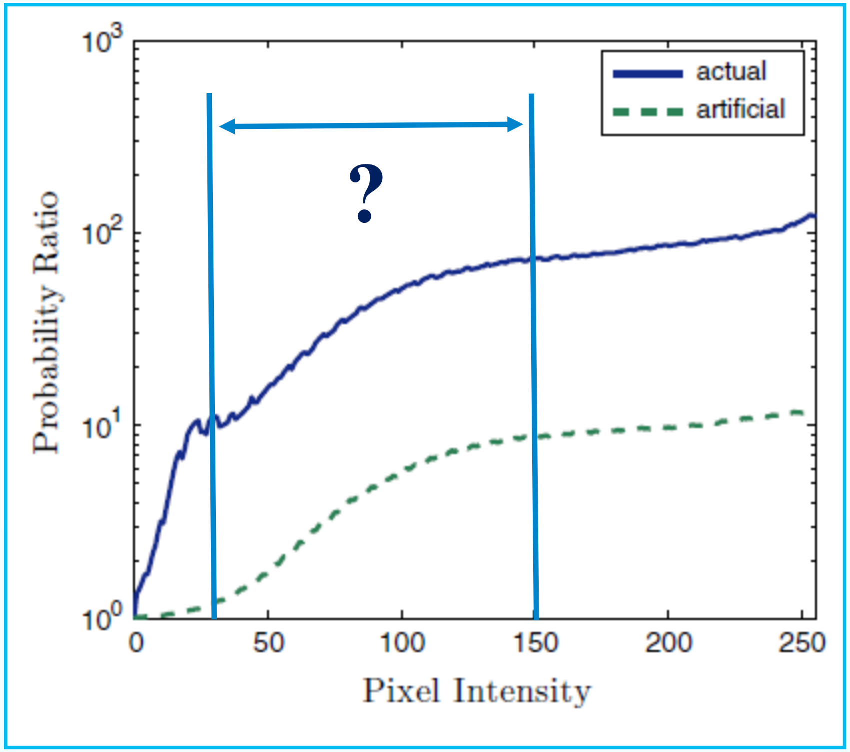


Fig. 5 Probability ratio of a pixel featuring an intensity level brighter than a certain value. Artificial data are discussed in Sect. 3.1

Non-spherical particles – multi-point measurements

Flow-particle separation: validation

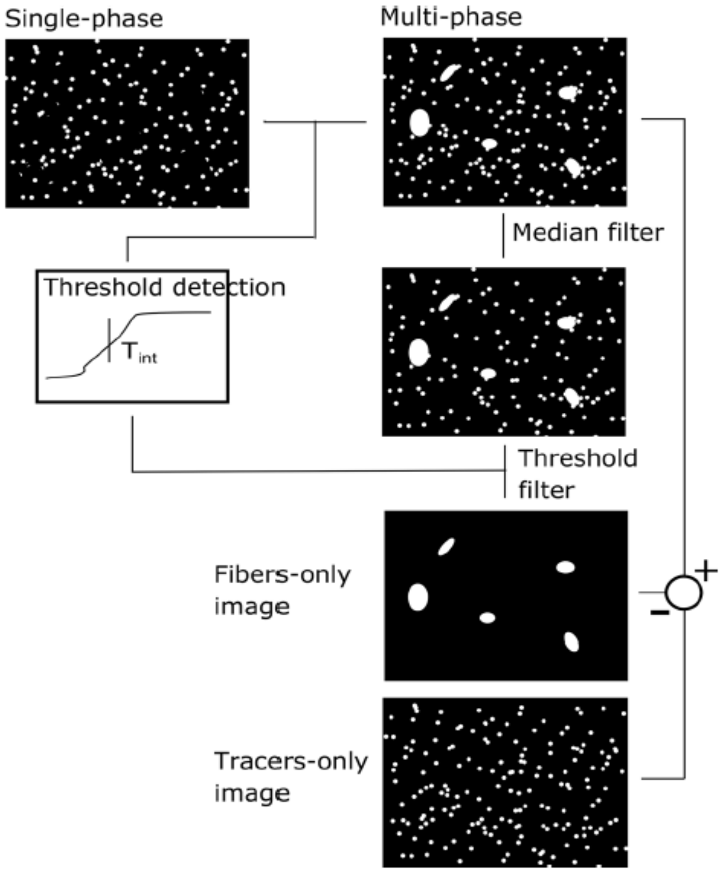


Fig. 6 Schematic of the phase discrimination algorithm

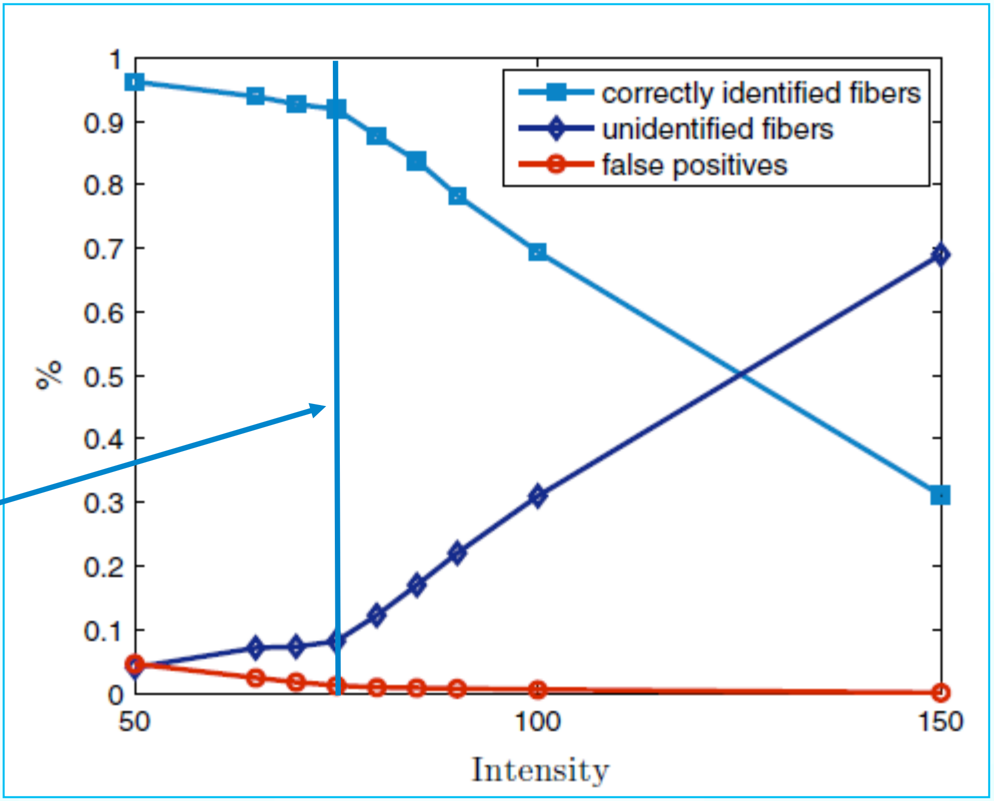
- Separation error by artificial two-phase images:
  1) Acquisition of tracer only and fiber only images
  2) Separate processing and location+velocity results
  3) Artificial multiphase image = tracer only+fiber only
  4) Phase discrimination (median + thresholding)
  5) Combined processing and location+velocity results
  6) Comparison as a function of threshold

- PIV average error on whole field below 3%
- Fibers detection error below 0.1%
- Detected particles 99.8%

Non-spherical particles – multi-point measurements

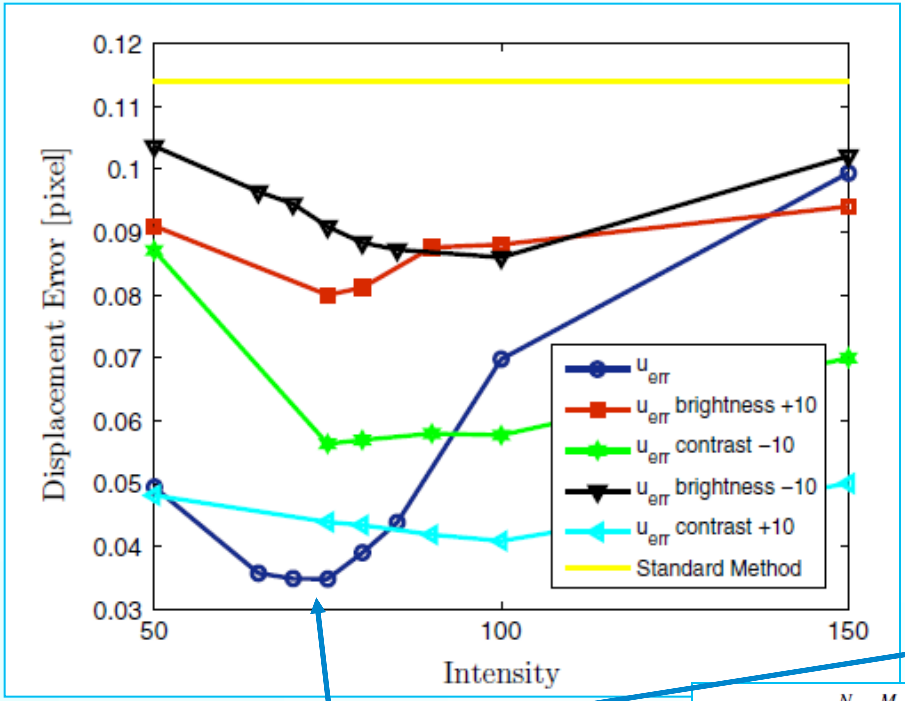
Flow-particle separation: validation location

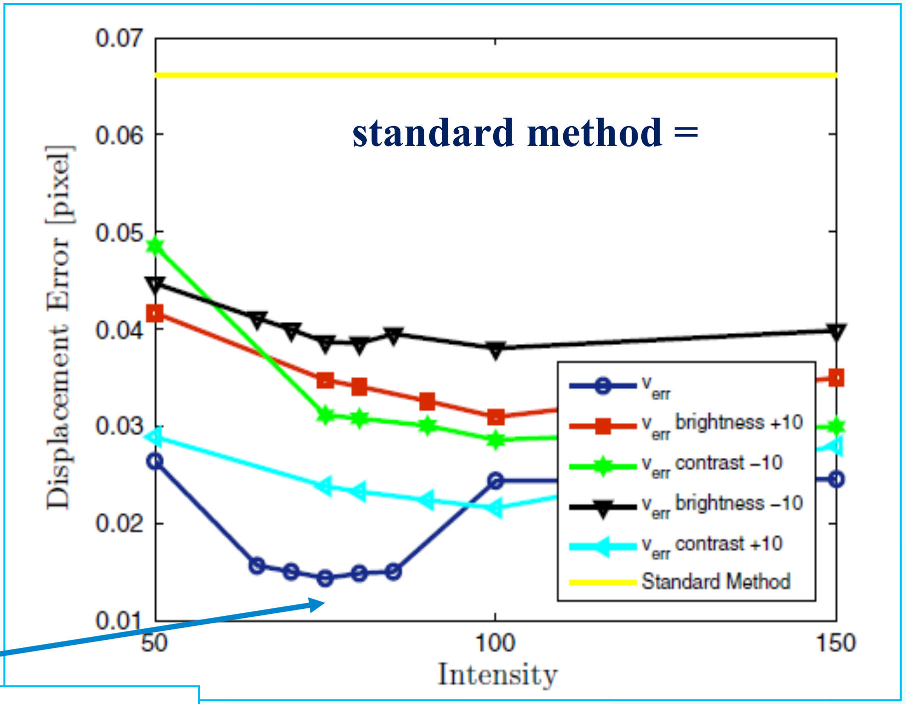
optimal around 75



Non-spherical particles – multi-point measurements

Flow-particle separation: validation velocity





optimal around 75

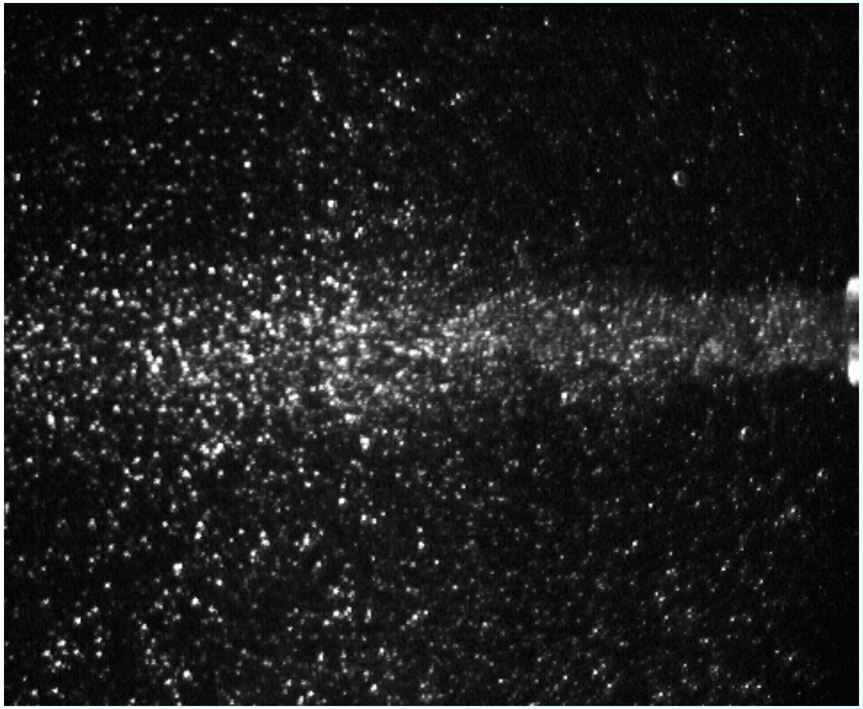
$$u_{\text{err}} = \frac{1}{NM}\sum_{i=1}^{N}\sum_{j=1}^{M}\left|u_{\text{com}(i,j)} - u_{\text{ori}(i,j)}\right|$$

$$v_{\text{err}} = \frac{1}{NM}\sum_{i=1}^{N}\sum_{j=1}^{M}\left|v_{\text{com}(i,j)} - v_{\text{ori}(i,j)}\right|$$

Turbulent jets

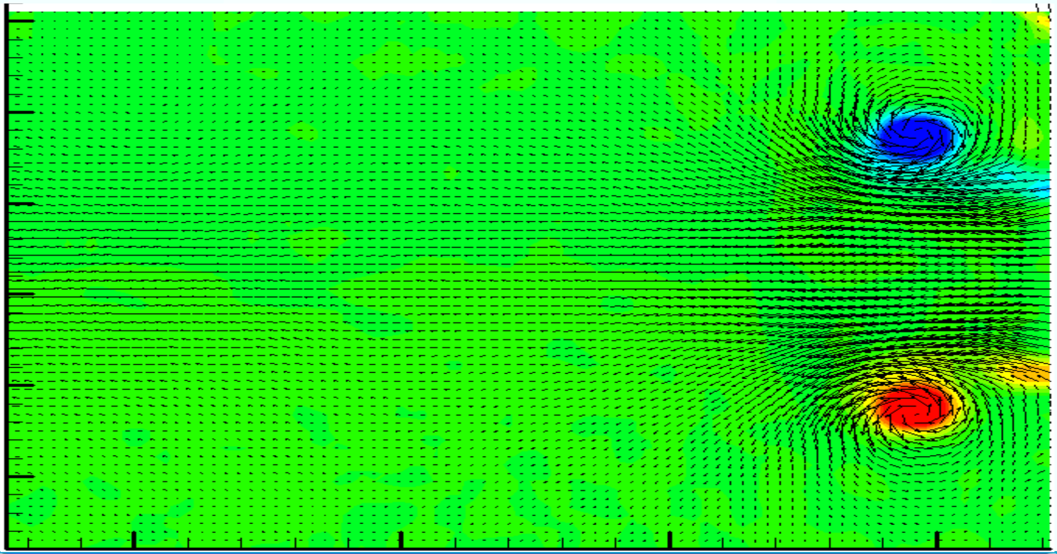
Kelvin-Helmholtz instability

PIV: Image Acquisition

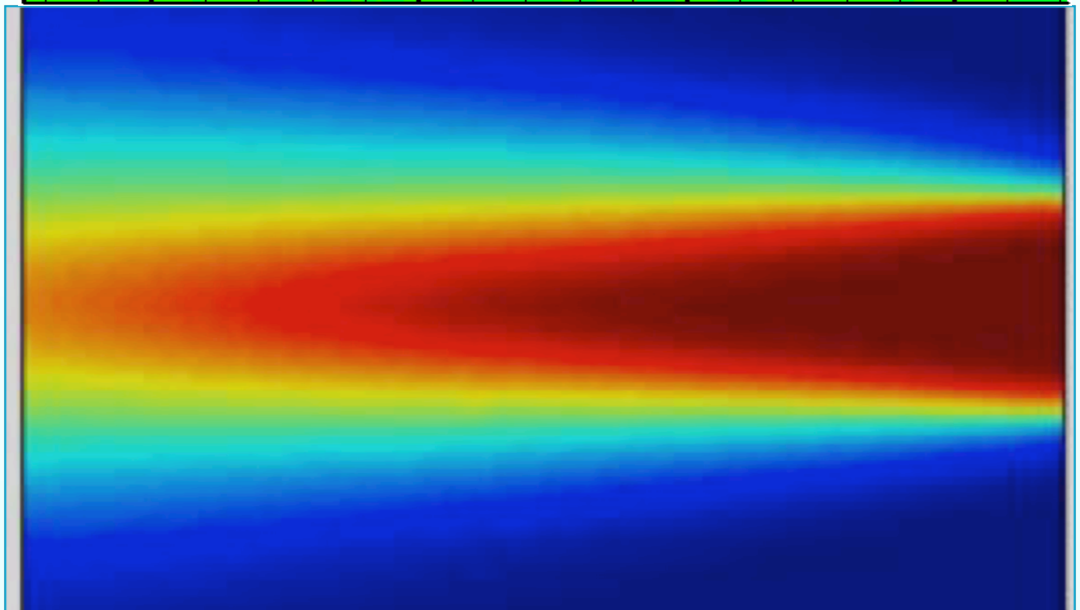


Turbulent jets

PIV
instantaneous field

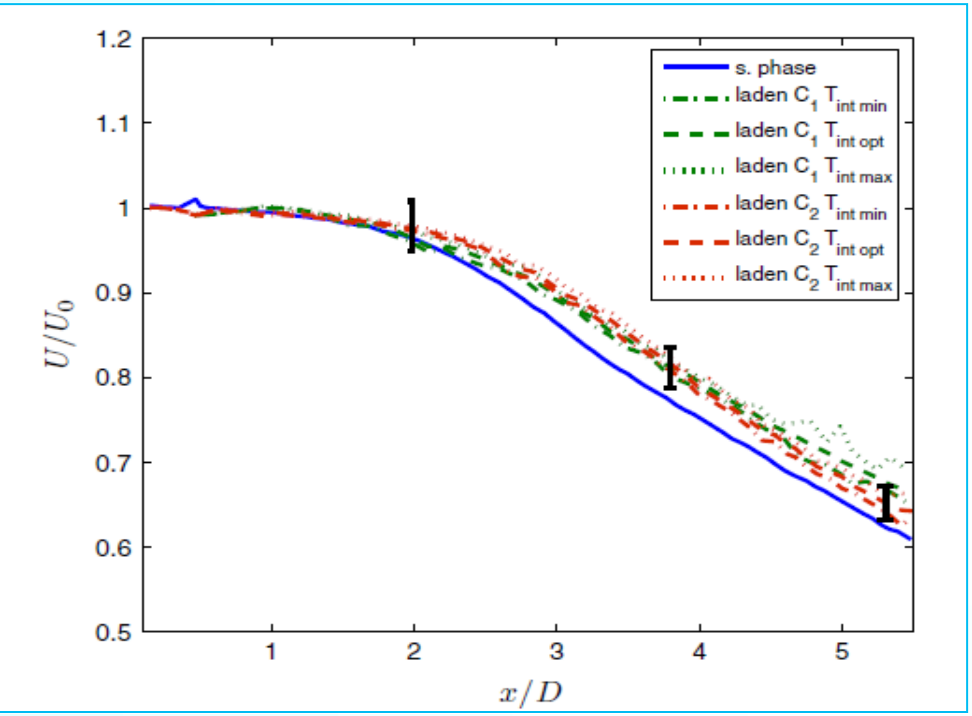


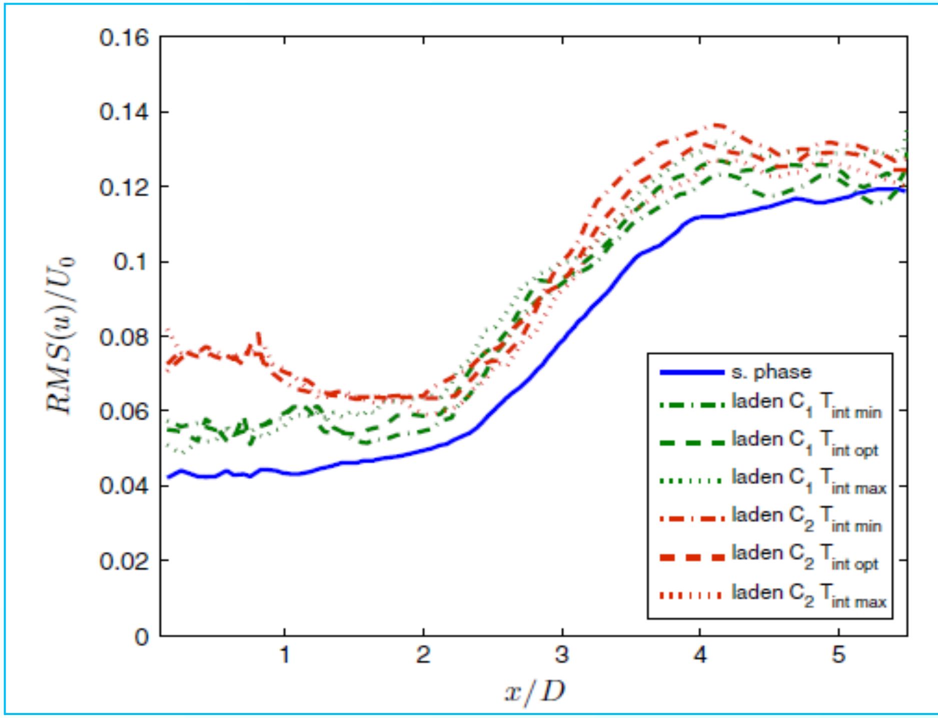
PIV:
mean field

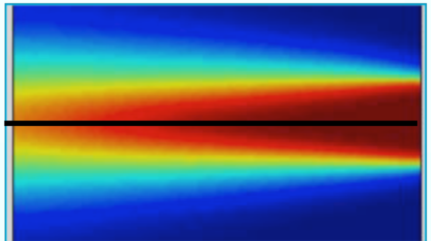


Non-spherical particles – multi-point measurements

Example: turbulent jet with fibers – effect on results

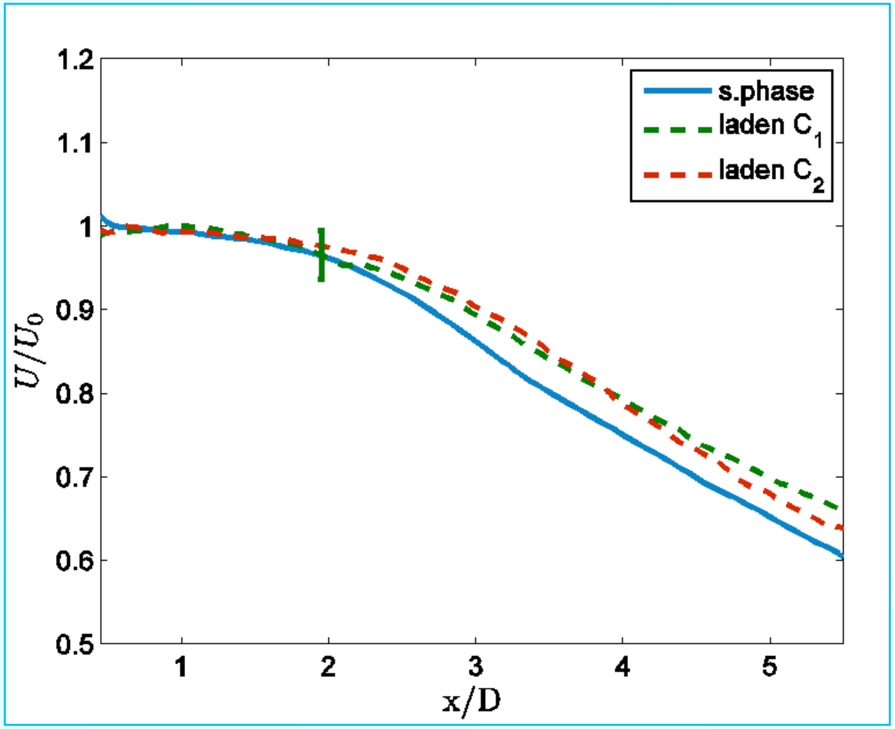


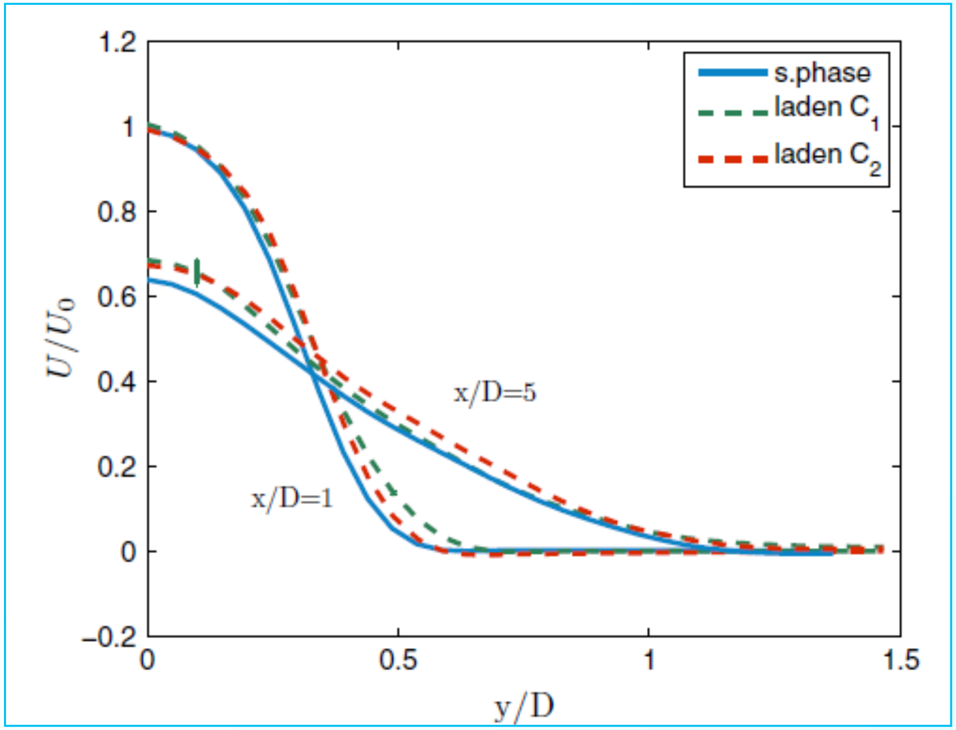


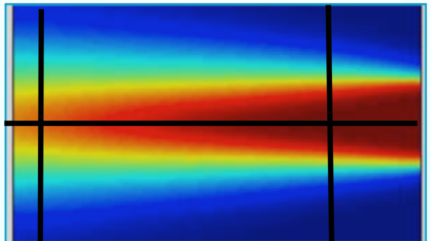


Non-spherical particles – multi-point measurements

Example: turbulent jet with fibers – overall mean field



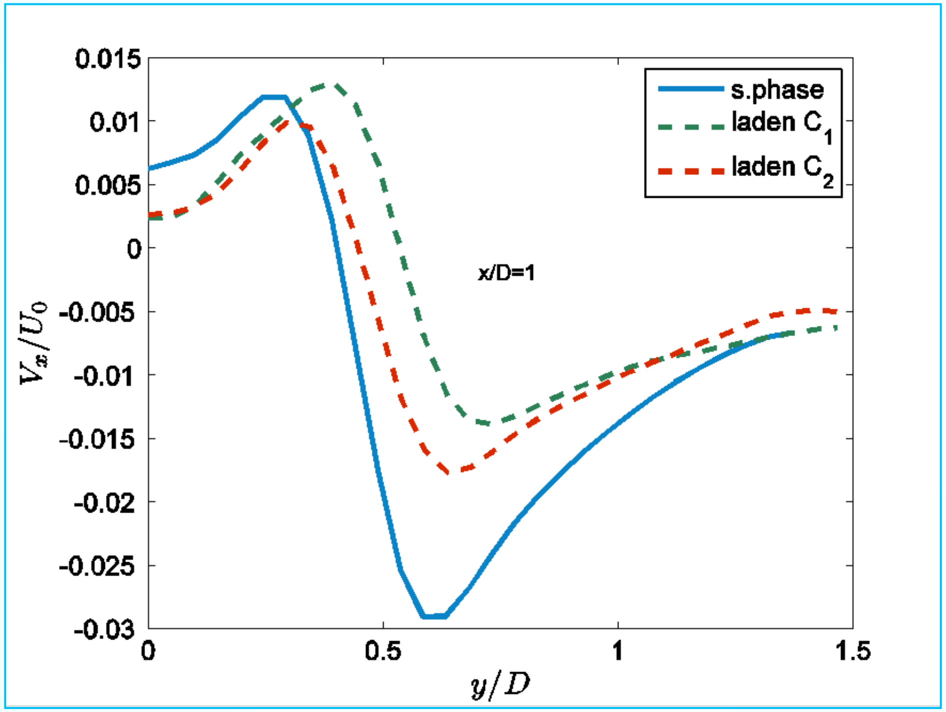


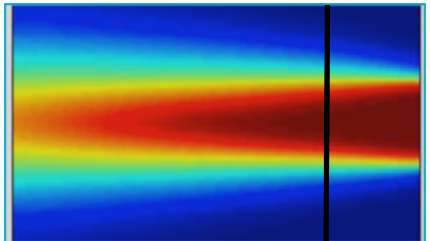


Fibers give smoother behaviours

Non-spherical particles – multi-point measurements

Example: turbulent jet with fibers – overall mean field

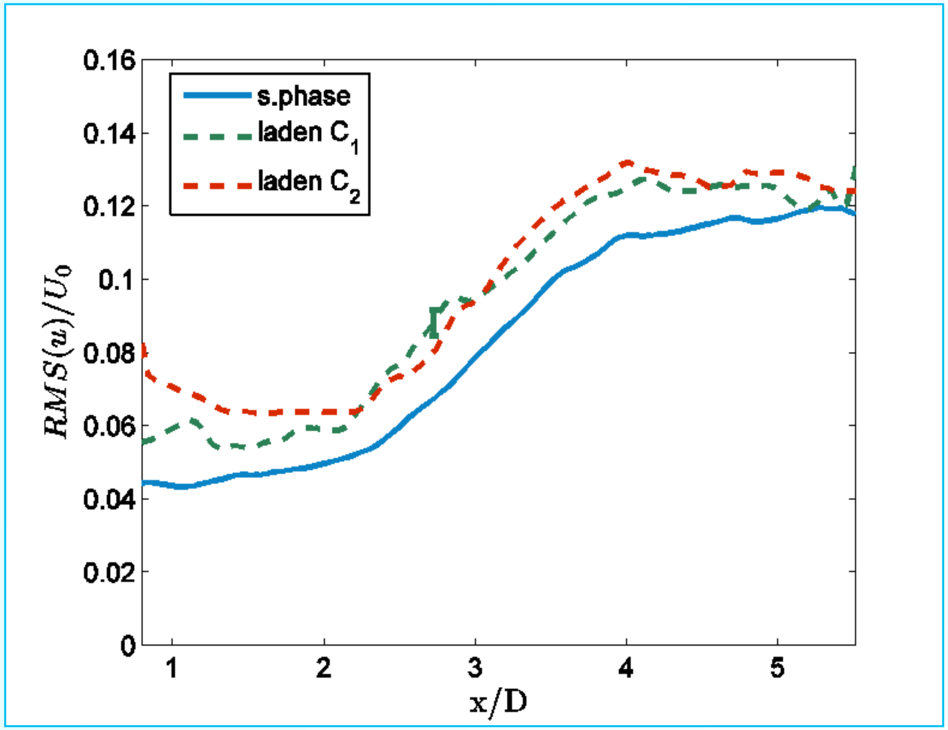


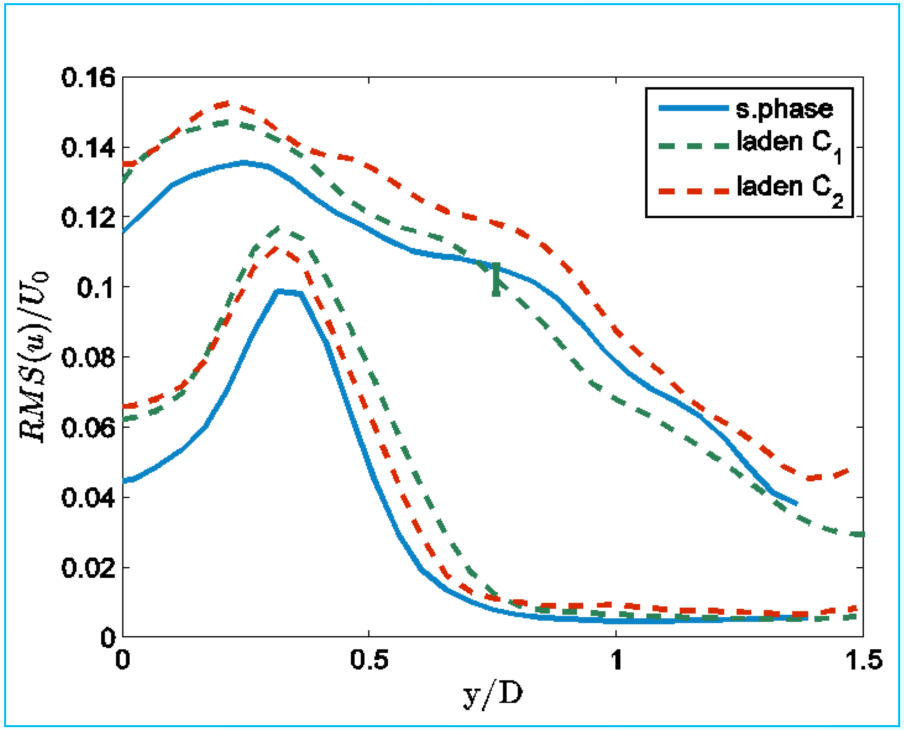


Vertical velocity does not increase

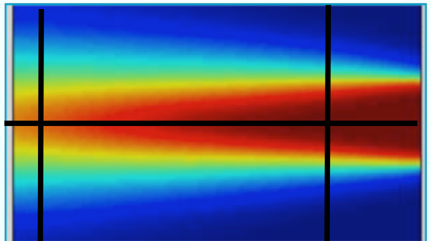
Non-spherical particles – multi-point measurements

Example: turbulent jet with fibers – rms overall field



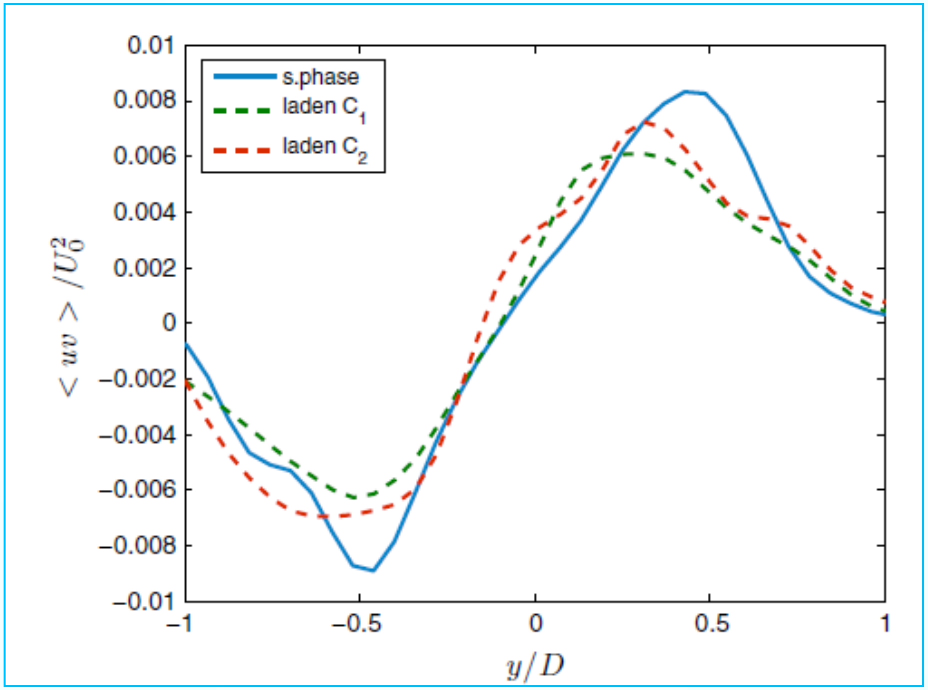


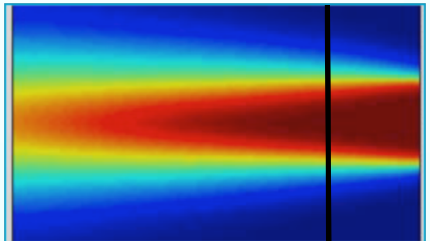
Turbulence enhancement within core region lower than spherical particles (Zoltani & Bicen, 1990)



Non-spherical particles – multi-point measurements

Example: turbulent jet with fibers – rms overall field

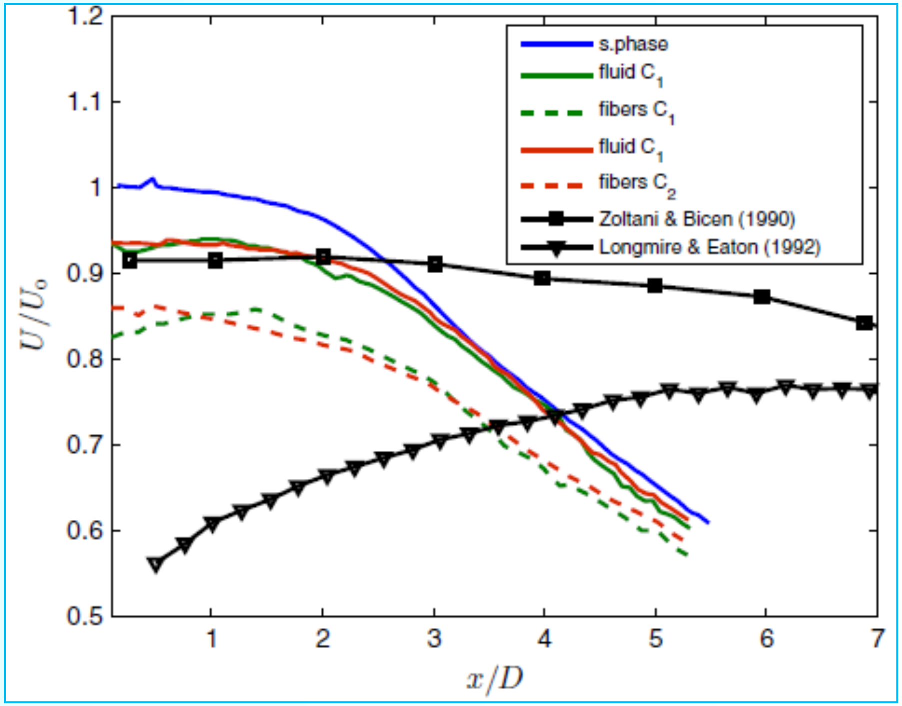


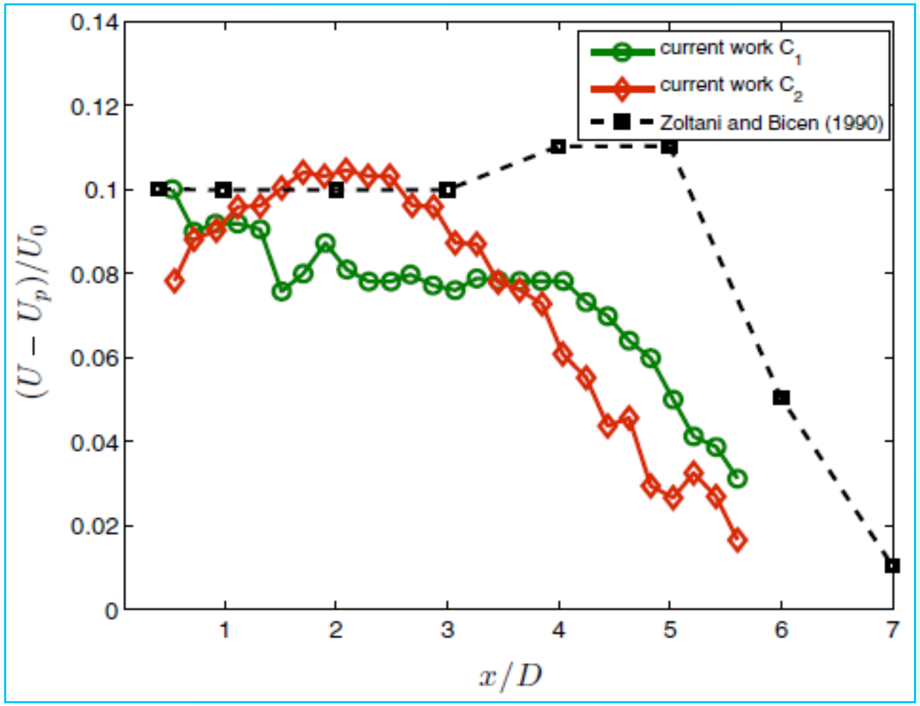


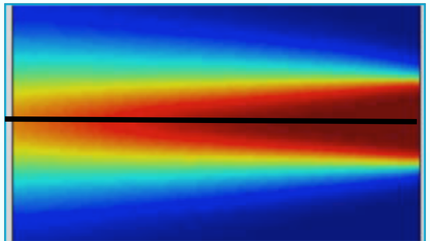
Reynolds stress attenuation
in shear layers

Non-spherical particles – multi-point measurements

Example: turbulent jet with fibers – fluid & fiber mean fields



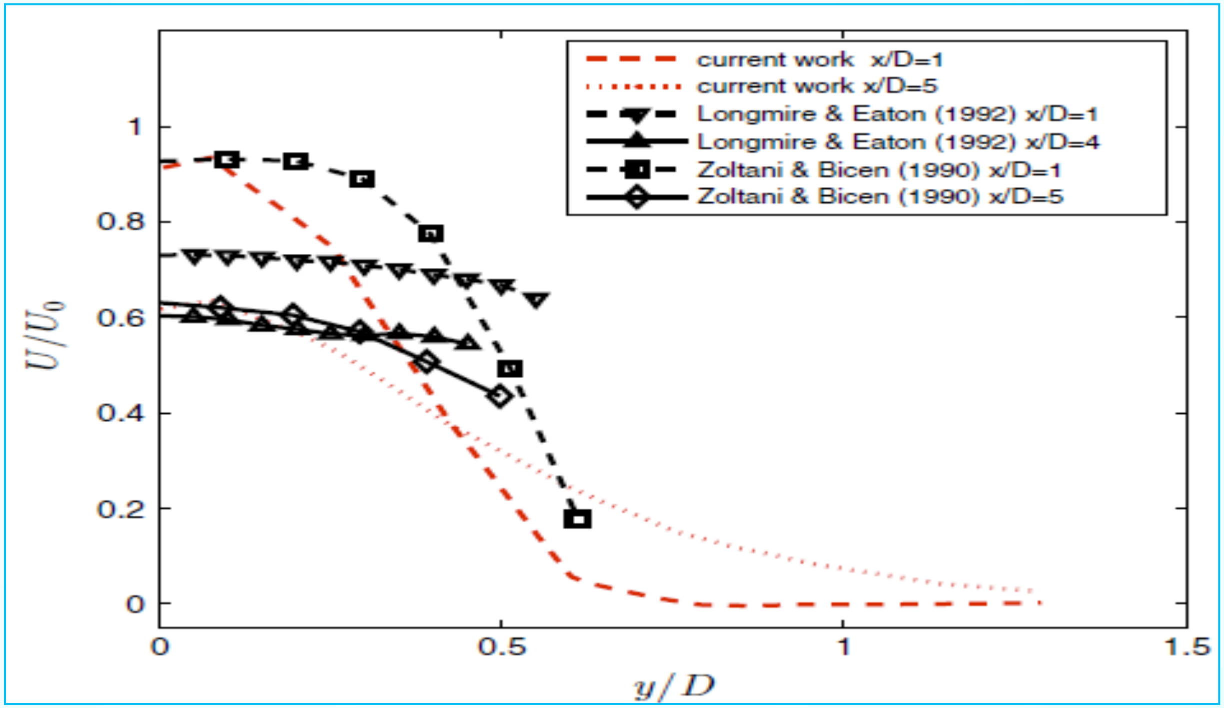




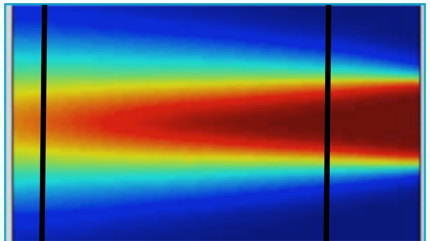
Higher slip-velocity,
faster recovery than spheres

Non-spherical particles – multi-point measurements

Example: turbulent jet laden with fibers – fiber mean field

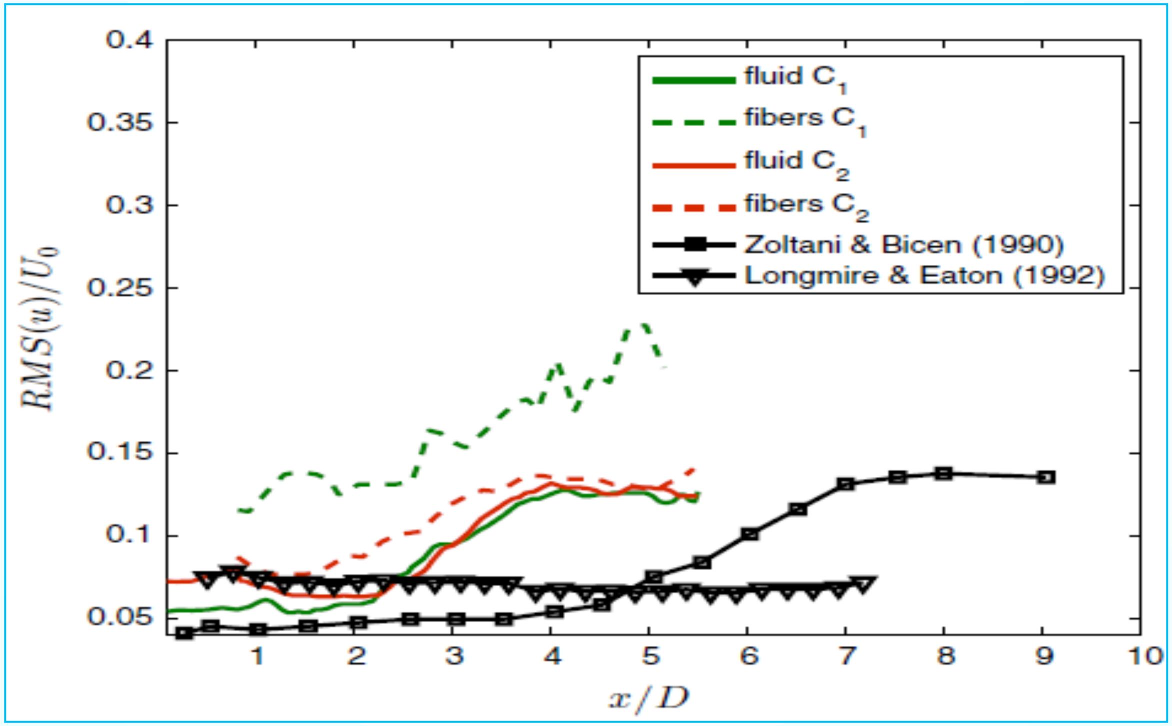


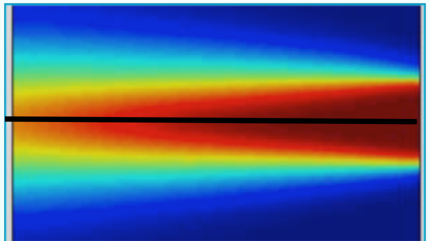
Fibers feature inertial effects as the jet spreads differently from spherical particles



Non-spherical particles – multi-point measurements

Example: turbulent jet laden with fibers – fiber rms field

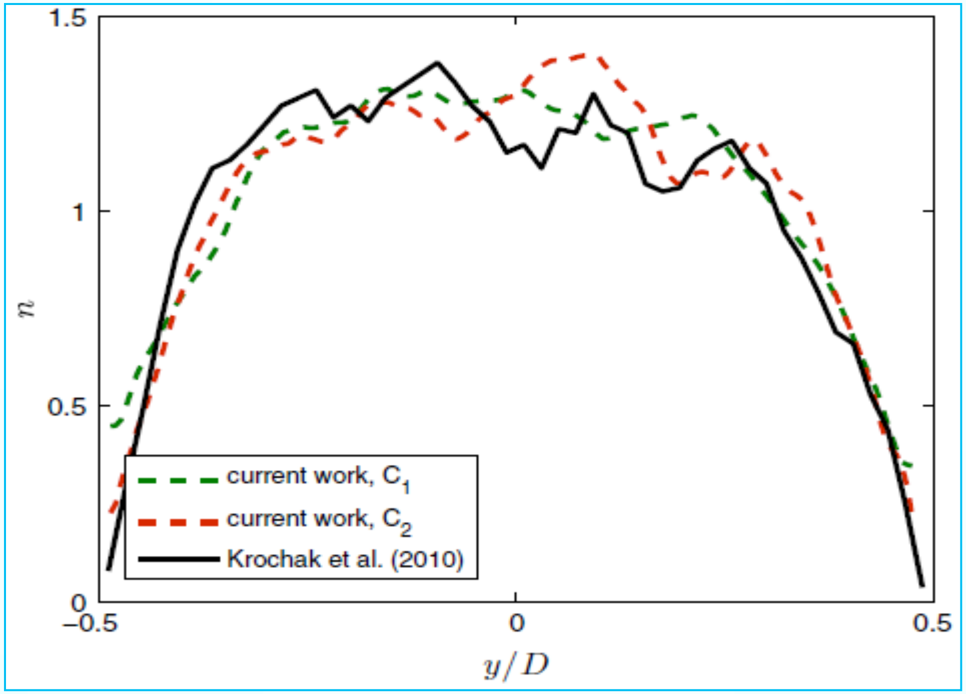


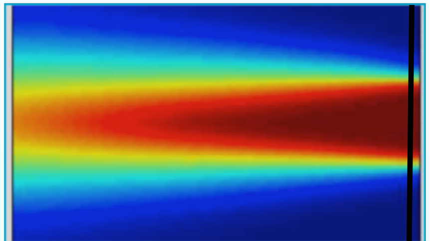


Fibers increase turbulence in comparison to fluid and spherical particles

Non-spherical particles – multi-point measurements

Example: turbulent jet laden with fibers – fiber concentration



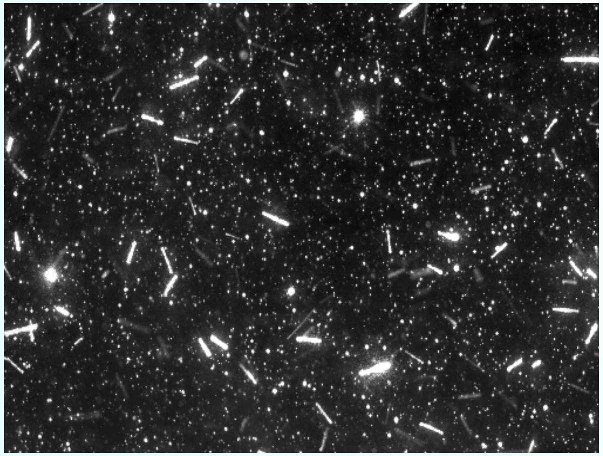


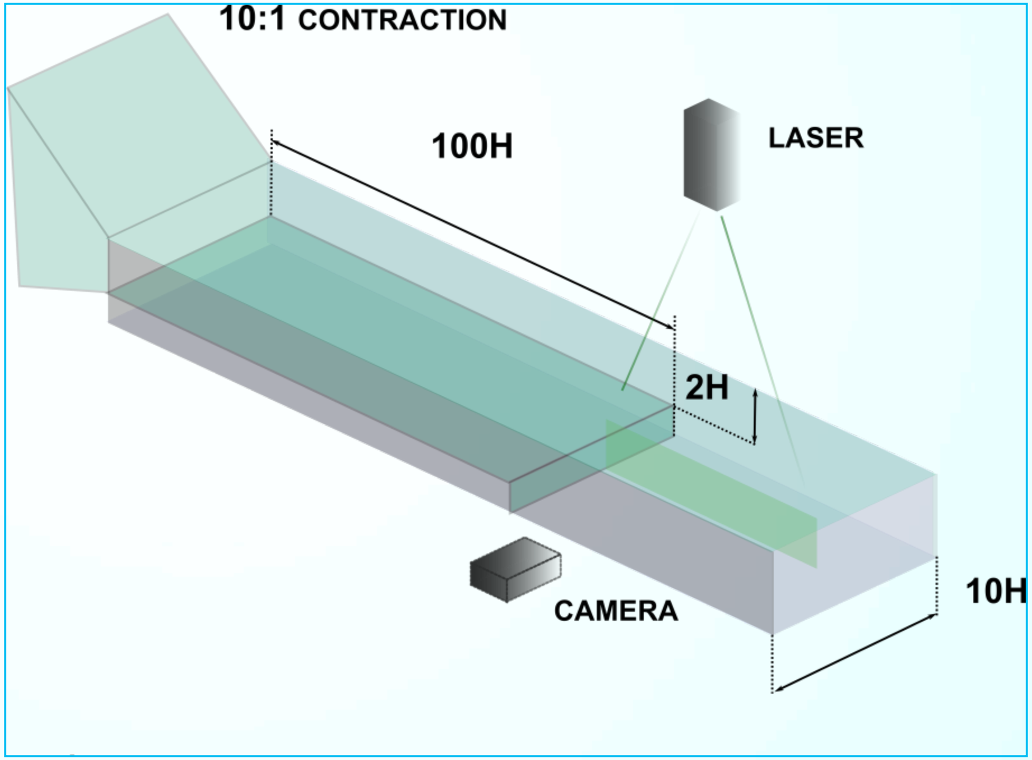
As in Krochak *et al*. 2010 (Poiseuille flow), fibers concentrate in low shear regions

Non-spherical particles – multi-point measurements

High spatial resolution: fibers NOT *eqv* to spheres

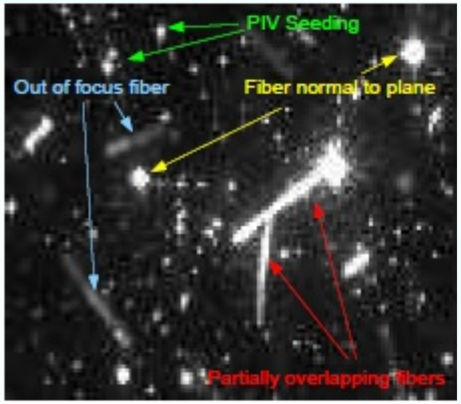
- Backward facing step
- Reynolds numbers 15000
- Stokes number ≈ 0.5
- Imaged region ≈ 1 cm
- Camera sensor 1024 pixel
- Spatial resolution ≈ 100 px/mm
- 1 fiber length ≈ 30 pixel

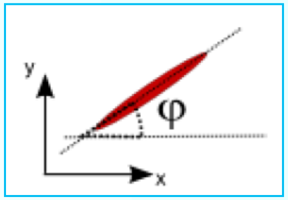




Non-spherical particles – multi-point measurements

High spatial resolution → orientation

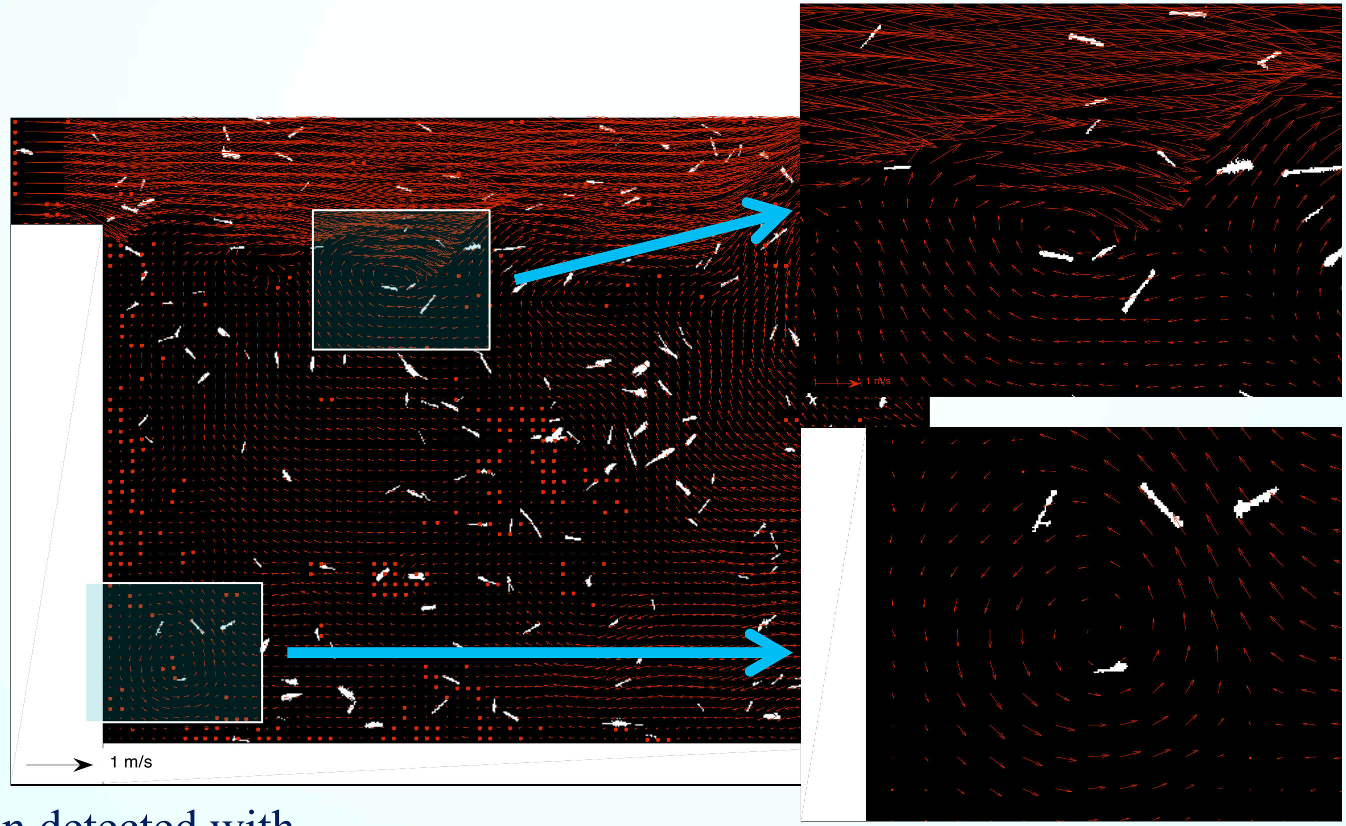




L=fiber length
D=fiber diameter

Non-spherical particles – multi-point measurements

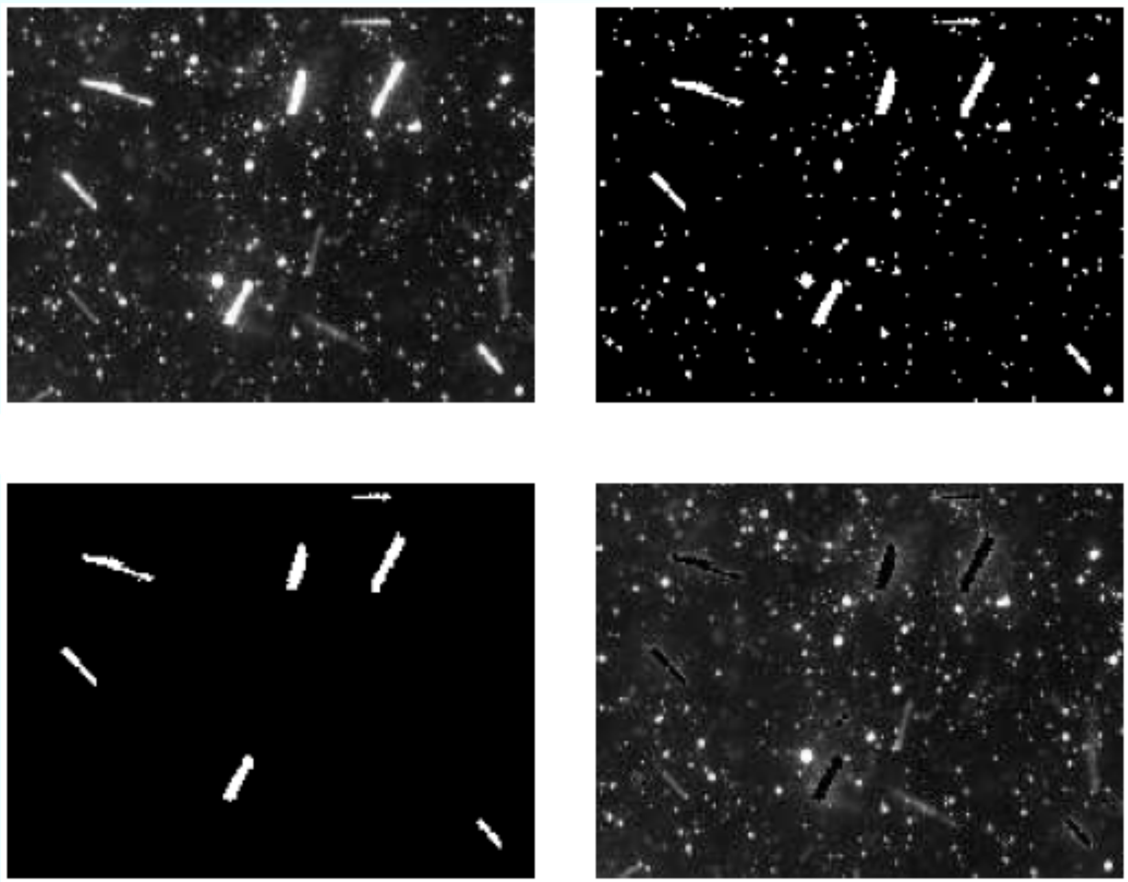
High spatial resolution ➡ orientation



Fibers orientation detected with
an ellipse-fitting algorithm Dearing *et al.*, 2015

Non-spherical particles – multi-point measurements

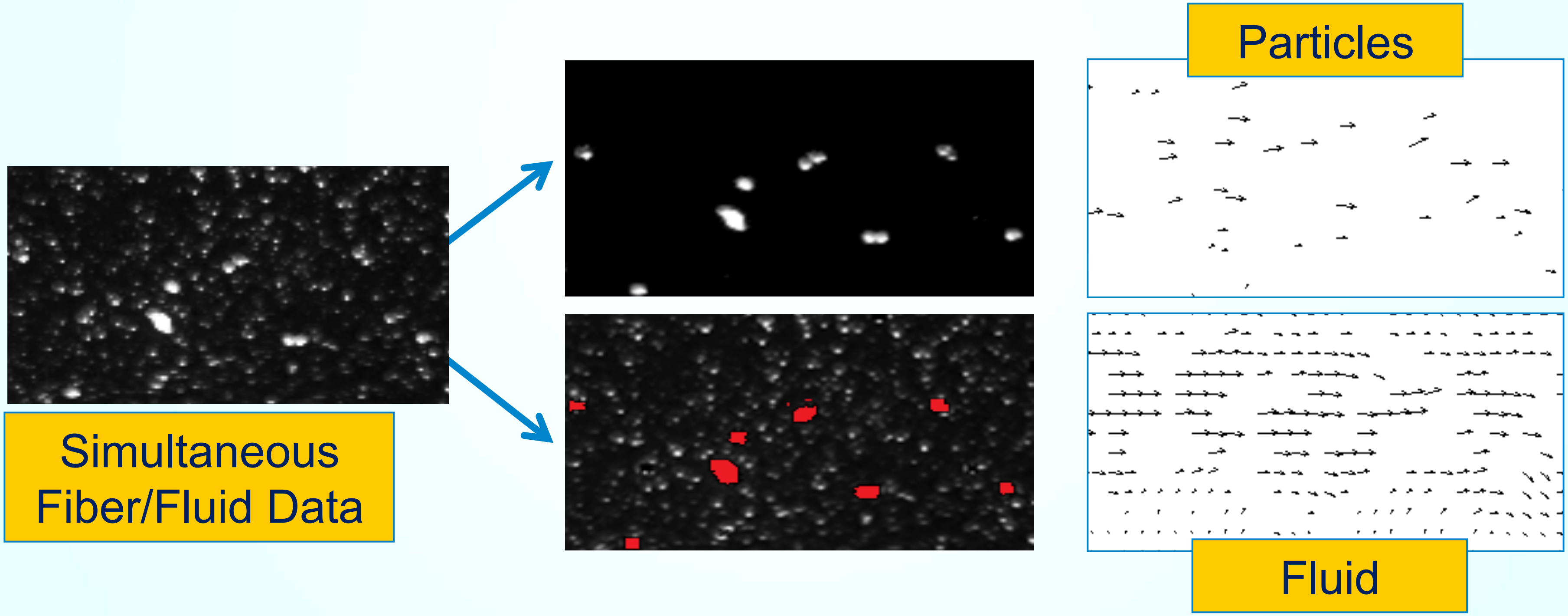
High spatial resolution → orientation



1) Image threshold + median filter 3×3
2) Ellipses labelled as “fibers” if
   $L/d>1.5$ and $L>9d_{tracer}$
3) Fibers subtracted from images
   → HOLES
4) Tracer processed with PIV
5) Fibers processed with
   Particle Tracking

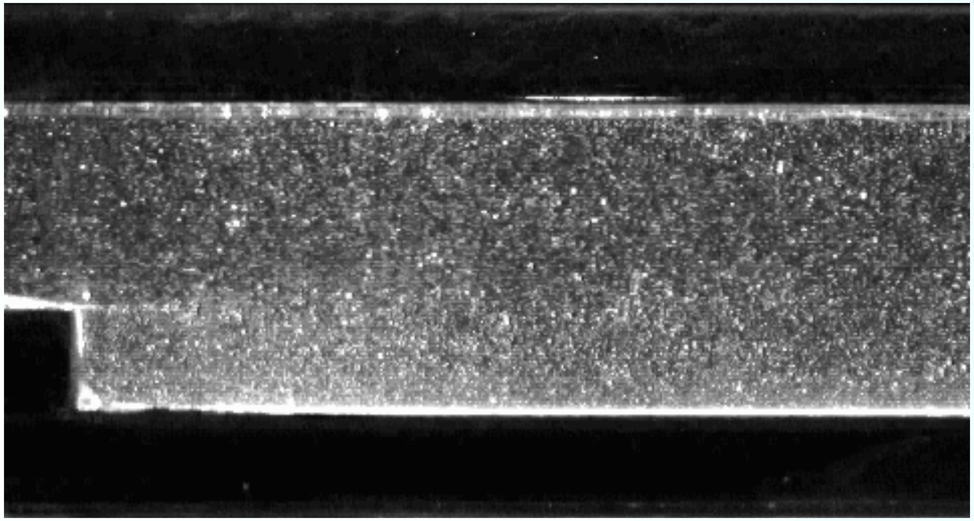
Non-spherical particles – multi-point measurements

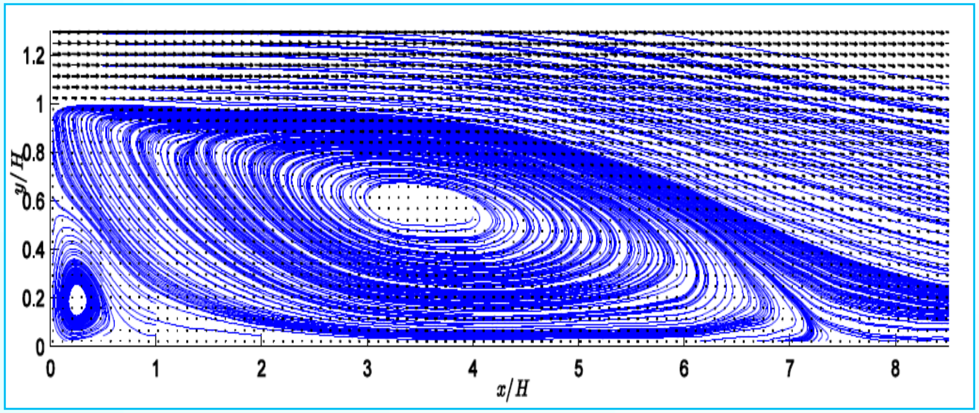
High spatial resolution → orientation



Backward facing step

PIV: **Image Acquisition**





PIV: **mean field**

Backward facing step

PIV: mean and rms fields

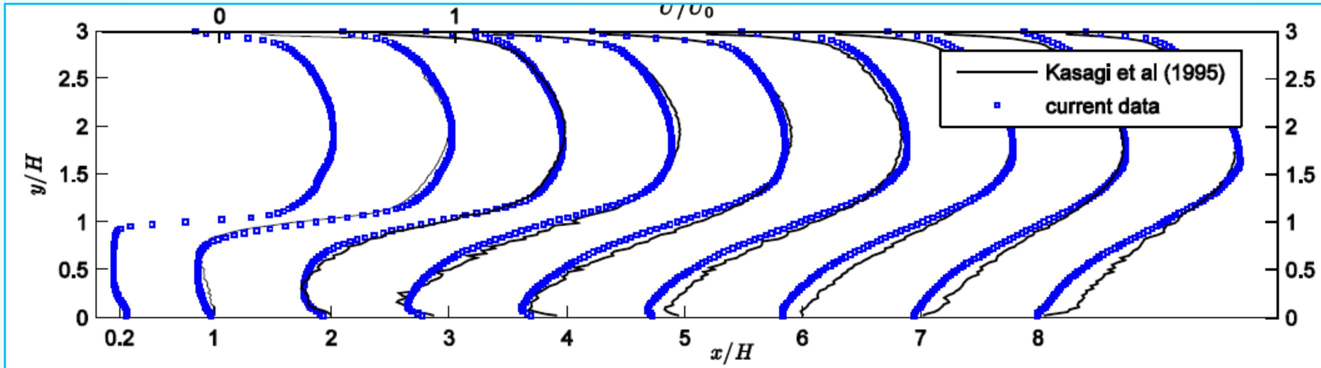


Figure 6. Single phase flow, mean streamwise velocity compared to Kasagi and Matsunaga [23] data downstream of the step.

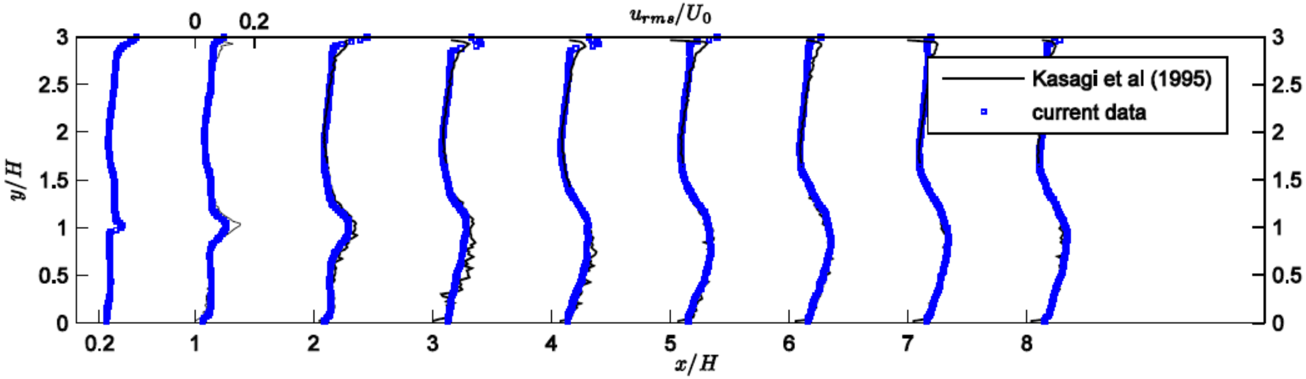
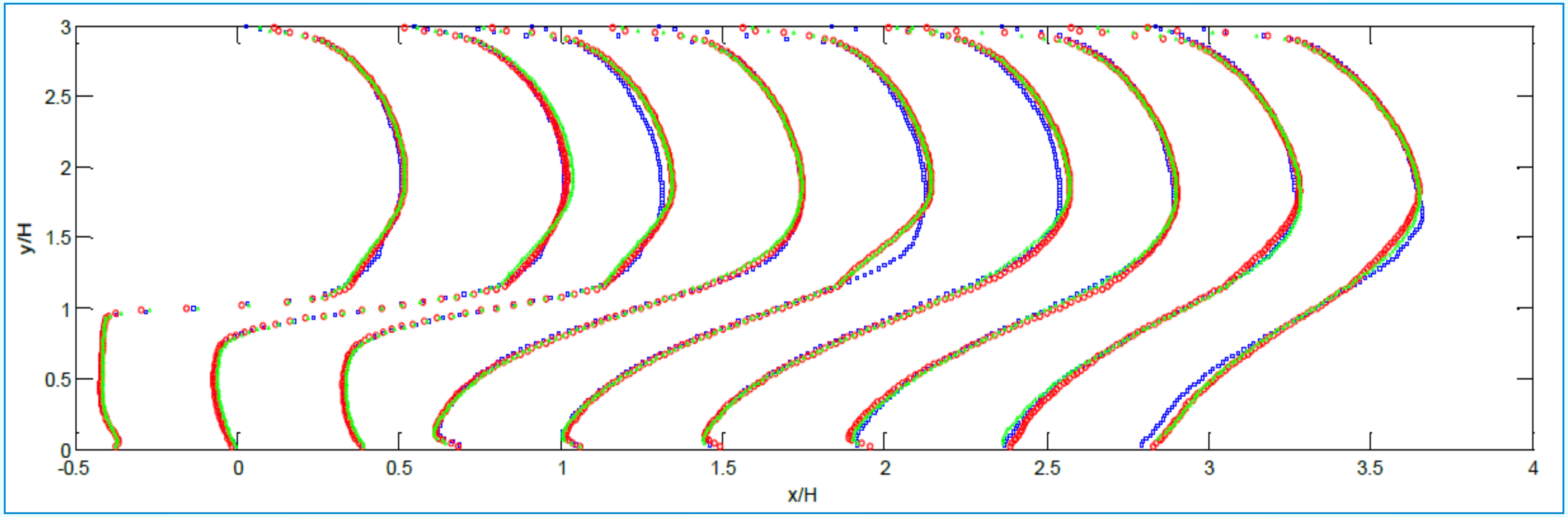


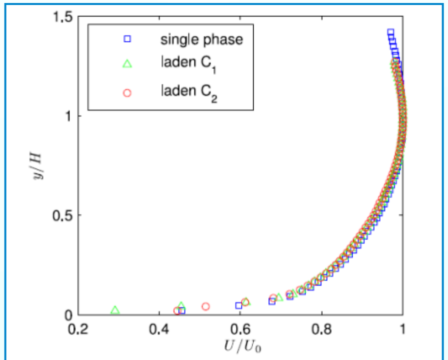
Figure 7. Single phase flow, RMS of streamwise velocity compared to Kasagi and Matsunaga [23] data downstream of the step.

Non-spherical particles – multi-point measurements

Example: BFS with fibers – overall mean field



downstream

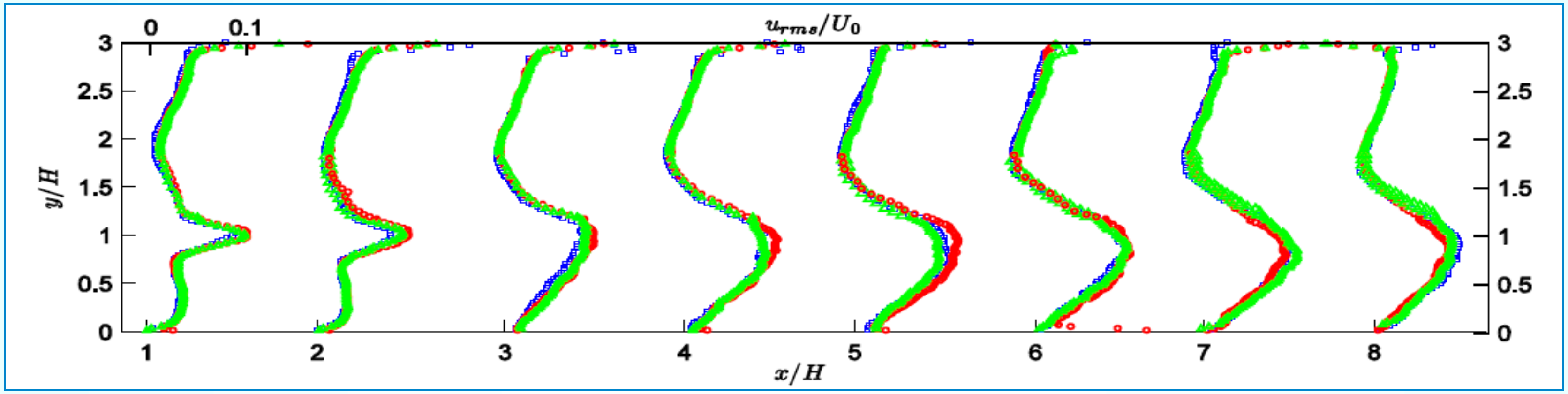


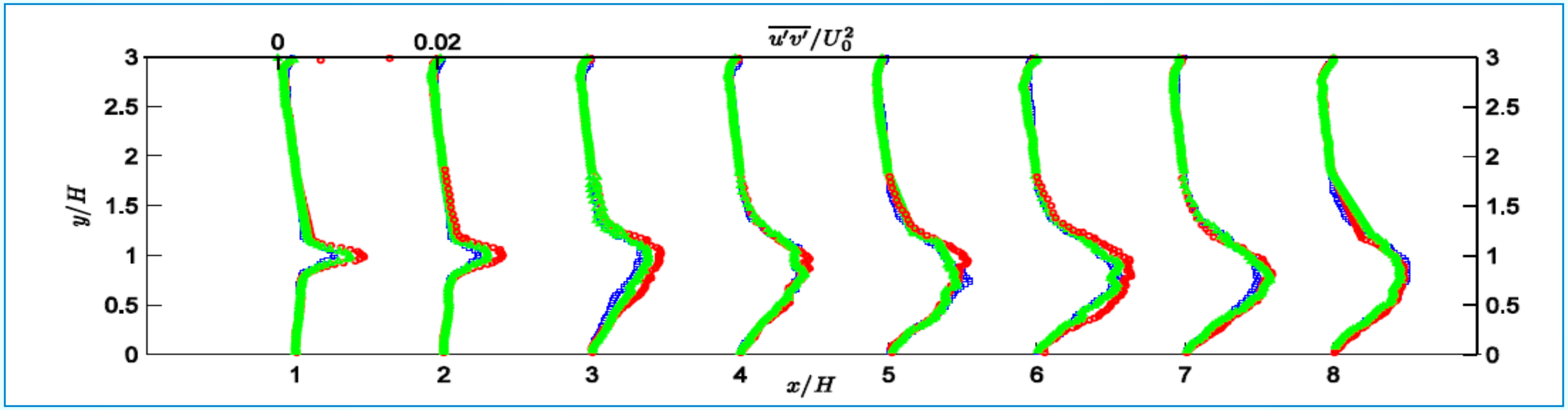
upstream

no noticeable effect
on the mean field

Non-spherical particles – multi-point measurements

Example: BFS with fibers – overall rms field



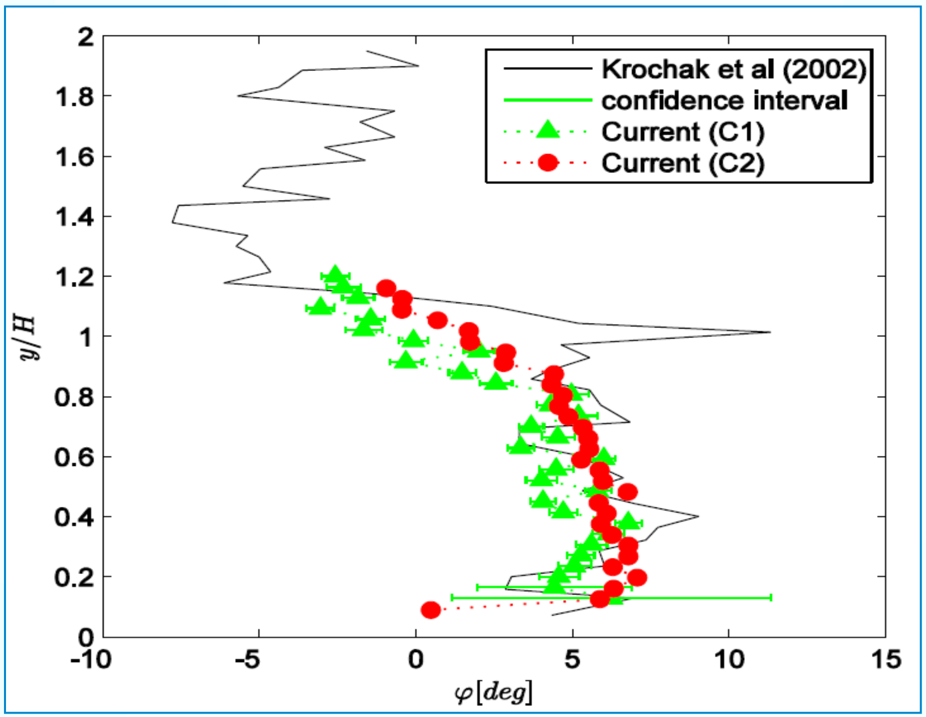


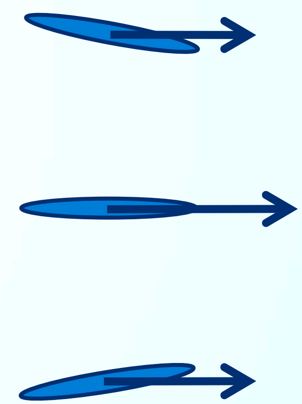
slight increase in turbulence

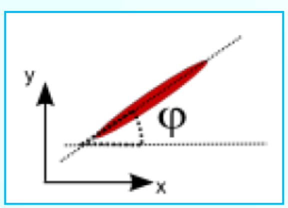
Non-spherical particles – multi-point measurements

Example: BFS with fibers – fiber orientation

upstream



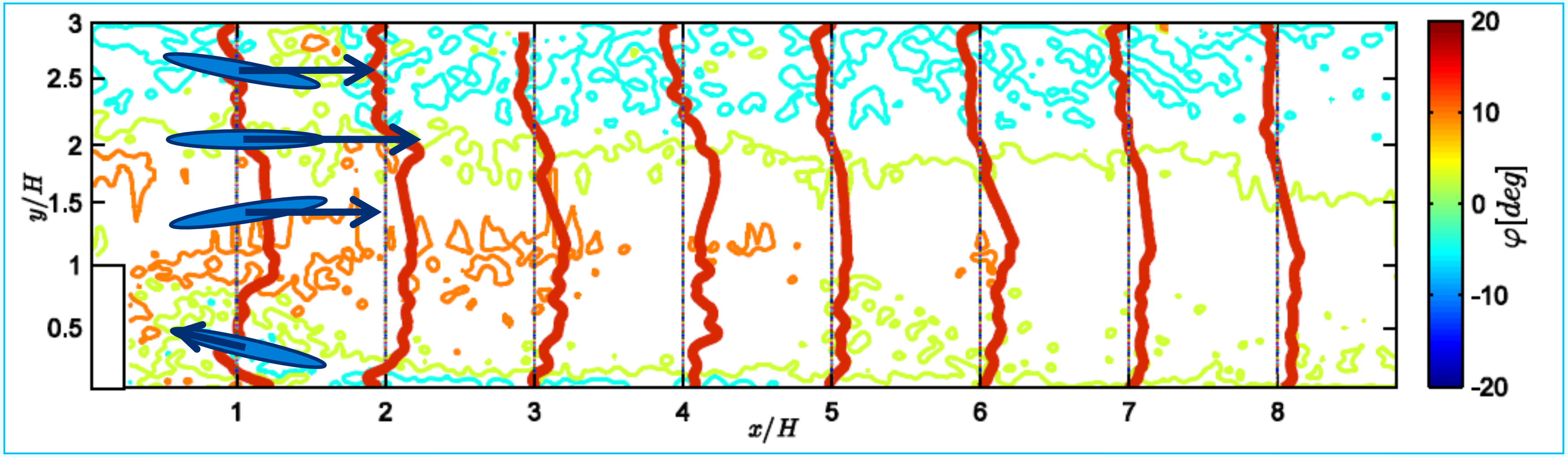




agreement with Poiseuille flow data

Non-spherical particles – multi-point measurements

Example: BFS with fibers – fiber orientation

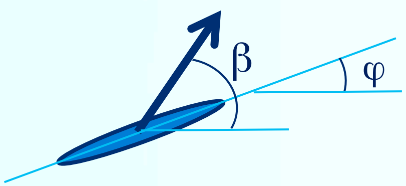


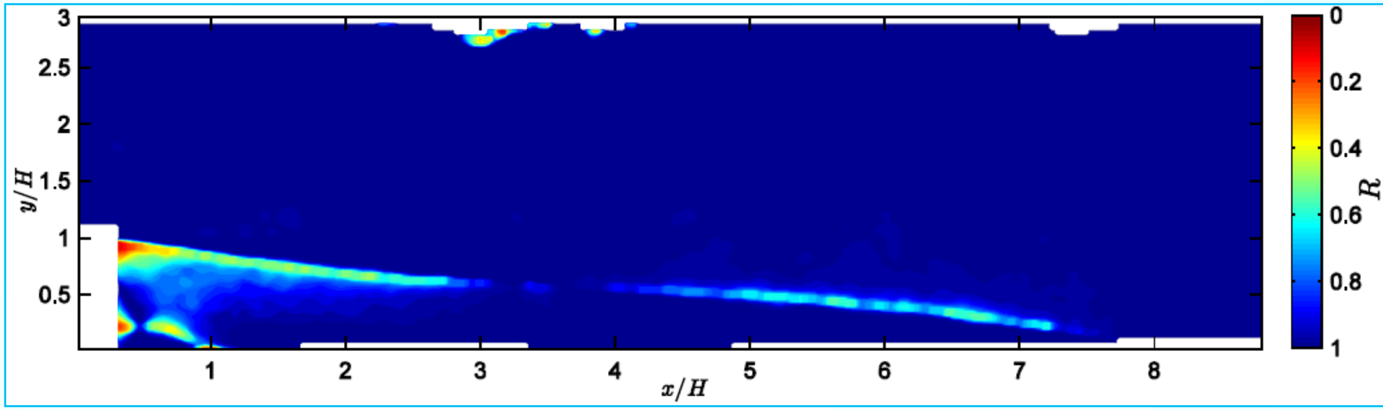
agreement with upstream flow data
correlation with with local velocity ?

Non-spherical particles – multi-point measurements

Example: BFS with fibers – fiber orientation

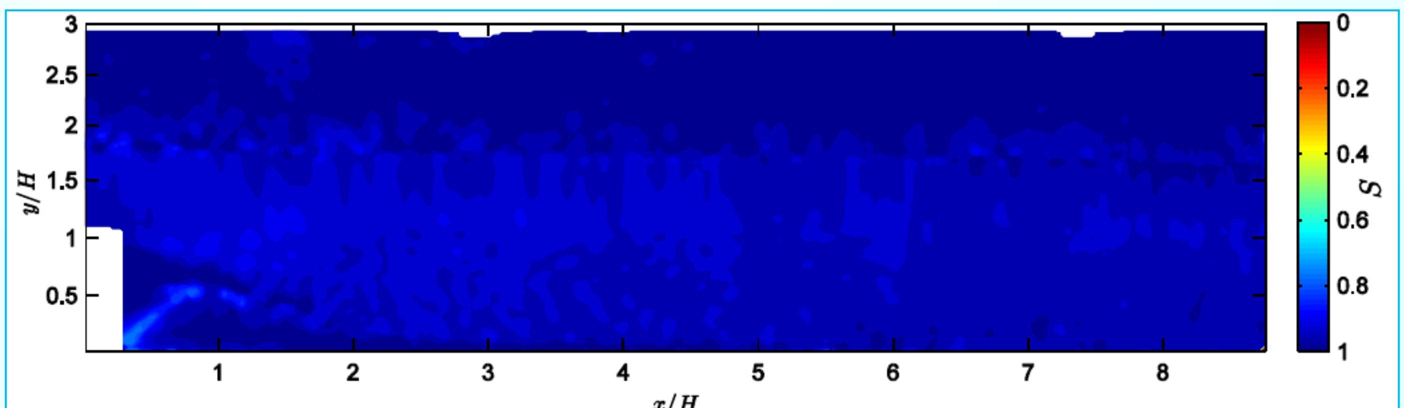
$$R = \frac{|\cos \beta|}{\cos \varphi}$$





$$S = \frac{|\cos \theta|}{\cos \varphi}$$

$$\tan 2\theta = -\frac{(\sigma_x - \sigma_y)}{\tau_{xy}}$$



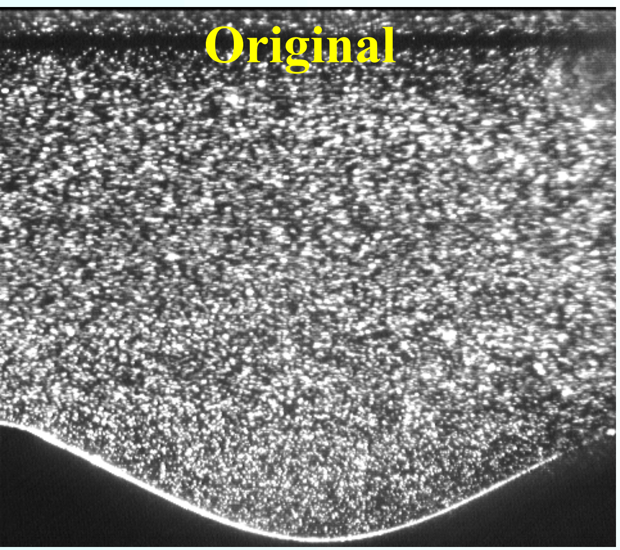
fibers not aligned perfectly with local velocity, rather they align with plane of maximum shear

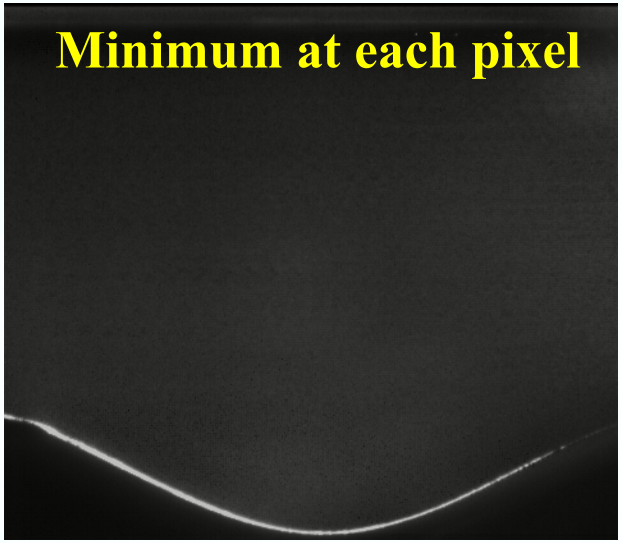
Image Pre-processing

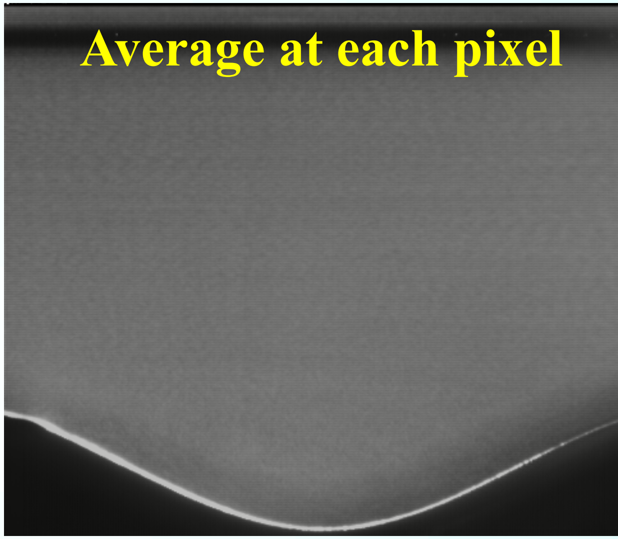
Large scale noise

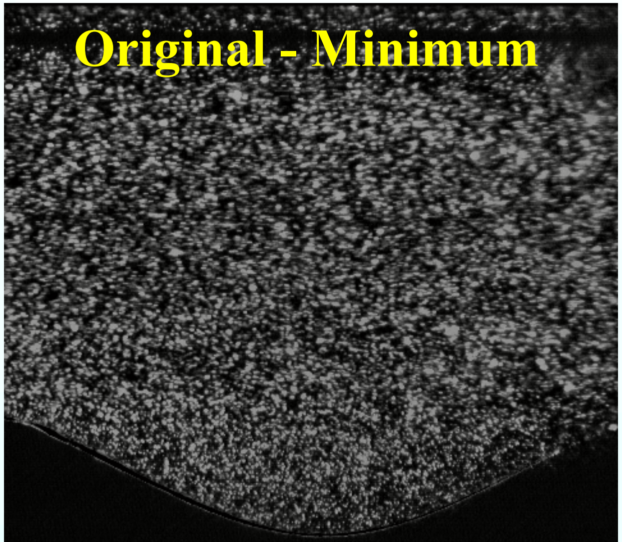
↓

Avoiding light reflections









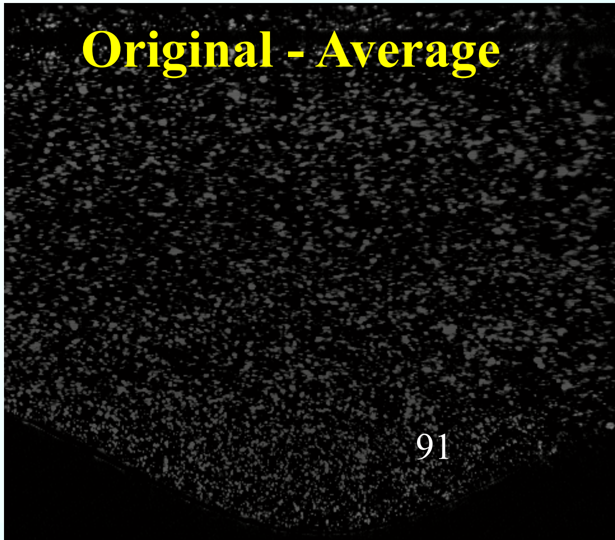


Image Pre-processing

Another example in a very noisy + geometrically complex test section

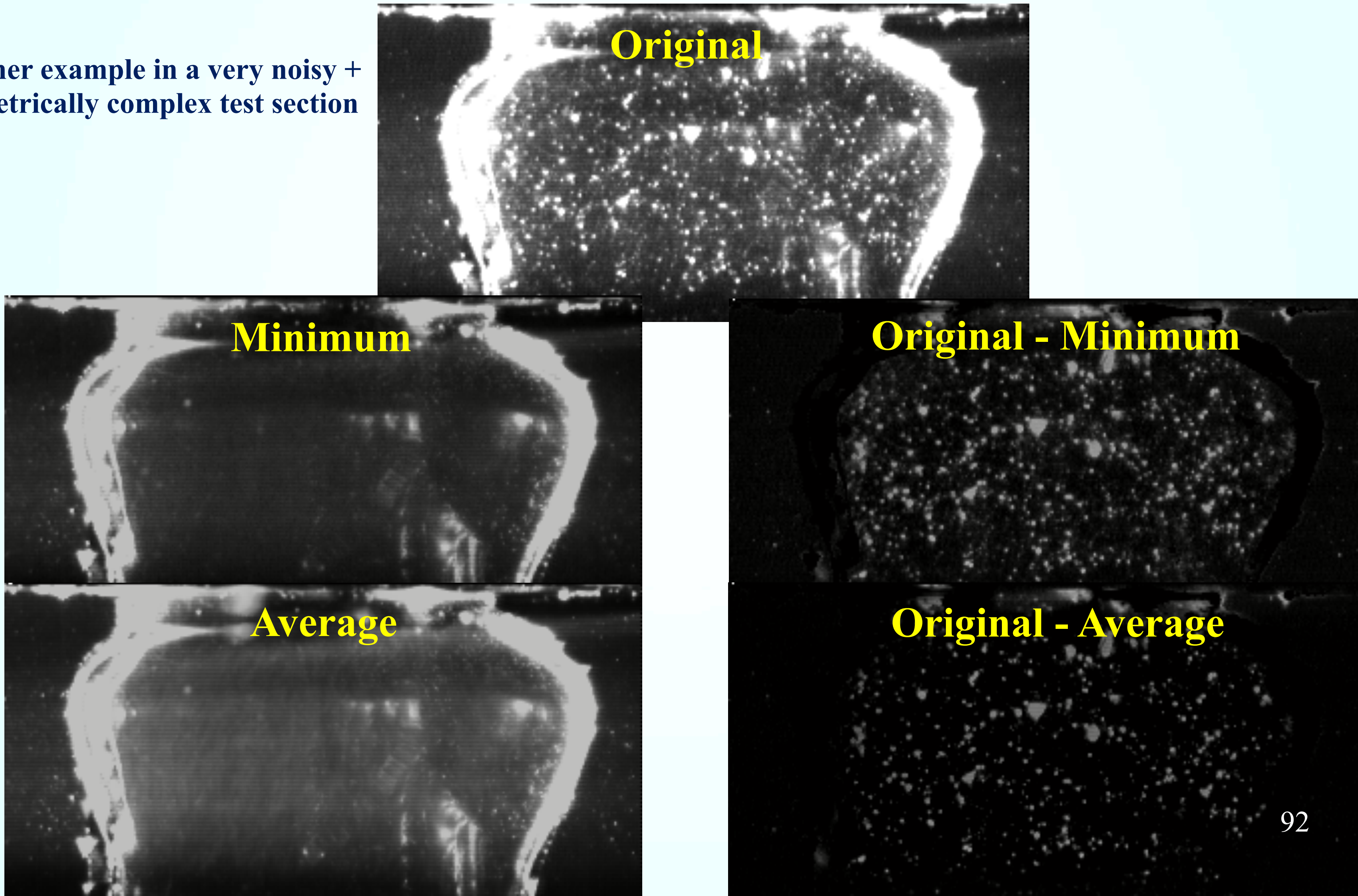
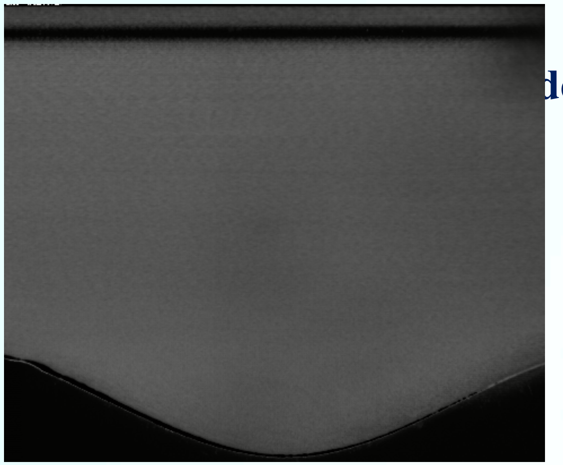
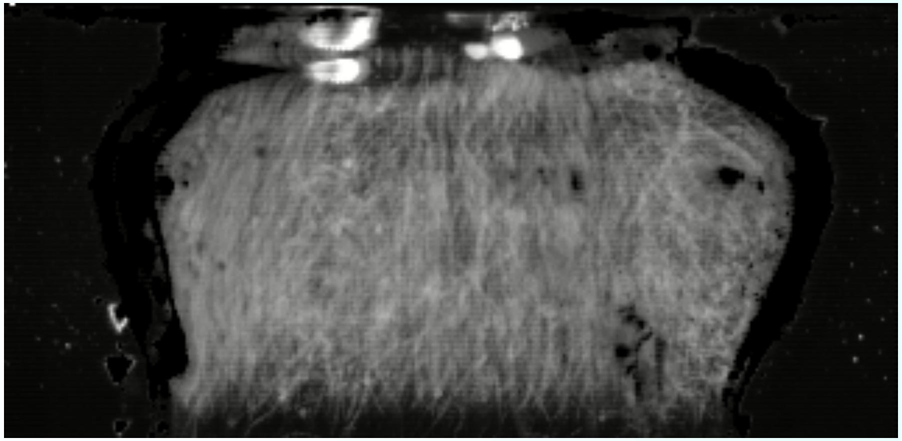


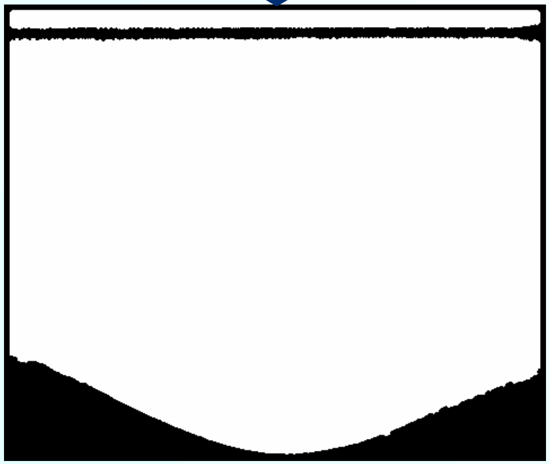
Image Pre-processing



Automatic
determination
of a mask

Std Dev.
Light intensity





Threshold
on Std Dev.

Remarks

- Tracers & particles

Use of optical techniques: the problem of tracers

Light scattering by particles: position and distance

Low concentration and size: follow the fluid without disturbing

-Single-point measurements

Spherical particles: Phase Doppler

Non-spherical particles: Shadow Imaging

- Multi-point measurements

Spherical particles: Global Phase Doppler & Interferometry

Non-spherical particles: Shadow Imaging & Image Analysis

Low spatial resolution: phase discrimination complex

High spatial resolution: orientation

Italian Foodscapes

Italian Foodscapes