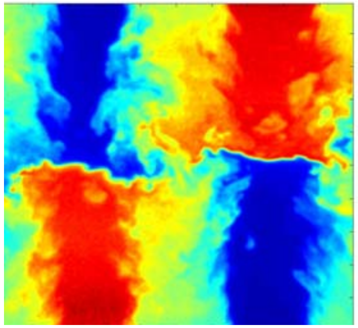
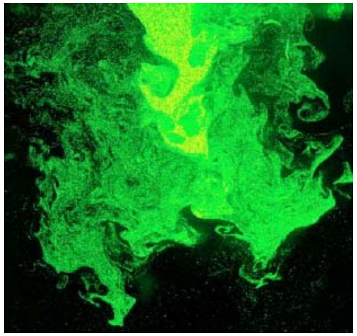
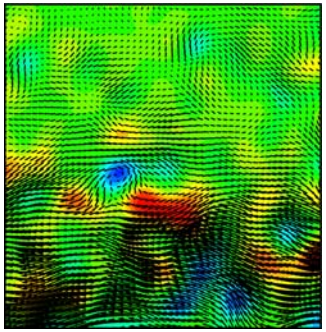
Towards two-dimensional measurements of small scales (scalar and velocity) : principles and limitations. Applications for laminar and turbulent flows

Bruno Renou
renou@coria.fr







CORIA, UMR 6614
INSA de Rouen
76801 Saint-Etienne-du-Rouvray
FRANCE

Introduction

Objectives = Accurate measurements of $\nabla \underline{u}$ and ∇Z by 2D optical diagnostics

Questions :

① Interest of spatial gradient measurements ?

- Fundamental quantities in turbulence/combustion/mixing process …

$\rightarrow$ dissipation, vorticity, …

② Are we able to measure scalar and velocity gradients ?

$\rightarrow$ Spatial resolution of such techniques *vs.* the different length scales ?

③ Are the 2D optical diagnostics well adapted for such measurements ?

Introduction

Why laser diagnostics for velocity and scalar gradient ?

-Non intrusive (or semi-intruive) : access and fluid perturbation

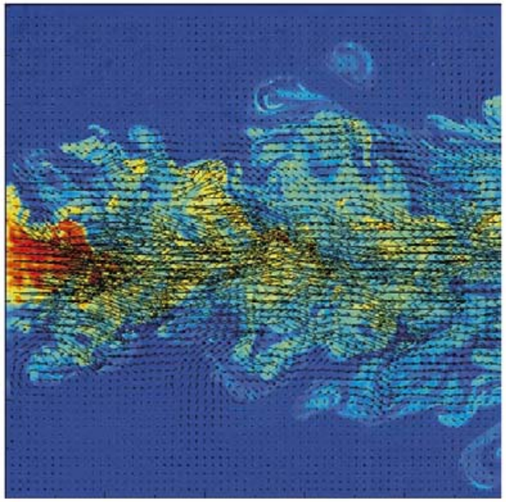
-High spatial resolution (up to 0.2 mm)

-High temporal resolution (~10 ns)

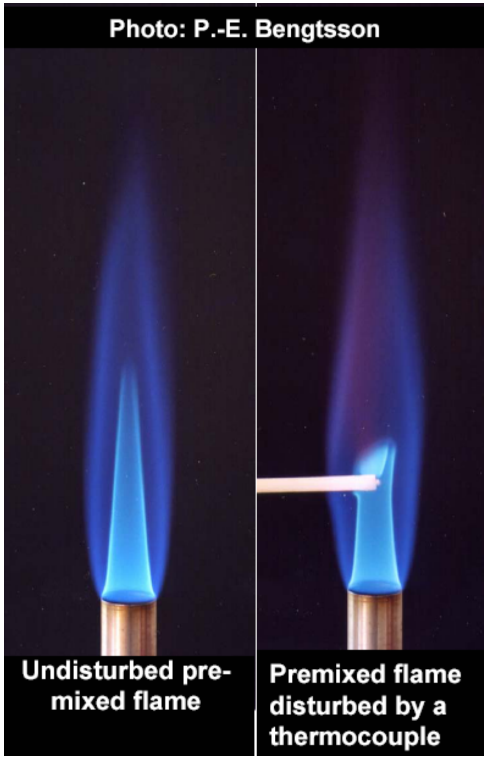
-Simultaneous measurements (2 scalars, velocity, ...)

-Large range of scalar measurements (Temperature, concentrations : NO, acetone, radicals, ...)

- Visualisation of the flow motion



Simultaneous scalar and velocity fields measurements in a turbulent jet



Introduction : Which techniques ?

Principle of laser diagnostics :

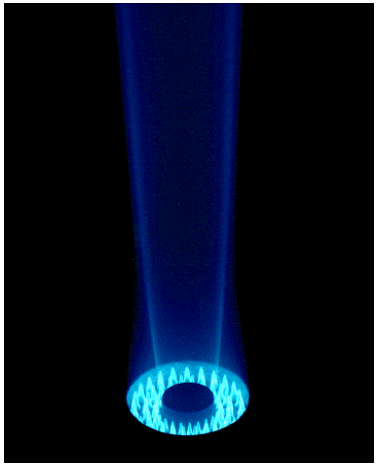
Measure
- Technique
- Operating conditions
- …

Analyse
-Post processing
- Accuracy
- …

Predict
-Experimental results
-Data bases
- Flow phenomena
- …

Temperature
- Heat release

Flow field
-Flow motion
-Turbulence statistics



Chemical species
- Mixing process
- Radical species (OH, ..)
- Combustion products

Structure – Topology
- fractal behavior
-…

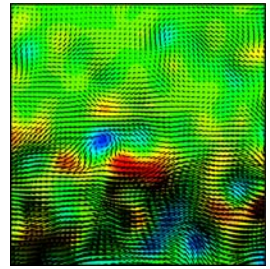
Ideal experiment:
- 3D
- time resolved
- multiple quantities

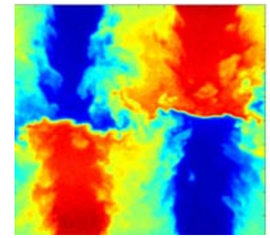
Impossible!

Introduction : Which techniques ?

Velocity and scalar measurements :

- Particle Image Velocimetry (PIV)
- Planar Laser Induced Fluorescence (PLIF)
- Rayleigh Scattering





Main characteristics :

- Flow illumination (Laser)
- Interaction between light and particles or molecules (scattering process)
  - ➢ Elastic scattering ($\lambda_{inc} = \lambda_{scat}$)
  - ➢ Non-elastic scattering ($\lambda_{inc} < \lambda_{scat}$)
- Interaction with particles ⇨ **Mie scattering** ($\phi_{part} > \lambda_{inc}$)
- Interaction with molecules ⇨ **Rayleigh scattering** ($\phi_{part} < \lambda_{inc}$)

FLOW SEEDING

Introduction : Small scales

Resolution requirement in fluid flows ?

Measurement probe :

- sufficient spatial resolution λ_R ← 2D optical diagnostics
- sufficient temporal resolution τ_R

→ λ_R should be smaller than the "**smallest scales"** of the spatial fluctuations of velocity and scalar

Classical approach :

Kolmogorov length scale λ_K = finest vorticity scale

$$\lambda_K \equiv \left(\frac{\nu^3}{<\varepsilon>}\right)^{1/4}$$

Batchelor length scale λ_B = finest concentration scale

$$\lambda_B \equiv \left(\frac{\nu D^2}{<\varepsilon>}\right)^{1/4}$$

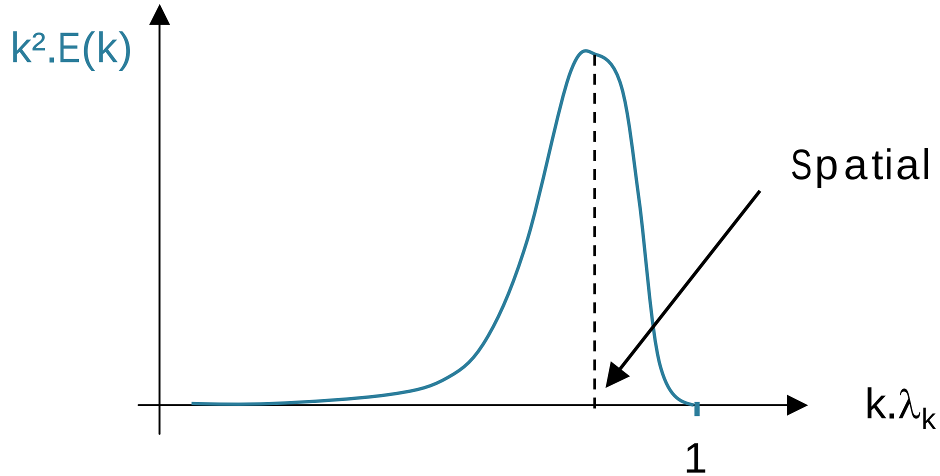
Finest scale = smallest scale at which velocity or scalar variation can occur

Resolution requirements : $\lambda_R < \lambda_K , \lambda_B$

$$\lambda_B = \lambda_K Sc^{-1/2}$$

→ **restrictive conditions !**

Introduction : Small scales



"Strain-diffusion" approach :

Inner viscous velocity scale $\lambda_v = \Lambda_K \,.\, \lambda_K$ where Λ_K is a constant

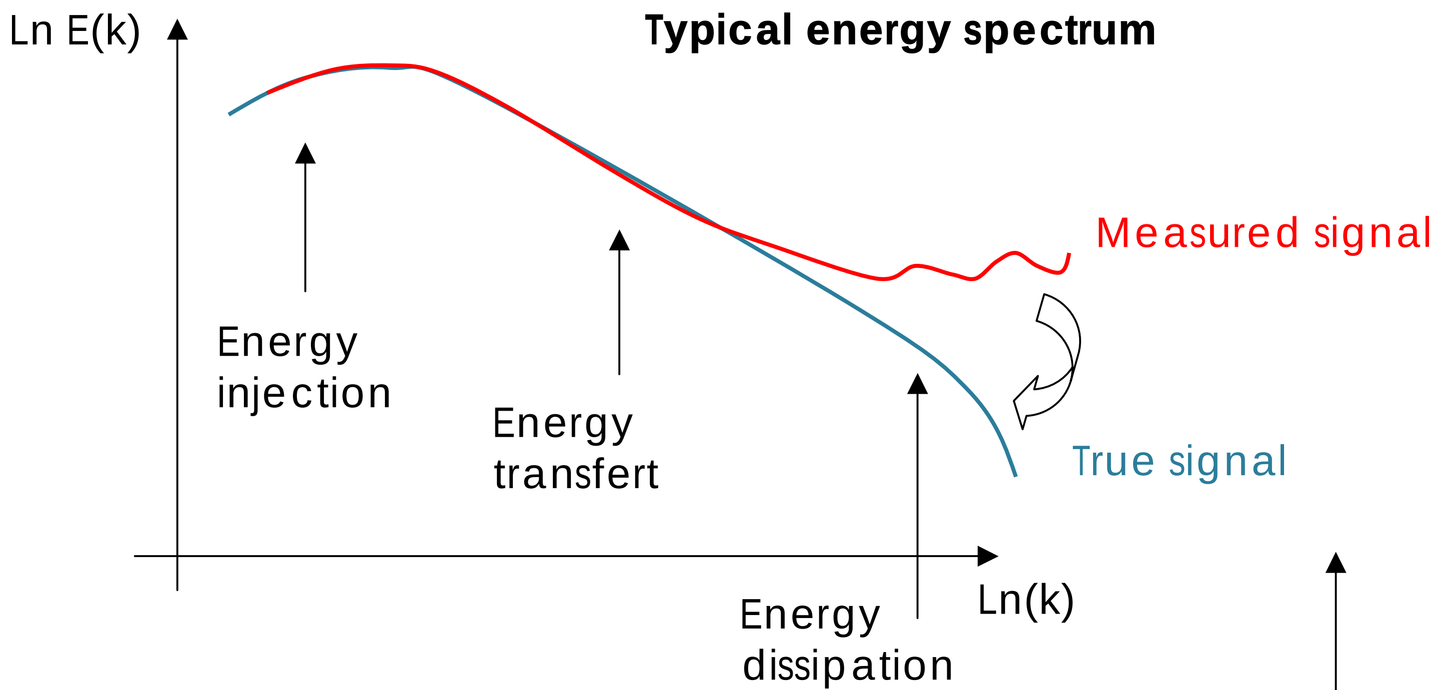
Inner viscous scalar scale $\lambda_D = \Lambda_B \,.\, \lambda_B$ where Λ_B is a constant

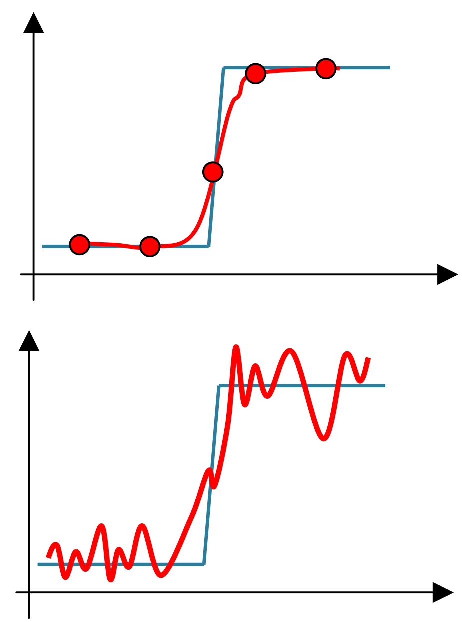
= Scales for which the action of mass diffusion (or viscosity) becomes important

Smallest scale of which velocity or scalar gradient can be sustained (Buch and Dahm, 1996 ; Su and Clemens, 2003)

With such approach : resolution requirements : $\lambda_R < \lambda_v , \lambda_D$

Introduction : Drawbacks and Cautions





3 limitations :

- Spatial resolution ⇨ decrease of scalar and velocity gradient
- Noise ⇨ increase of scalar and velocity gradient
- Derivative schema ⇨noise addition ?

Introduction : Contents and Objectives

Spatial velocity gradient measurements : PIV

- Principles and limitation of PIV technique
- Noise and spatial resolution estimation
- Derivative schema : optimization ?
- Accurate spatial velocity gradient measurement ?

Spatial scalar gradient measurements

- Principles and limitation of PLIF and Rayleigh scattering
- Noise and spatial resolution estimation
- Optimal data filtering

Illustrations and perspectives

- Laminar flame thickness measurement
- Quantitative measurements of molecular mixing
- Strain tensor analysis by DPIV

PIV : Principles

What is PIV ?

- PIV = Particle Image Velocimetry
- Two-dimensional and instantaneous measurement of flow velocity (u,v,**w** components)

Interests ?

-Large scale flow visualization (≠ 1D technique)

• *Industrial burner (swirl), Flow motion in car engine (tumble)*

- Technological progress during the 1990's

•Laser (*ex : Nd:YAG*)

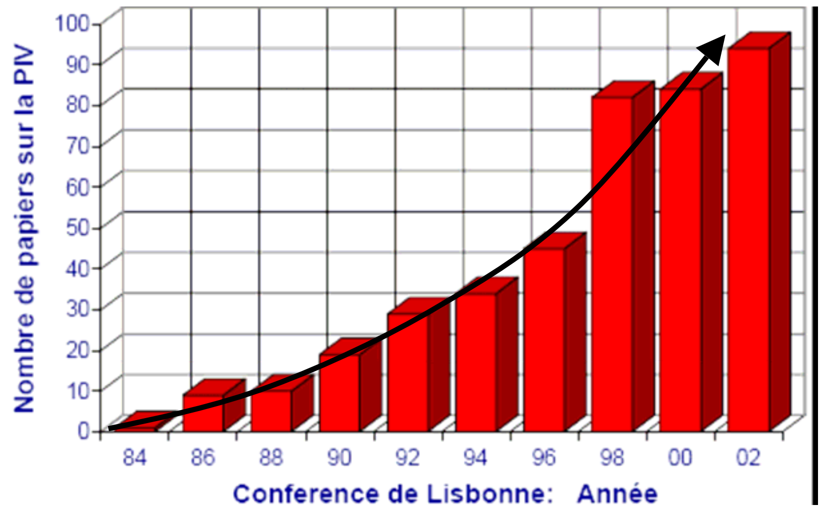
•Acquisition system (High speed *camera CCD, high resolution ≈ 2k x 2k*)

•Data transfer and computing system

-Very easy to use and to obtain first velocity field ?

(Not very true)

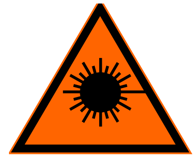
- Very popular technique



International Symposium on Applications of Laser Techniques to Fluid Mechanics (Lisbon)

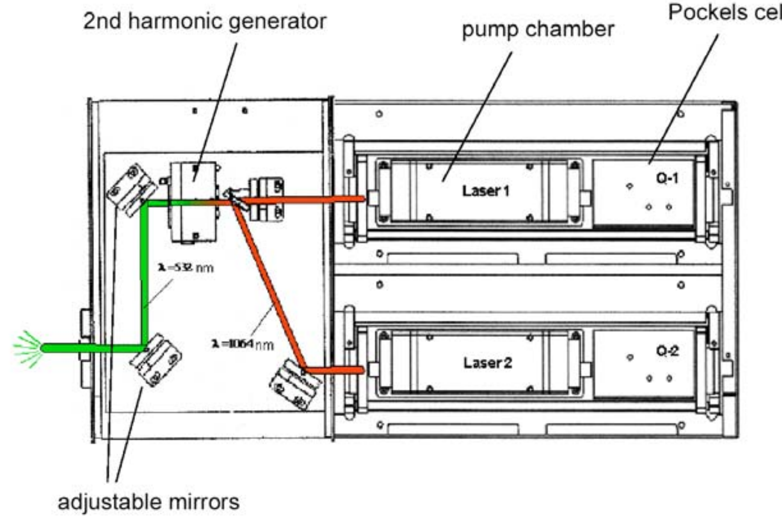
PIV : Principles

What do we need ?



- **LASER (Nd:YAG)** → flow illumination
  - Pulsed laser : <10 ns
  - Typical laser energy 100mJ/pulse
  - Wavelength λ= 532 nm (visible : green)
  - Two successive laser shots

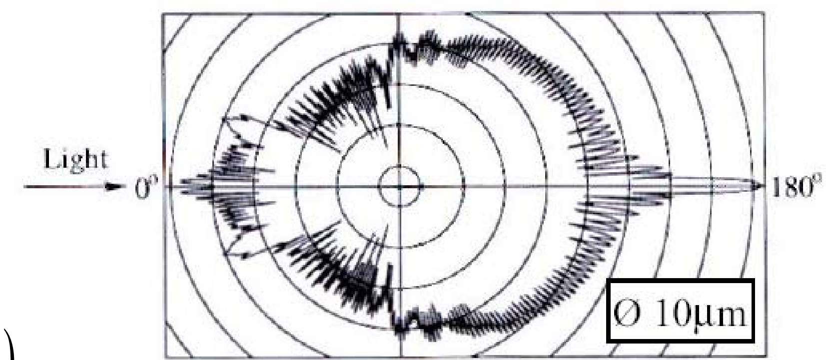
    (→ 2 spatially superimposed laser)
  - Laser sheet by spherical and cylindrical lenses



- **Seeding particles**
  - micronical particles (solid, liquid, smoke, ...)
  - Compromise between drag/flow illumination

    → Stocks number << 1

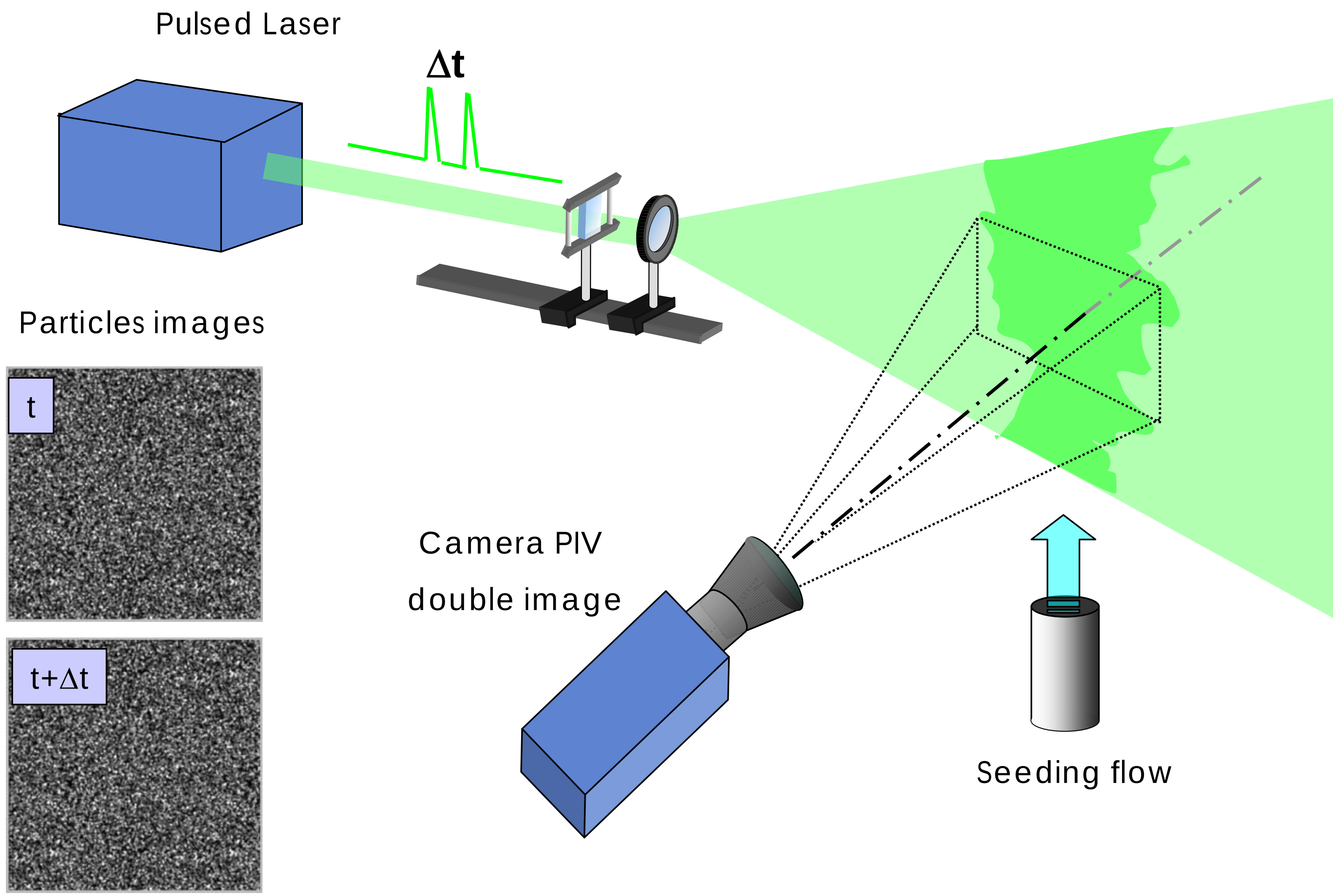
$$\frac{d\vec{u}_p}{dt} = \frac{18\mu}{\rho_P d_p^2}\left(\vec{u}_f - \vec{u}_p\right)$$



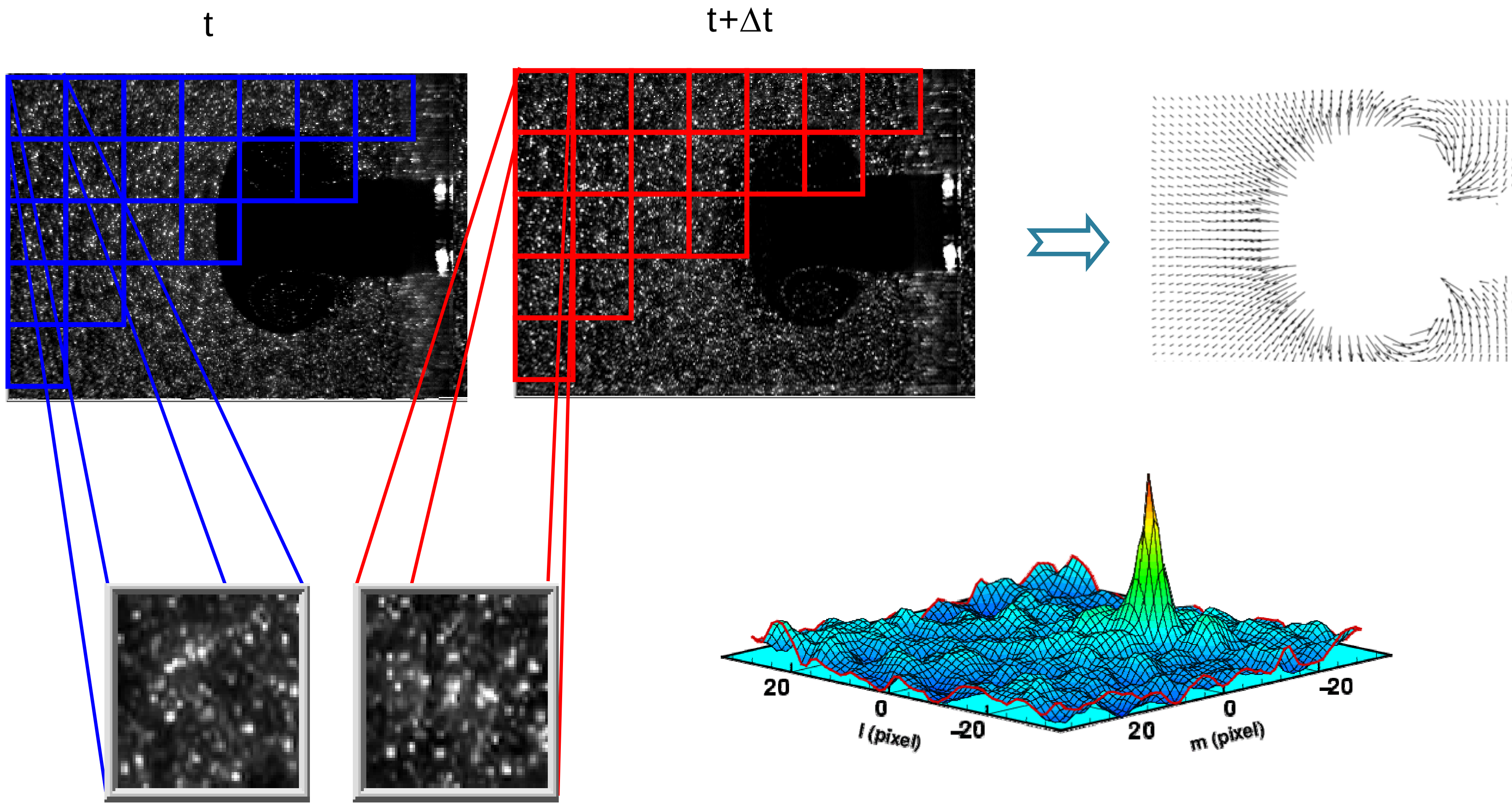
Mie scattering

- **CCD camera** (Resolution, sensitivity, frame transfer, ...)

PIV : Principles



PIV : Principles



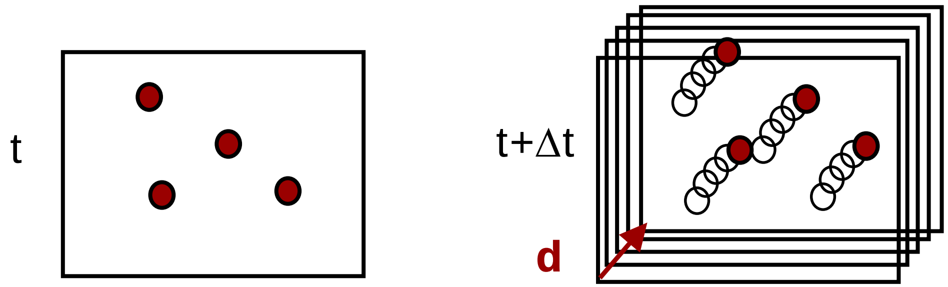
$$R(m,n)=\frac{\sum_{i=-N}^{i=N}\sum_{j=-M}^{j=M}[I(i,j)-\bar{I}][J(i-m,j-n)-\bar{J}]}{\sqrt{\sigma_I^2\sigma_J^2}}$$

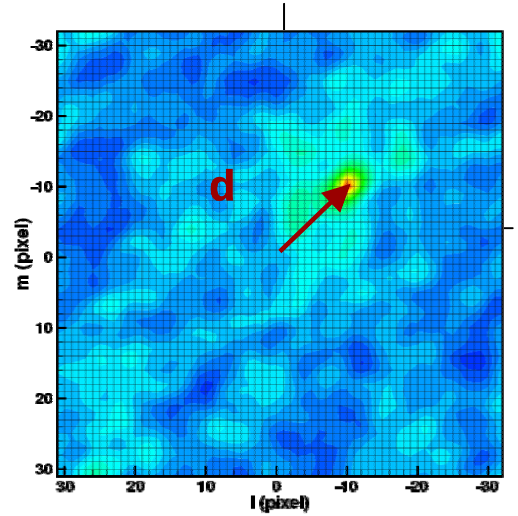
Cross-correlation on grey levels between interrogation windows

PIV : Principles

Cross-correlation function :

- Statistical information on particles displacement in the whole interrogation window !!
≠ each particle displacement



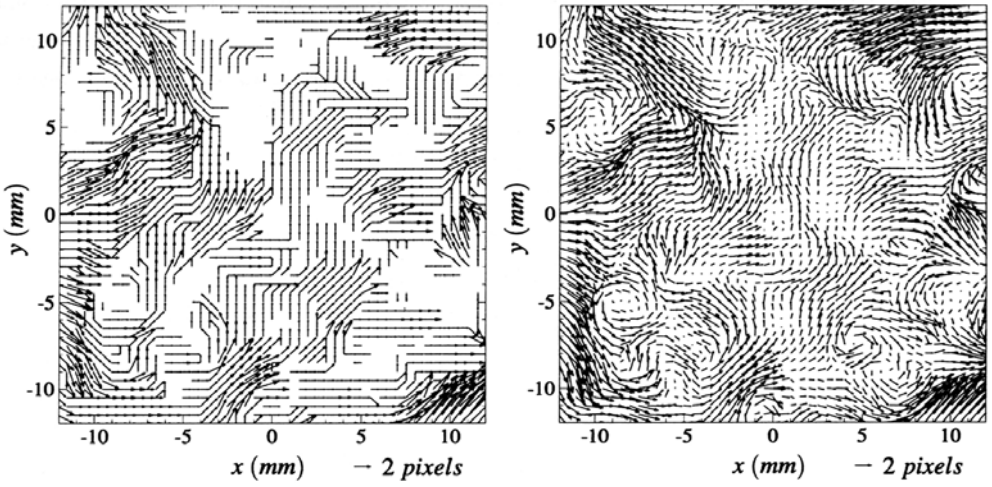


$$R(m,n) = \frac{\sum_{i=-N}^{i=N} \sum_{j=-M}^{j=M} [I(i,j) - \bar{I}][J(i-m, j-n) - \bar{J}]}{\sqrt{\sigma_I^2 \sigma_J^2}}$$

- I(i,j) = grey level of the pixel (i,j) for the first image (time t)
- J(i,j) = grey level of the pixel (i,j) for the second image (time t t+Δt)
- I, J = mean value of grey levels for both images
- σ_i, σ_j = grey levels r.m.s. for both images
- 2N, 2M = interrogation windows size, usually 2^n (8-16-32-64-128 pixels^2)
- Sampling process (cross-correlation coefficient – pixel)

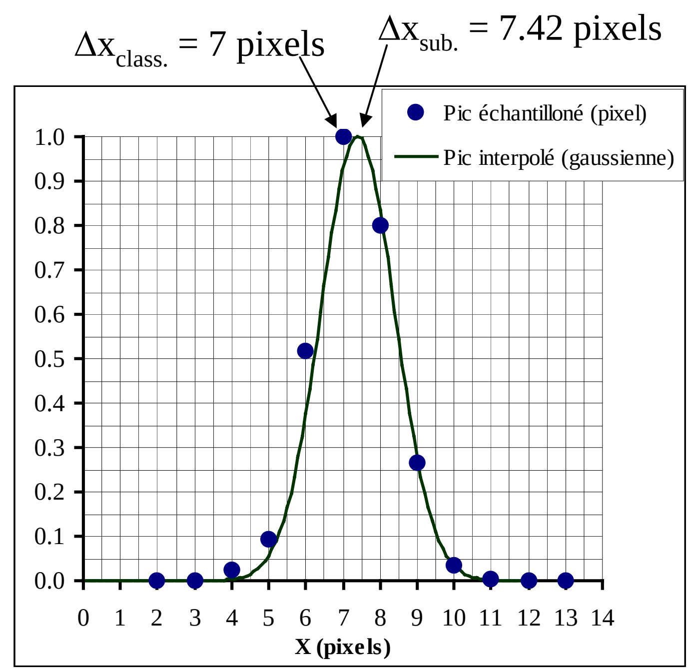
PIV : Principles

Cross-correlation fit



(a) Sans sub-pixel

(b) Avec sub-pixel



Interpolation function :

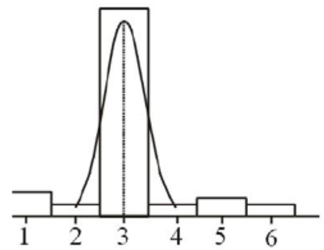
- Gaussian or parabolic (2D) or (2x1D)
- number of points : 3, 5 or 7
- Influence on the displacement measurement (especially for small displacement ?)

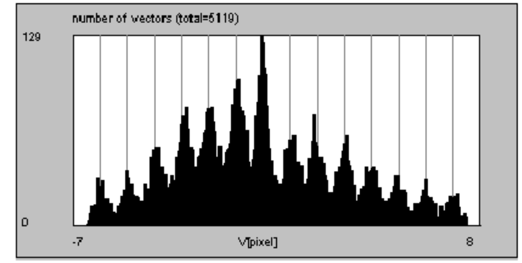
Strong influence on PIV noise !

PIV : Principles

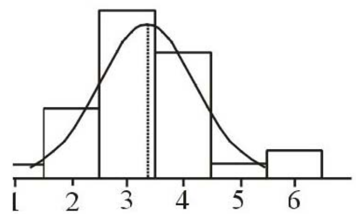
<u>**Peak locking effect ?**</u>

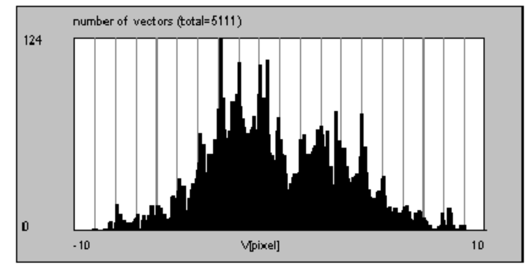
- Cross correlation function fit leads to a bias (integer values of particles displacement are privileged)





- Role of particle image size (image quality !)

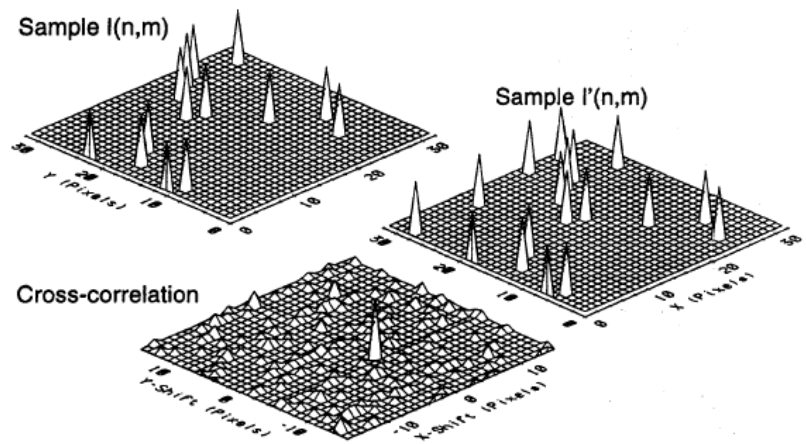




- **How to remove :**

  - Particle image size > 2 pixels

  - Iterative PIV with decreasing interrogation windows size



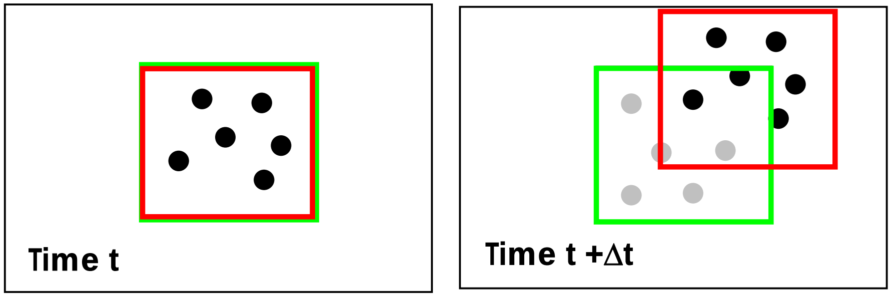
- Effect on turbulence statistics estimation !!!

(ex : artificial increase of u' and v' by 10%)

PIV : Principles

Iterative PIV (Windows Deformation Iterative Multigrid)

Lecordier et al., (2001), Scarano and Reithmuller (1999)



Classical PIV

Window translated by the predicted displacement

1st step

- Initial computation : predicted displacement (U_n,V_n)
- Windows translation

2nd step

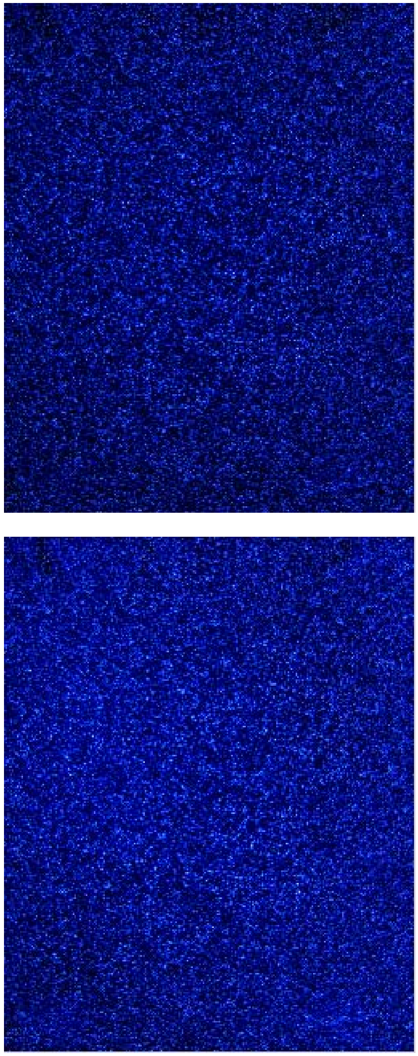
- New computation : corrected displacement (U_{cor},V_{cor})
- Displacement $(U_{n+1},V_{n+1})=(U_n,V_n)+(U_{cor},V_{cor})$

Until $(U_{cor},V_{cor})=(0, 0)$

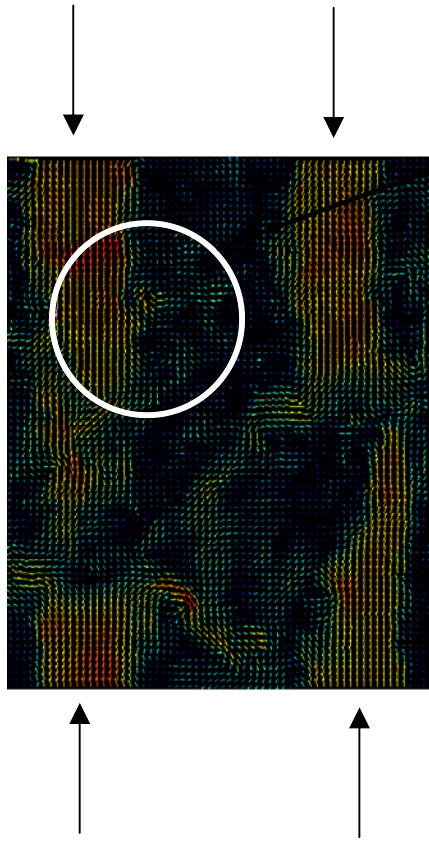
Including : vector validation during these steps and windows size decreasing

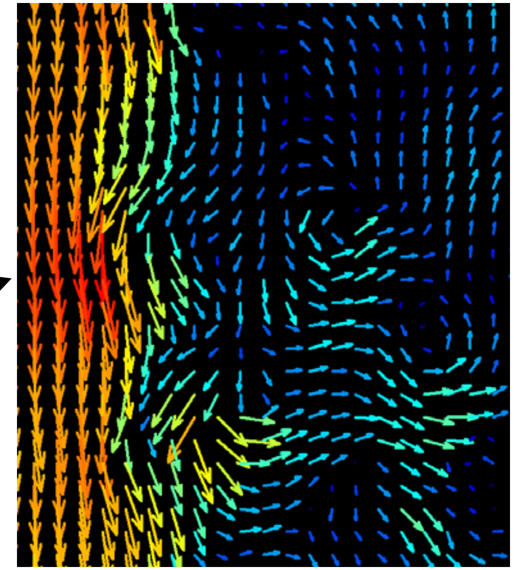
PIV : Principles

Results (Assuming ideal particle images, PIV algorithm, ...)



4 impinging jets

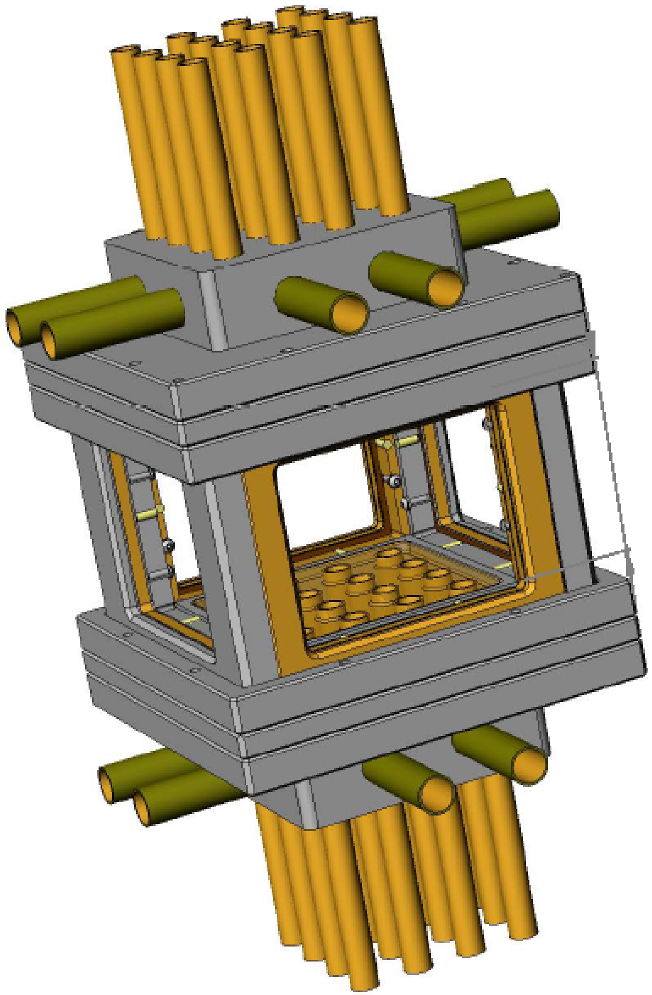


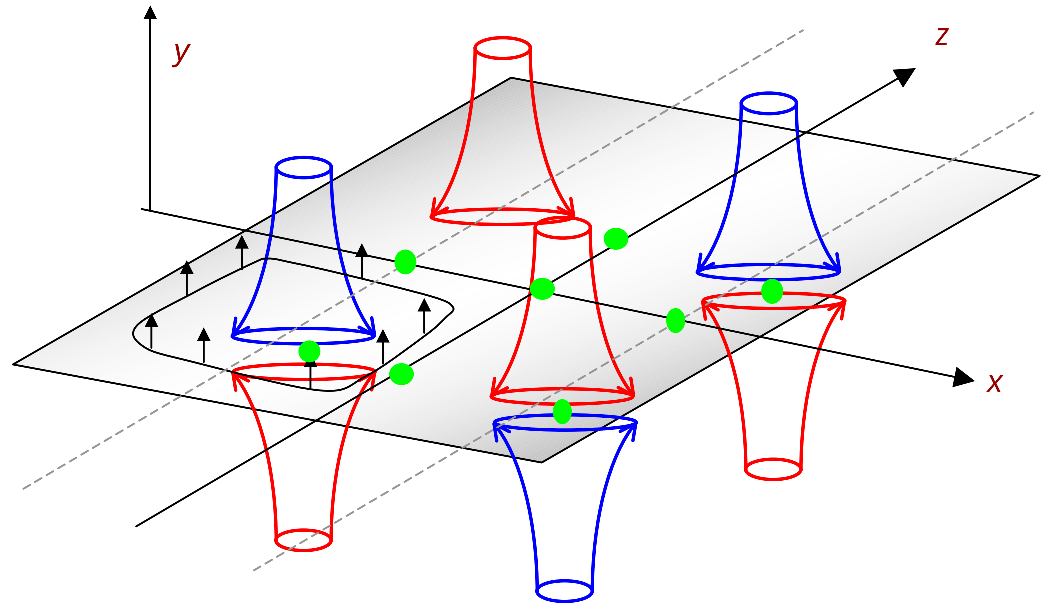


Beautiful velocity field !!!

BUT, what about :

- **Spatial resolution ?**
- **Noise ?**
- **Velocity derivative**



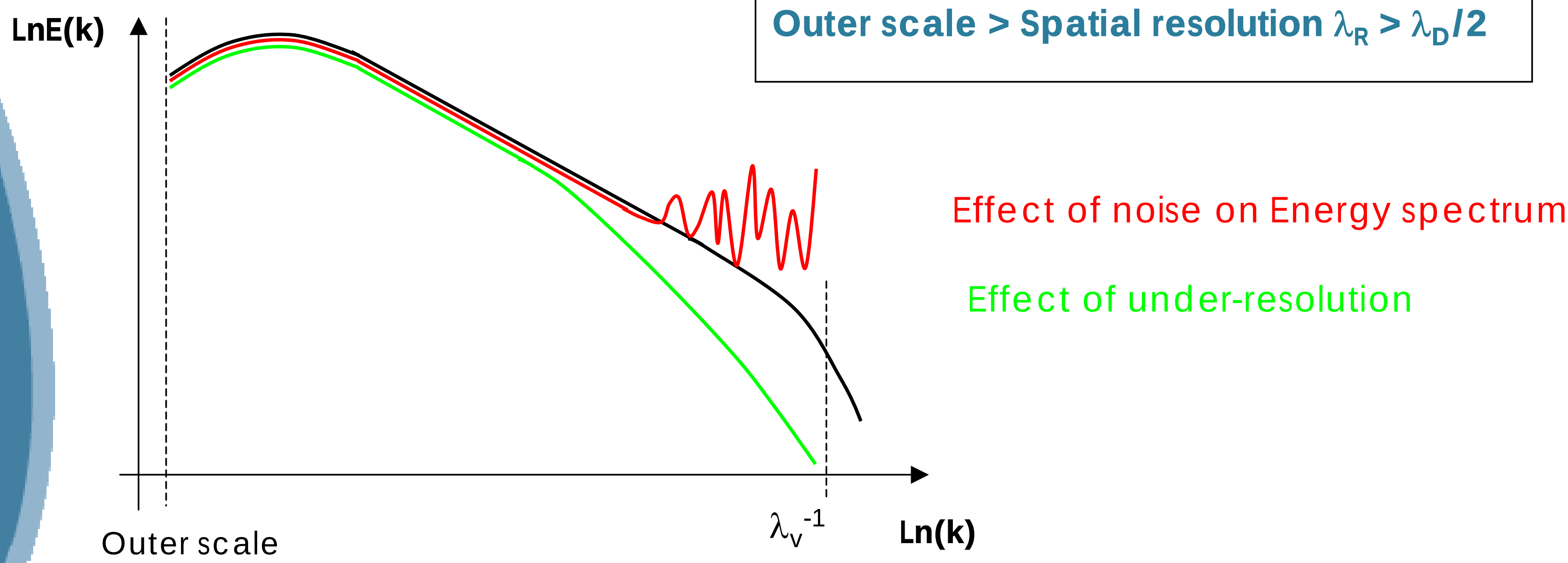

y
z
x

PIV : Spatial resolution

Resolution requirement in fluid flows (less restrictive case)

Spatial resolution must be smaller than the smallest scale of which velocity gradient can be sustained = strain limited vorticity thickness $\lambda_v \approx$ 4-8 Kolmogorov scale (Buch and Dahm, 1998)

Outer scale > Spatial resolution $\lambda_R > \lambda_D/2$



$$\text{Dynamic Spatial Range (DSR)} = \frac{\text{Measured outer scale}}{\text{Measured dissipative scale}} = \frac{\text{Outer scale}}{\text{Dissipative scale } \lambda_v} \quad (?)$$

PIV : Spatial resolution

Limitations :

- Noise (false vectors, peak locking effect, ...)

- Particle motion ≈ fluid particle motion at these smallest scales ?

- Schmidt number of solid or liquid particles ? (Diffusion)

- Limited dynamic spatial range (Number of pixels of the CCD and physical size of one pixel)

- Sampling effect
  - particle seeding : minimum length scale = $l_m > 2d$ (d = mean distance between two particles)
  - vector output : minimum length scale = $l_m > 2\Delta$ (Δ = mean distance between two vectors)

- Spectral response of PIV

= measurement of the response to an impulse signal or to a white noise

≈ Response to a "zero" input signal in PIV (motionless record) = Transfer function

Model for energy spectrum :

Transfer function

$$E_{PIV}(k_1,k_2) = \boxed{E_{True}(k_1,k_2)}.TF(k_1,k_2) + E_{Noise}(k_1,k_2)$$

Noise contribution (additive ?)

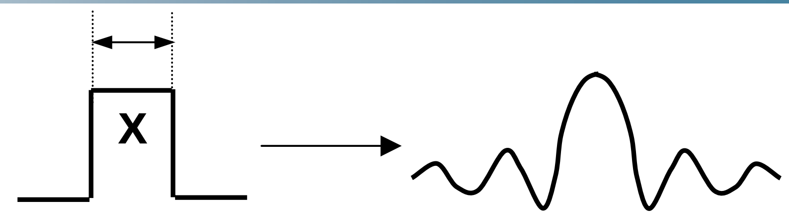
PIV : Spatial resolution

Transfer function *(Foucaut et al. 2004)*

-Model = “sinc” function

$$E = E_0 \left(\frac{\sin \frac{KX}{2}}{\frac{KX}{2}} \right)^2$$

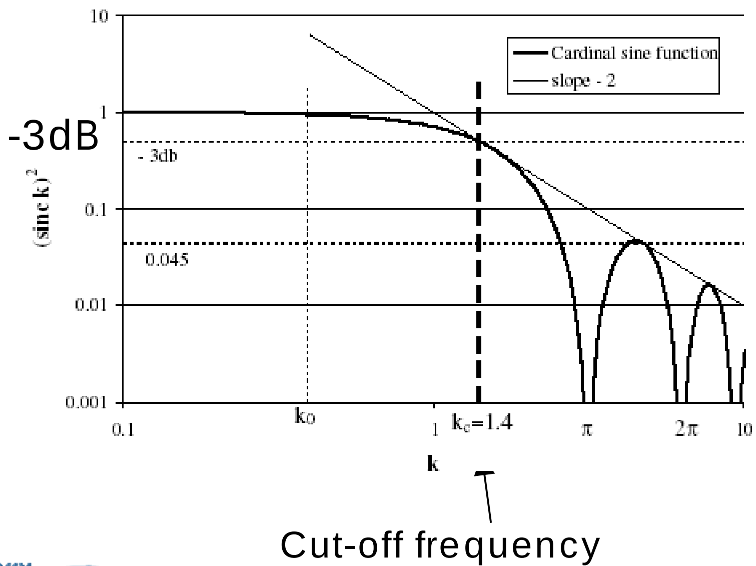
$$TF(k_1, k_2) = \frac{E_{Noise}(k_1, k_2)}{E_0}$$

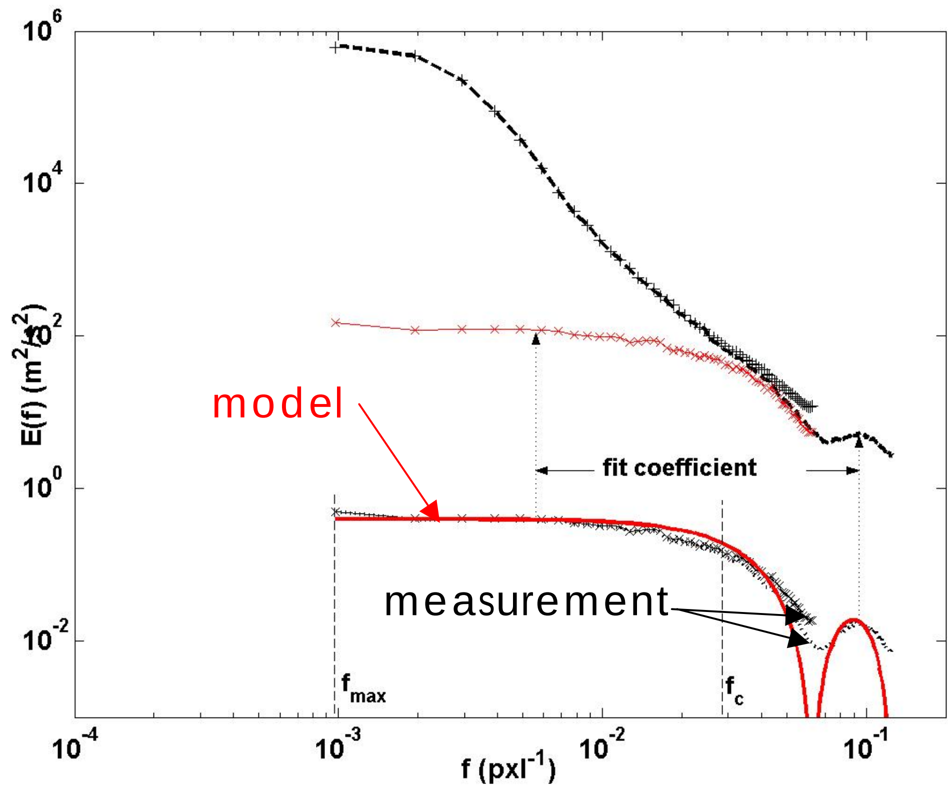


-Low pass filtering effect (cut at –3dB)

$\kappa_c = 1.4$

$\mathbf{K_c = 2.8/X}$





PIV : Spatial resolution

2 different spatial scales :

Outer scale : λ_{max} (resolved)

Cut-off scale : $\lambda_c = (2\pi X)/2.8$ where X = window size (pixels)

$\rightarrow$ independent of window overlapping (sampling effect)

Spatial resolution close to λ_c <u>with moderate noise</u> …

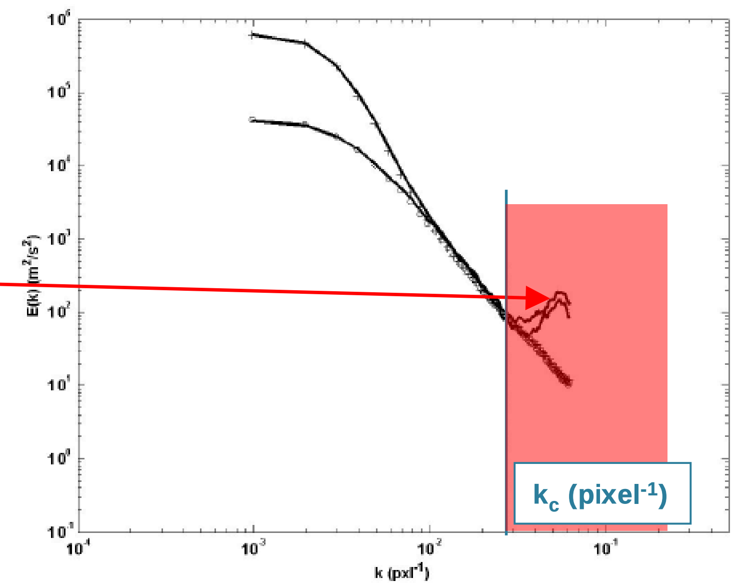
$$TF(k_1,k_2) = \frac{E_{Noise}(k_1,k_2)}{E_0}$$

Towards the estimation of E_{true} :

$$E_{PIV}(k_1,k_2) = E_{True}(k_1,k_2).TF(k_1,k_2) + E_{Noise}(k_1,k_2)$$

Inverse problem !

$$\boxed{E_{True}(k_1,k_2) + E_0 = E_{PIV}(k_1,k_2)/TF(k_1,k_2)}$$



PIV : Noise

Different noises :

- Instrumental noise : (SNR CCD, Analogical/numerical converter, ...)

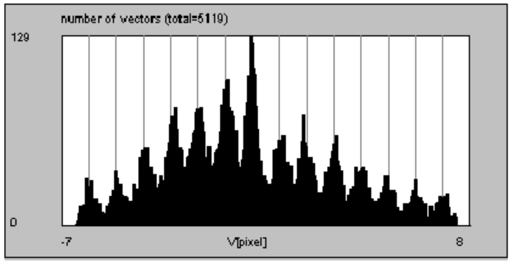
- Physical noise. It comes from lighting (laser system, technology, ...), or from 2D projection onto CCD plane

- Noise or “errors” linked to the sub-pixel estimation of maximum correlation

  - Correlation peak fit
  - Peak locking effect

  → Minimized by the image quality and the PIV algorithm

  (Stanislas et al., 2005 and Europiv project)



- Problems coming from the flow and seeding :

  - High velocity gradient within the interrogation window
  - Particles coalescence

  → False vectors (Validation step)

PIV : Derivative filter

Derivatives of the velocity is of first importance in fluid dynamic (vorticity, strain tensor, dissipation, ...)

BUT :

-Limited PIV spatial bandwidth

- Residual noise still present in the velocity field

Which is the best estimator for velocity derivative ?

Various derivative schema exist :

- Centred schema of order n
- High order compact schema
- Least square filter
- ...

TRANSFERT FUNCTION OF THE DERIVATIVE ESTIMATOR

PIV : Derivative filter

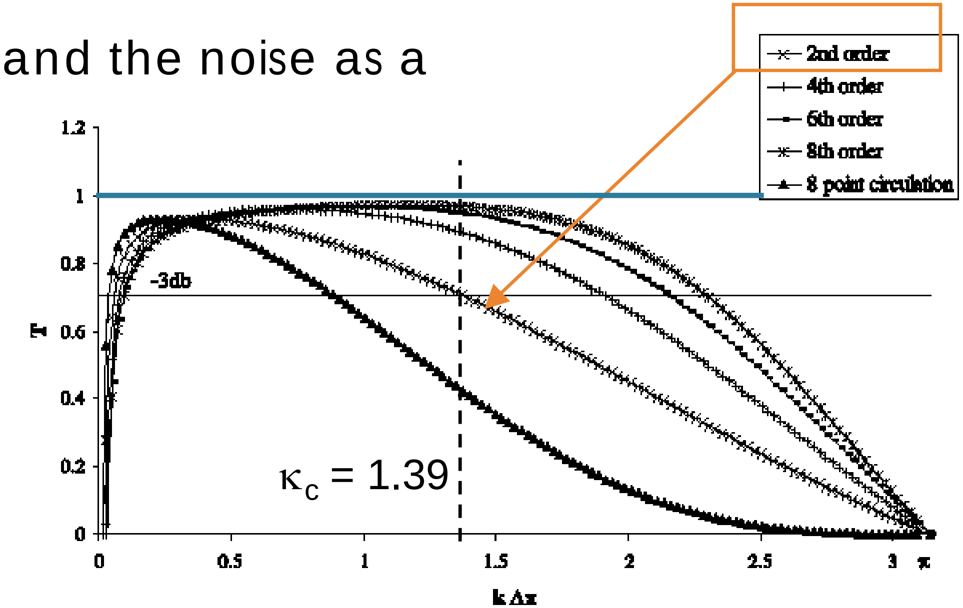
Methodology (example for centred schema of order n)

$$\left.\frac{\partial u}{\partial x}\right|_j = \underbrace{\boxed{\frac{1}{a\Delta x}\sum_{i=1,n/2} a_i\left(u_{j+i}-u_{j-i}\right)}}_{\text{Estimated derivative}} + \underbrace{\boxed{\sum_{i=n+1,\infty}\alpha_i \frac{\Delta x^{i-1}}{i!}\left.\frac{\partial^i u}{\partial x^i}\right|_j}}_{\text{Truncation error}} + \underbrace{\boxed{\varepsilon\frac{\sigma_u}{\Delta x}}}_{\text{Noise}}$$

Compromise between the truncation and the noise as a function of the order !

TRANSFERT FUNCTION

$$T = \left.\frac{\partial u}{\partial x}\right|_{Est.} \Big/ \left.\frac{\partial u}{\partial x}\right|_{True}$$



- Cut-off wave number comparable to that of PIV
- 2nd order centred scheme is enough for a good accuracy of the derivative

Foucaut and Stanislas (2002)

PIV : Accurate spatial velocity gradient measurement ?

Methodology :

- Seeding optimization (density, homogeneity, S_T<<1, ...)

- Image quality (focus, distortion, particle image shape, background scattering, laser profile, optimized interval time, ...)

- Iterative PIV algorithm with decreasing size

- Vector validation (false vectors, ...)

→**Velocity vectors optimization = first condition**

- Estimation of PIV bandwidth (outer range λ_{max} and cut-off scale λ_c)

- Comparison of the cut-off scale with the smallest scale of the flow (strain limited vorticity thickness λ_v)

- Derivative computation with a 2nd order centred scheme valid in the PIV bandwidth

Validation procedure : - DNS/PIV approaches. *Lecordier et al., (2001)*

- Application in well known flows. *Foucaut et al., (2004)*

PIV : Conclusions on the technique

Advantages :

- Two dimensional approaches, 2C or 3C (Stereoscopic PIV)

  → Dual Plane Stereoscopic PIV

- Spatial statistics (No Taylor hypothesis)

- Very helpful for flow understanding (flow visualization)- Coherent view of the flow

Drawbacks :

- Limited bandwidth

- Poor spatial resolution. Strong limitation by particle seeding, interrogation windows, noise

  → Development of Super Resolution PIV *(Stitou et al., 2001)*

- Limited temporal statistics (Laser frequency)

  → High speed PIV (up to 10kHz)

Strong complementarity with hot wire measurements

Introduction : Contents and Objectives

Spatial velocity gradient measurements : PIV

- Principles and limitation of PIV technique
- Noise and spatial resolution estimation
- Derivative schema : optimization ?
- Accurate spatial velocity gradient measurement ?

Spatial scalar gradient measurements

- Principles and limitations of PLIF and Rayleigh scattering
- Noise and spatial resolution estimation
- Optimal data filtering

Illustrations and perspectives

- Laminar flame thickness measurement
- Quantitative measurements of molecular mixing
- Strain tensor analysis by DPIV

PLIF : Basic principles

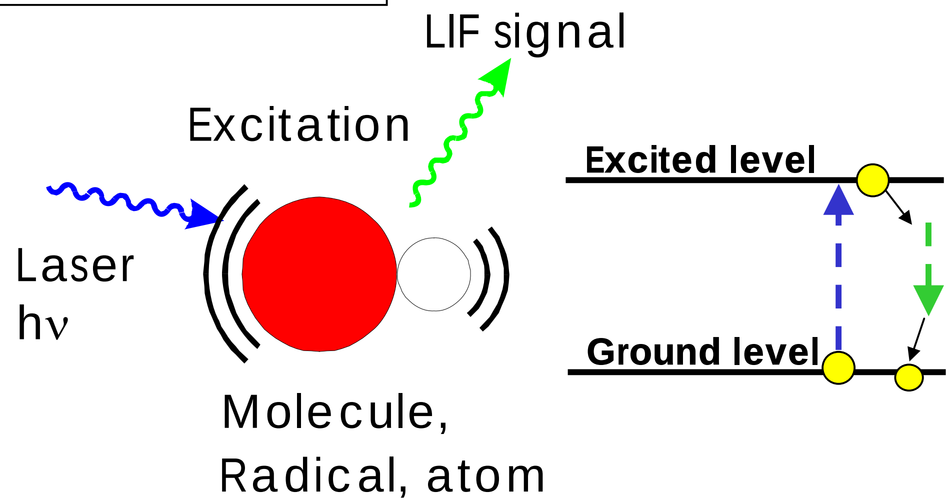
Planar Laser Induced Fluorescence

- Species selective
- High detection sensitivity (ppm)
- 2-D measurements (or more with dual plane technique)
- Scalar = concentration or temperature
- wavelength shift of the fluorescence signal ($\lambda_{Fluo} > \lambda_{Inc}$)

Scalar :
- specie present in the flow (OH, CH, ...) → PLIF (combustion studies)
- molecular tracer added to the flow (acetone, 3-pentanone, toluene, NO, ...)

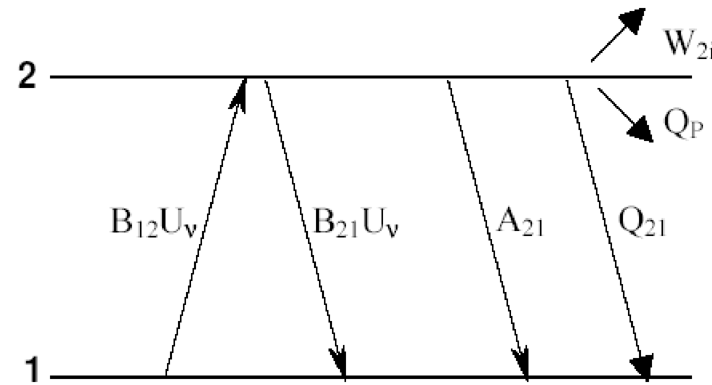
→ Tracer PLIF (imaging of scalar studies)

Definition : Fluorescence is the spontaneous emission of radiation from an upper energy level which has been excited in some way (optically, thermally or chemically)



PLIF : Basic principles

Two Levels model



Radiative processes :

-Absorption ($B_{12}U\nu$)

-Induced emission ($B_{21}U\nu$)

-Spontaneous emission (A_{21})

Non-Radiative processes :

- Internal transfers (K)
- Collisional quenching (Q_{21})
- Photoionization(W_{2i})

- $N_2(t)$ = population density of the excited level
- $N_1(t)$ = population density of the ground level

Fluorescence signal collected :

$$S_F = \iiint_V h\nu_{21} N_2(t) A_{21} \frac{\Omega}{4\pi} dV$$

Photon energy **To solve ...** **Solid angle collection** **Volume measurement**

Daily (1997) ; Kohse-Höinghaus et al. (2002) ; Schulz et al. (2005)

PLIF : Basic principles

Hypothesis :

- Pumping time < laser pulse duration → S_F independent of time
- Laser irradiance → linear regime
- Energy measured constant in the measurement volume

How to quantify Q_{21} ?

$$S_F = h\nu_{12}\frac{\Omega}{4\pi}VN_1B_{12}U_\nu\frac{A_{21}}{A_{21}+Q_{21}+K}$$

Fluorescence signal

Fluorescence quantum yield

Molar fraction

$$S_F(x,y) = I_0(x,y,\lambda)\ dV_c\eta_{opt}\left[\frac{\chi_{Traceur}(x,y)\ P}{kT}\right]\sigma(\lambda,T)\ \phi\left(\lambda,T,P,\sum_i \chi_i\right)$$

Local laser intensity

Absorption cross-section of the molecule

Measurement volume [cm³]

Collection system efficiency

PLIF : Basic principles

Quenching effect

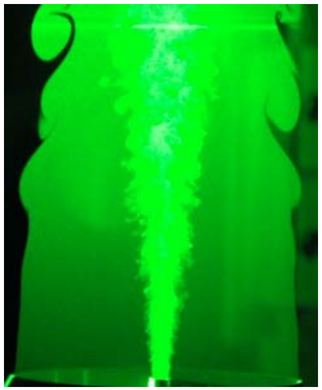
Generally $Q_{21} >> A_{21}+K$ → Quantum yield very small !!

→ Decrease of detectability

AND, Q_{21} is mainly controlled by the local flow composition (Species i)

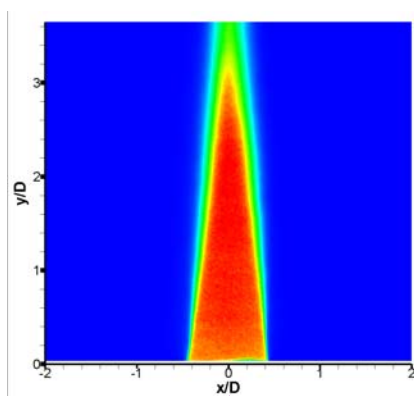
$$\boxed{Q_{21} \propto \sum_{i} \chi_i \ .\sigma_{Seeder/i}(T)}$$

Example : Turbulent jet – Mean scalar concentration measured by PLIF on NO



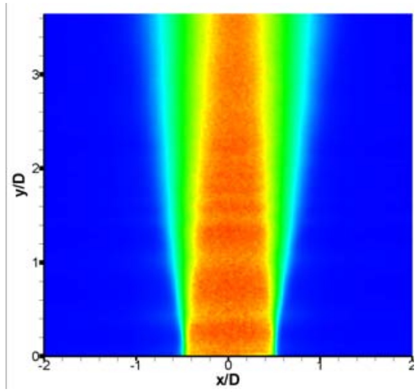
N_2 O_2

N_2/NO (300ppm)



O_2 O_2

N_2/NO (300ppm)



N_2 N_2

N_2/NO (300ppm)

PLIF : Basic principles

Towards quantitative measurements by tracer PLIF ...

- Knowledge of the instantaneous and local composition of the flow for Q_{21} estimation ...

  → Very difficult to implement

(*Lozano et al.*, 1992)

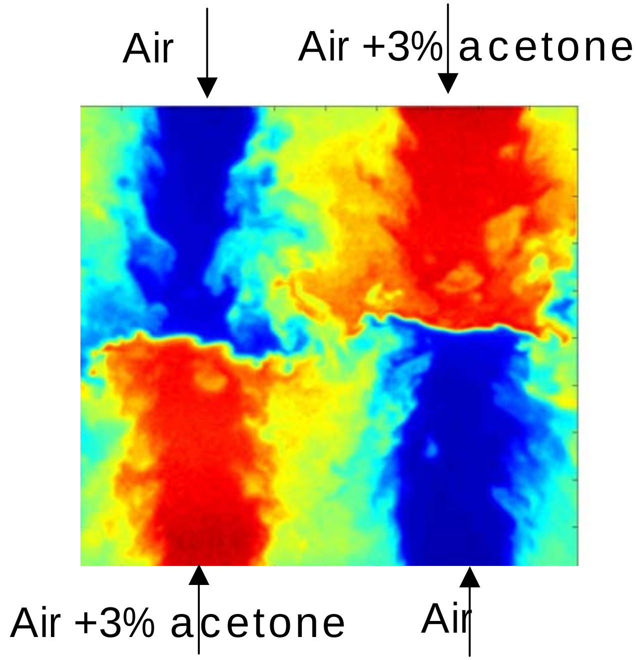
- Use of non-sensitive tracer to quenching effect

$$\boxed{S_F = h\nu_{12}\frac{\Omega}{4\pi}VN_0B_{12}U_\nu\frac{A_{21}}{A_{21}+Q_{21}+K}} \longrightarrow K >> A_{21} + Q_{21}$$

Exemple : Acetone, 3-pentanone

Choice of scalar tracer :

- Strong fluorescence signal
- Absorption coefficient *vs.* laser wavelength available
- Temperature/pressure dependence
- Similar mass diffusivity than the flow
- Easy to use and not (too much) toxic product
- ...



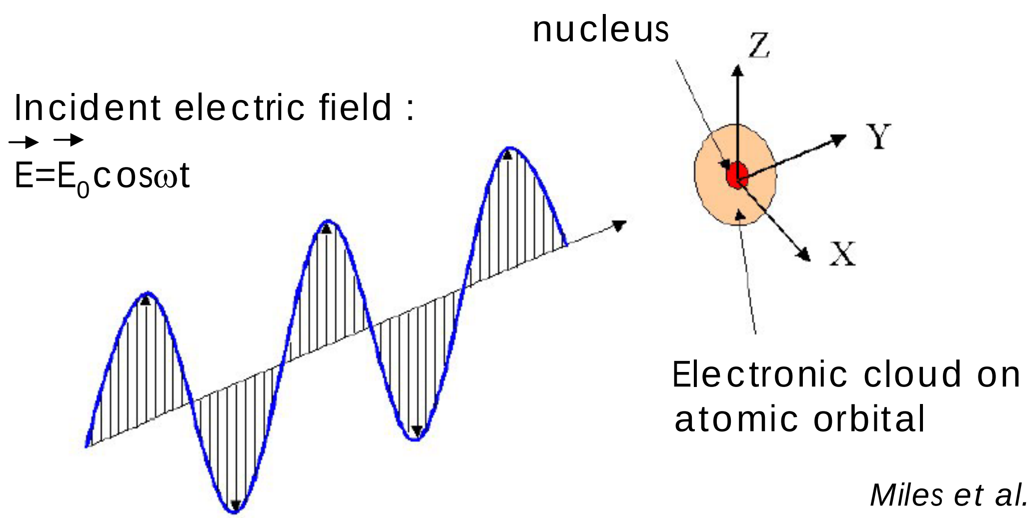
RAYLEIGH SCATTERING : Basic principles

Rayleigh scattering = Powerful diagnostic tool for the study of gases
→ Scalar (concentration or temperature) measurements

Rayleigh scattering = Elastic interaction between electromagnetic wave (laser) with molecules or small particles (d << λ)

Mechanism conceptually straightforward <u>BUT</u> features of the mechanisms of the scattering are complex

“Simplest” approach = electric dipole radiation model



Miles et al., (2001), Zhao et al., (1993)

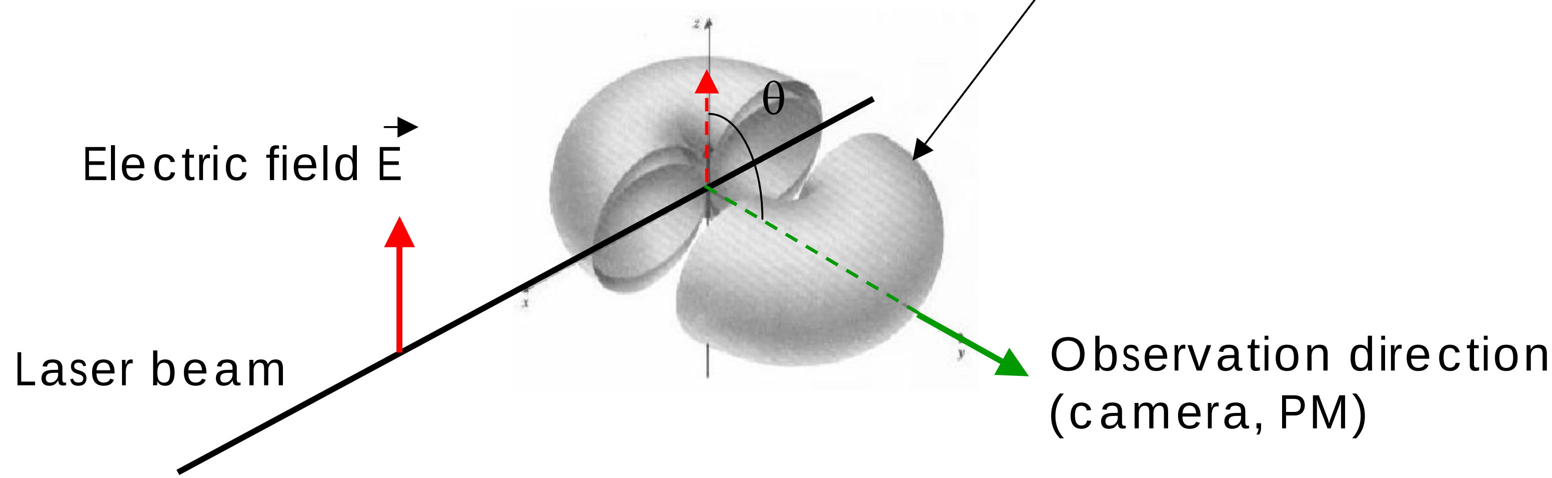
RAYLEIGH SCATTERING : Basic principles

Rayleigh scattering = Interaction between electric field and electronic cloud

→ small oscillating dipole

→ electronic field propagating from this dipole (amplitude and intensity)

Non isotropic scattering



RAYLEIGH SCATTERING : Basic principles

Rayleigh scattering signal :

$$\boxed{S_R(x,y) = I_0(x,y,\lambda).C_1.N(x,y).\sum_i \chi_i(x,y)\left(\frac{\partial\sigma}{\partial\Omega}\right)_i}$$

Laser intensity

Transmission factor

Molecule number for a given point in space (x, y)

Mole fraction of specie i

Rayleigh scattering cross-section of specie i

$$\boxed{\left(\frac{\partial\sigma}{\partial\Omega}\right)_i = \frac{4\pi^2}{\lambda^4}\left(\frac{n_i - 1}{N_0}\right)^2 \sin^2(\theta)}$$

short λ favourable

Laser wavelength

Refractive index of specie i

Loschmidt number

(Nbre of molecules/m³)

(λ=532nm) Gas species	Rayleigh cross-section ($\times 10^{28}$ cm^2 ster^{-1})
Hydrogen	1.1
Methane	11.6
Ethylene	25.5
Oxygen	4.4
Nitrogen	5.1
Argon	4.7
Helium	0.1
Air	5.1
Freon 22	59.5
Water vapour	3.8
Carbon dioxide	11.9
Carbon monoxide	6.8
Nitric oxide	5.2

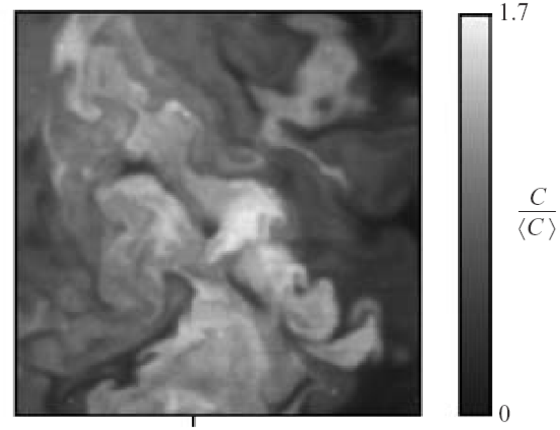
RAYLEIGH SCATTERING : Basic principles

Concentration measurement :

- Isothermal fluid

- Two species with strongly different crossections present in the flow

$$S_R(x,y) = I_0(x,y,\lambda).C_2.\left[\chi_1\left(\frac{\partial\sigma}{\partial\Omega}\right)_1 + (1-\chi_1)\left(\frac{\partial\sigma}{\partial\Omega}\right)_2\right]$$



Scalar concentration in a turbulent jet,

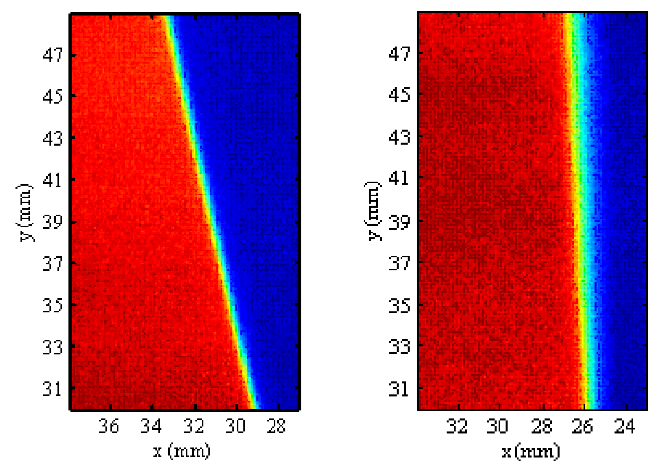
(Su et al., 2003)

Temperature measurement :

-T directly from the gas law: p=NRT, as Rayleigh is proportional to N.

-Quasi-constant Rayleigh scattering cross-section

$$S_R(x,y) \propto I_0(x,y).C_3.\frac{1}{T(x,y)}$$



Laminar flame temperature,

(Lafay et al., 2007)

RAYLEIGH SCATTERING : Basic principles

Advantages of Rayleigh scattering technique :

- Quite strong signal → 2D measurements possible.
- No quenching dependence
- Signal intensity increasing with increasing pressure.

Disadvantages of Rayleigh scattering technique :

- Not species selective, it is impossible to separate between the different species contributing to the signal.

-The signal is at the same wavelength as the laser, which makes the technique very sensitive to scattering from optical components, or from particles such as dust or soot.

-Mie scattering is about 1000 times stronger than Rayleigh scattering, so gases must be filtered to remove particles. Scattering from optics or other surfaces must be eliminated (Background light)

PLIF / RAYLEIGH SCATTERING : Basic principles

What do we need ?

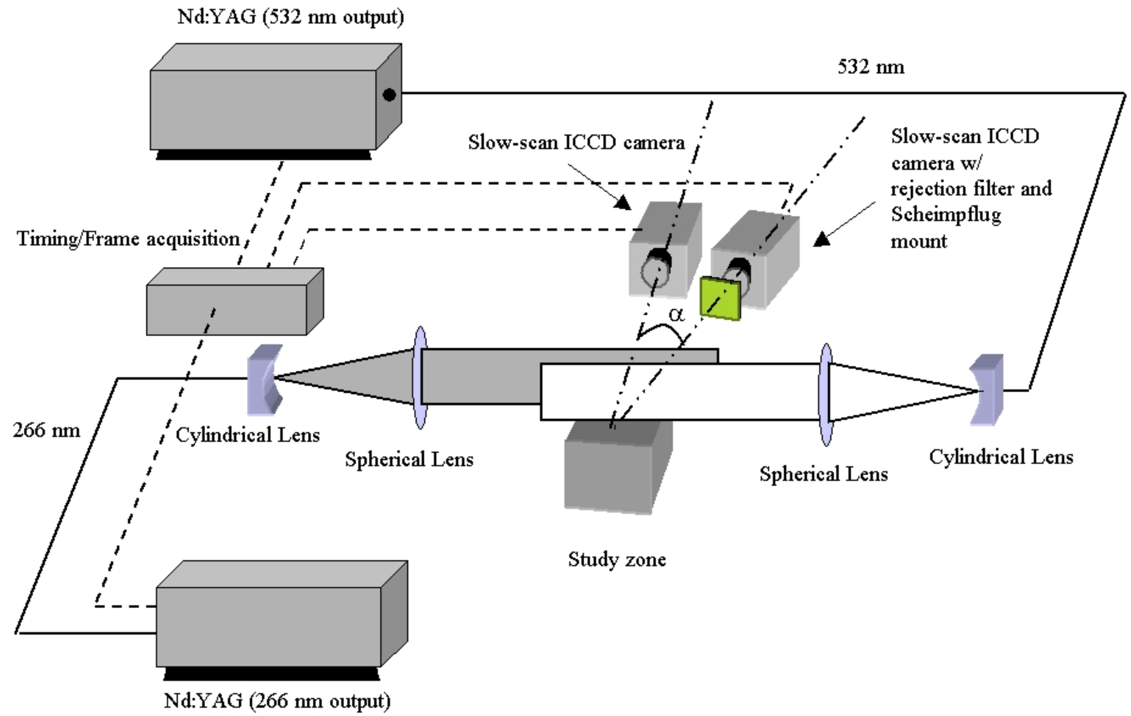
RAYLEIGH Scattering or TRACER PLIF : UV LASER (Nd:YAG, Excimer)

→ flow illumination

- Pulsed laser : <10 ns
- Typical laser energy > 200mJ/pulse
- Wavelength λ= 266, 355, 248, 308 nm(UV)
- Laser sheet

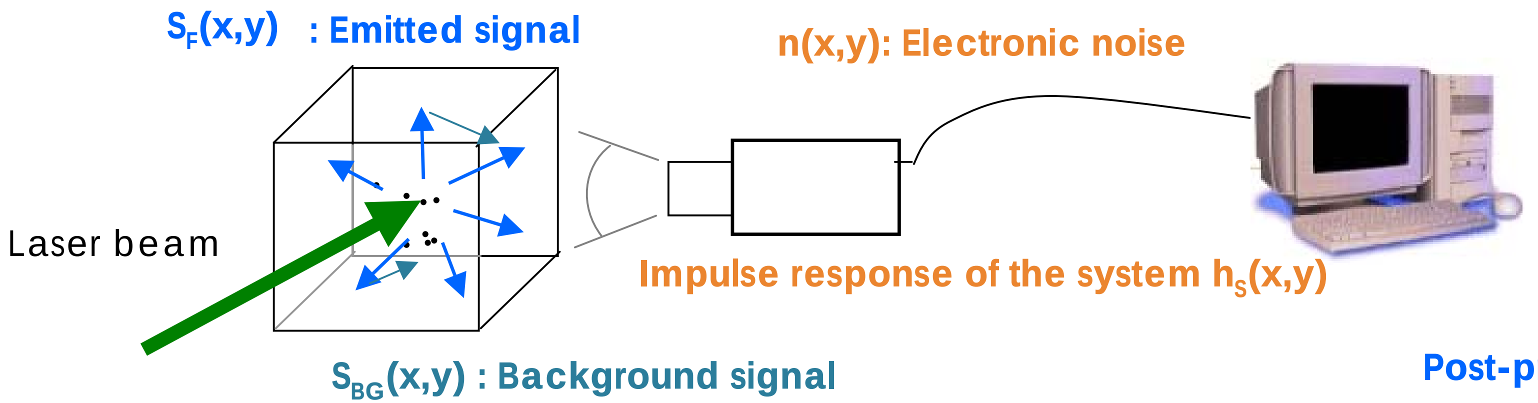
Intensified CCD camera or very sensitive back illuminated camera

(Resolution, sensitivity, frame transfer, ...)



Experimental set-up for simultaneous measurements of temperature and fuel mole fraction in laminar flames (Degardin *et al.*, 2006)

PLIF / RAYLEIGH SCATTERING : Residual problems



Post-processing (filter ?)

Data reduction

Derivative filter

Dissipation

Modeling of measured signal :

$$\boxed{s_M(x,y) \equiv h_S(x,y) \otimes s_F(x,y) + h_S(x,y) \otimes s_{BG}(x,y) + n(x,y)}$$

Measured signal True signal

$$\boxed{s_M(x,y) \equiv h_S(x,y) \otimes s_F(x,y) + n_1(x,y)}$$

Impulse response :

➔ spatial resolution effect

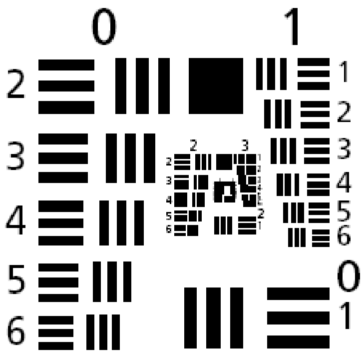
➔ must be in accordance with smallest scales to be measured

➔ Inverse problem ?

Krawczynski *et al.*, (2006); Wang *et al.*, (2007)

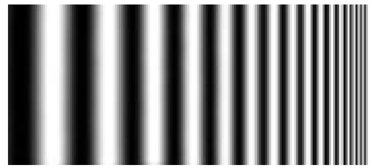
PLIF / RAYLEIGH SCATTERING : Residual problems

Spatial resolution : Function Transfer Modulation (FTM)

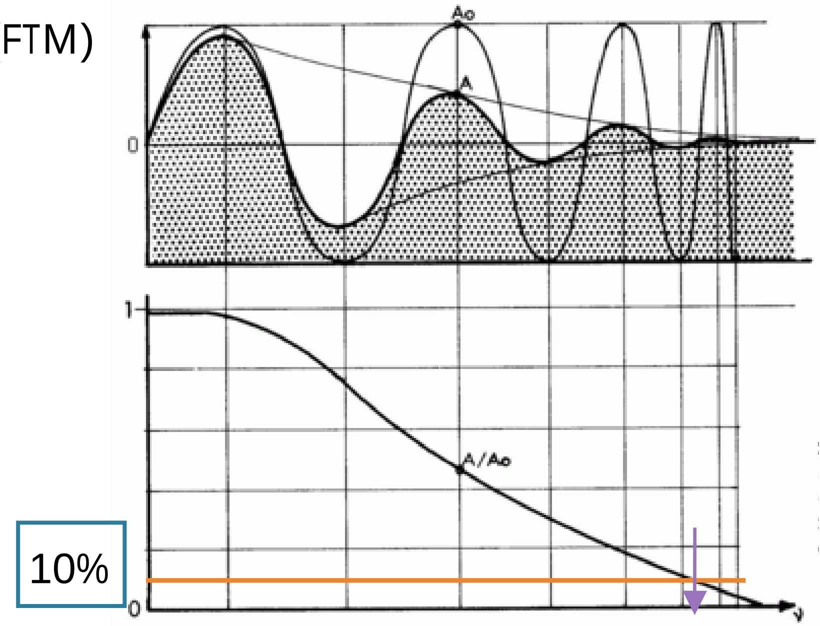


USAF 1951 test target
(nbre of lines pairs per mm)

Initial target



Recorded target



Spatial resolution

Another approach :

-Edge response

-Derivative → Impulse response

-FFT (Impulse response) → FTM

- Spatial resolution = 10% contrast

FTM = Tool to find the highest resolution pattern where detail is visible

PLIF / RAYLEIGH SCATTERING : Residual problems

Electronic noise : different sources

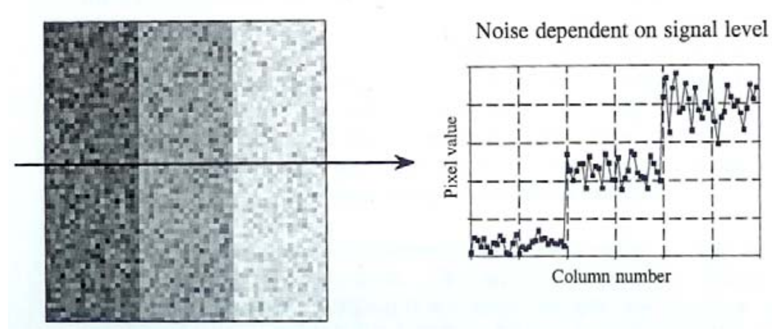
1) Fixed CCD pixel-pattern noise (removable by offset)

2) CCD readout noise (amplifiers on-board the CCD)

3) Image intensifier multiplication (electron avalanche noise)

→ proportional to the local/pixel signal and some power of the intensifier gain

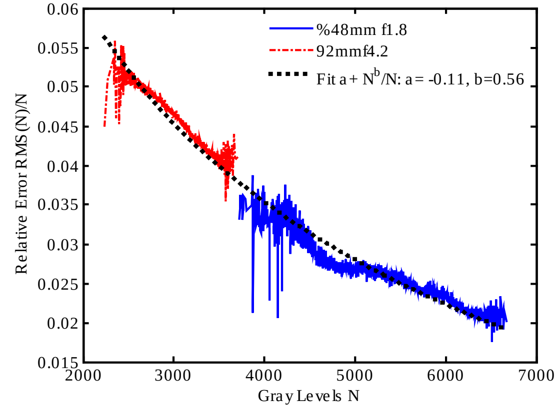
→ operate the intensifier/CCD at as low a gain as is feasible.



4) Photon shot noise

→ a finite number of particles that carry energy(photons) is small enough to give rise to detectable statistical fluctuations in a measurement $Relative\ error = \sqrt{N}/N$

→ increase the number of photons



PLIF / RAYLEIGH SCATTERING : Residual problems

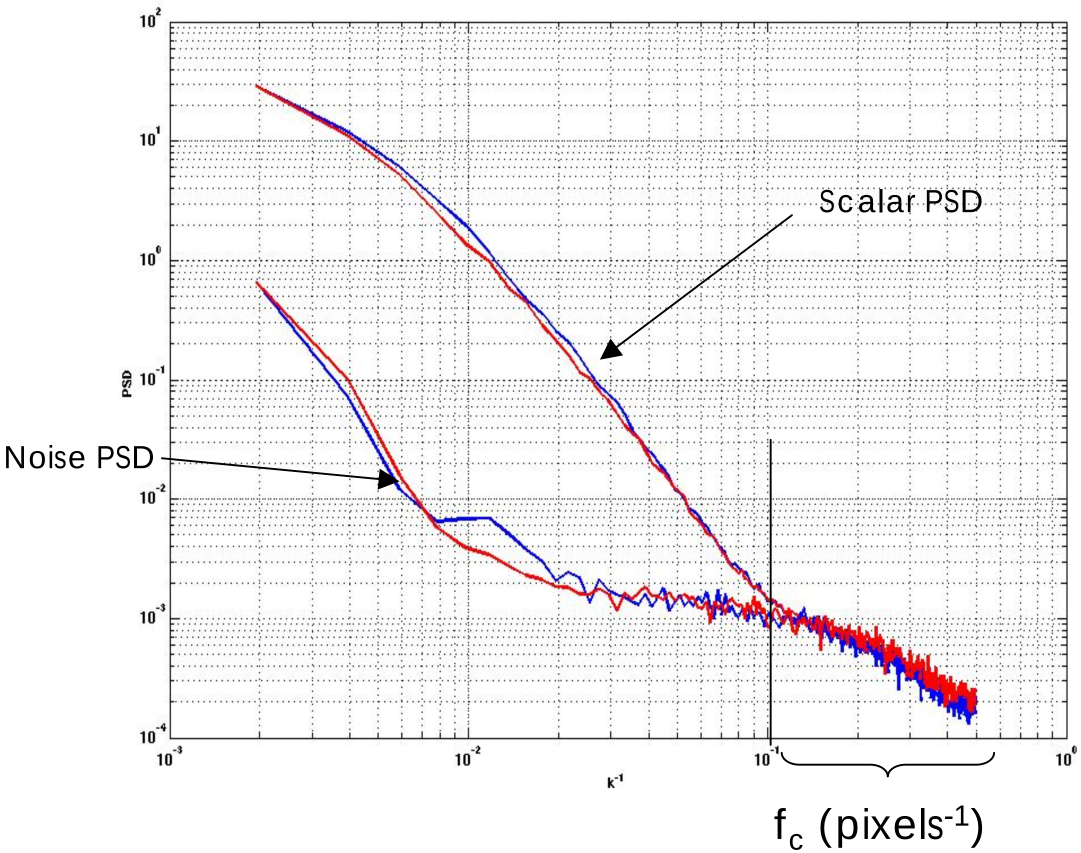
Effect on scalar spectrum

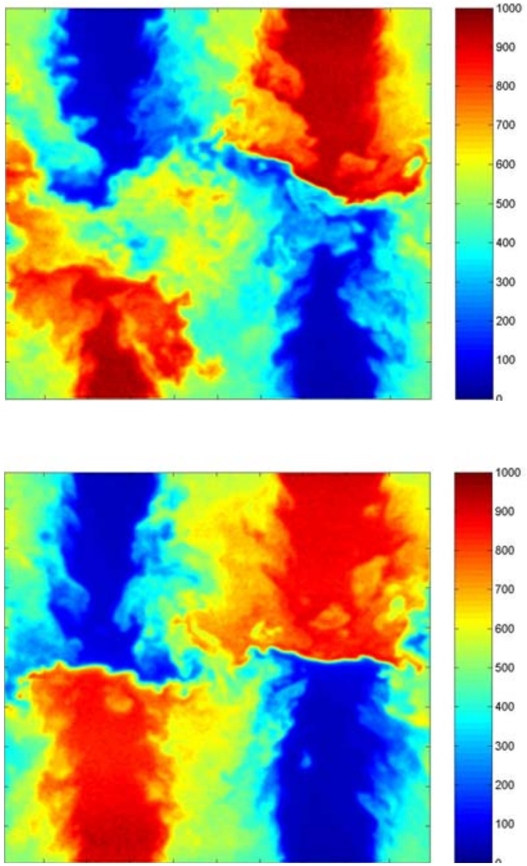
➔ 2D scalar spectra with FFT routines

➔ cut along x or y direction

➔ Cut off frequency f_c

➔ Need to be filtered ?





PLIF / RAYLEIGH SCATTERING : Residual problems

Optimum data filtering (1)

Measured signal :

$$s_M(x,y) \equiv h_S(x,y) \otimes s_F(x,y) + n_1(x,y) \quad \rightarrow \quad S_M(u,v) \equiv H_S(u,v) \otimes s_F(u,v) + n_1(u,v)$$

Design of an optimal filter (Wiener filter) : $\phi(u,v)$

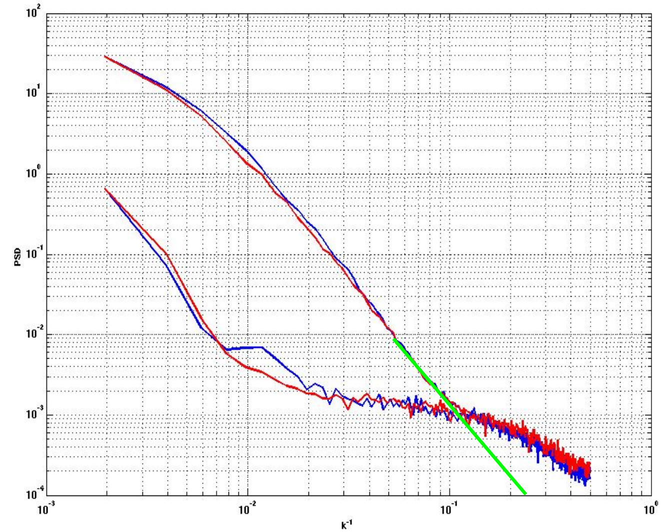
with an assumption : uncorrelated noise + H_S=1 (Dirac function)

Filtered signal : $\tilde{S}(x,y)$ with $S'(u,v)$; $\tilde{S}(u,v) = S_M(u,v).\phi(u,v)$

Optimal filter :

$$\phi(u,v) \approx \frac{\left|H_S(u,v).S'(u,v)\right|^2}{\left|S_M(u,v)\right|^2} = \frac{\left|S_M(u,v)\right|^2 - \left|N(u,v)\right|^2}{\left|S_M(u,v)\right|^2}$$

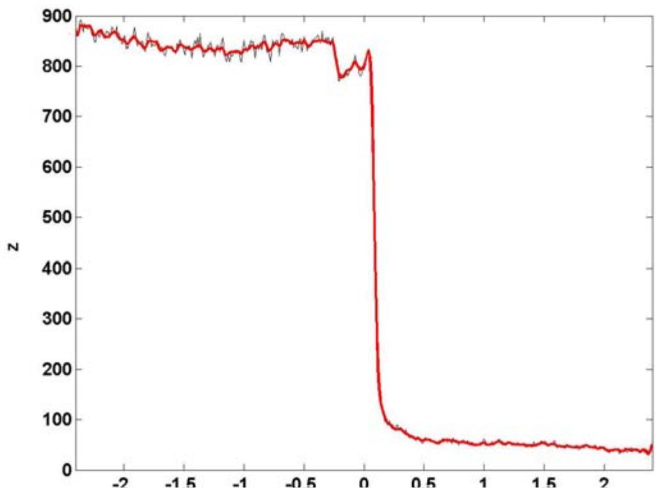
$$; \quad \frac{\text{Small scales modelling}}{\left|S_M(u,v)\right|^2}$$

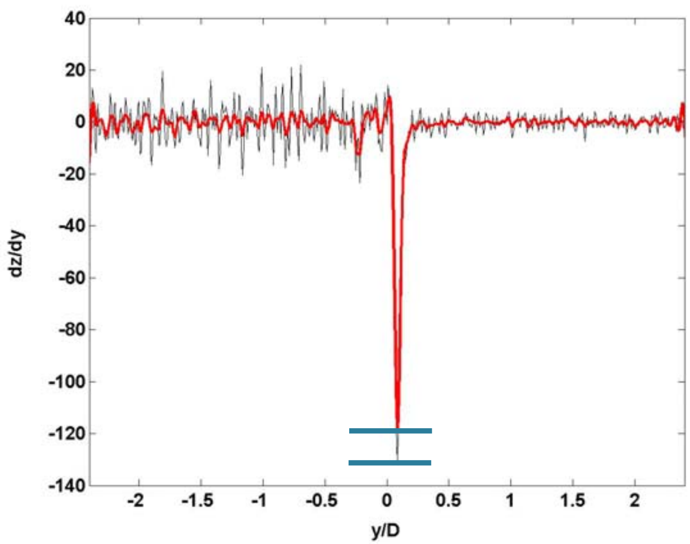


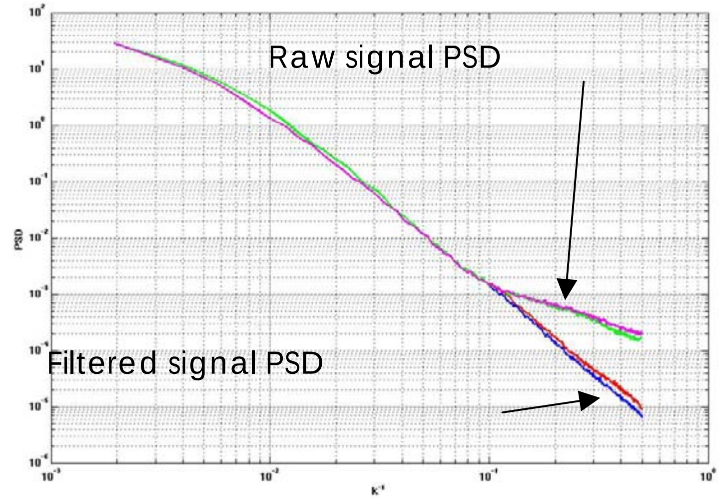
Krawczynski *et al.*, (2006)

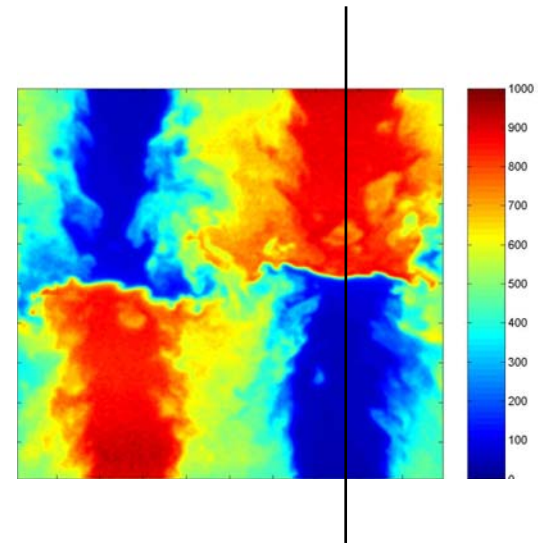
PLIF / RAYLEIGH SCATTERING : Residual problems

Optimum data filtering (2)









PLIF / RAYLEIGH SCATTERING : Conclusion

Advantages :

- Two dimensional approaches for scalar measurement
- Spatial statistics (No Taylor hypothesis)
- Very helpful for flow understanding (flow visualization)- Coherent view of the flow

Drawbacks :

- Limited bandwidth
- Poor spatial resolution. Strong limitation by finite size of the CCD, electronic noise, …
- Data need to be filtered (optimal filter)
- Limited temporal statistics (Laser frequency)

Strong complementarity with one point measurements

(Cold wire, 1D Rayleigh scattering or 1D PLIF)

Introduction : Contents and Objectives

Spatial velocity gradient measurements : PIV

- Principles and limitation of PIV technique
- Noise and spatial resolution estimation
- Derivative schema : optimization ?
- Accurate spatial velocity gradient measurement ?

Spatial scalar gradient measurements

- Principles and limitation of PLIF and Rayleigh scattering
- Noise and spatial resolution estimation
- Optimal data filtering

Illustrations and perspectives

- Laminar flame thickness measurement
- Quantitative measurements of molecular mixing
- Strain tensor analysis by DPSPIV

Application : Laminar flame thickness

(Lafay et al., 2007)

PREMIXED COMBUSTION

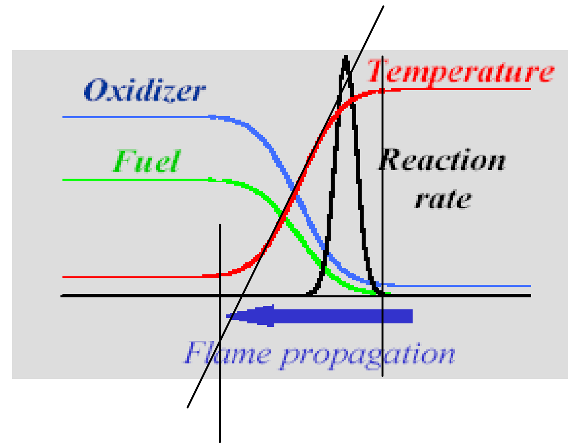
- Key parameter in combustion (equivalence ratio, fuel, pressure, temperature, strain…)

⇨ Heat release ratio τ=7-8, hundred chemical reactions, heat and mass transfer ….

- Thermal flame thickness : 0.1 to few mm

- Reaction zone flame thickness : 0.1x thermal thickness

⇨ **Necessity to measure temperature gradient**



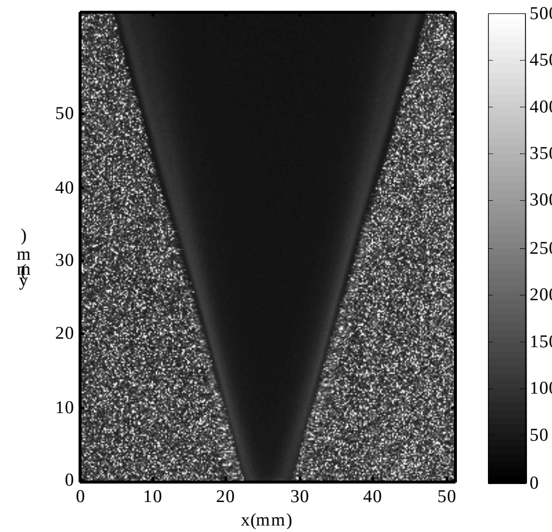
$$d_L = \frac{T_B - T_U}{(\nabla T)_{max}}$$

Laminar, premixed and unstretched flame !

⇨ **Flame stabilized on heated rod**

⇨ **Optical diagnostic = Rayleigh scattering**

⇨ **Numerical solution with detail chemistry**



V-shaped flame (Laser tomography)

Application : Laminar flame thickness

ENERGY EQUATION

$$\cancel{\rho C_p \frac{\partial T}{\partial t}} + \dot{m} C_p \frac{\partial T}{\partial x} = \underbrace{\frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right)}_{\text{Conduction}} - \underbrace{\sum_j \cancel{C_{p,j} J_{j,x}} \frac{\partial T}{\partial x}}_{\text{Species diffusion term}} - \underbrace{\sum_j h_j^0 \dot{\omega}_j W_j}_{\text{Heat release rate for each species j}}$$

with for a one-dimensional flame: $\dot{m} = \rho u \;\; (kg/m^2 s)$

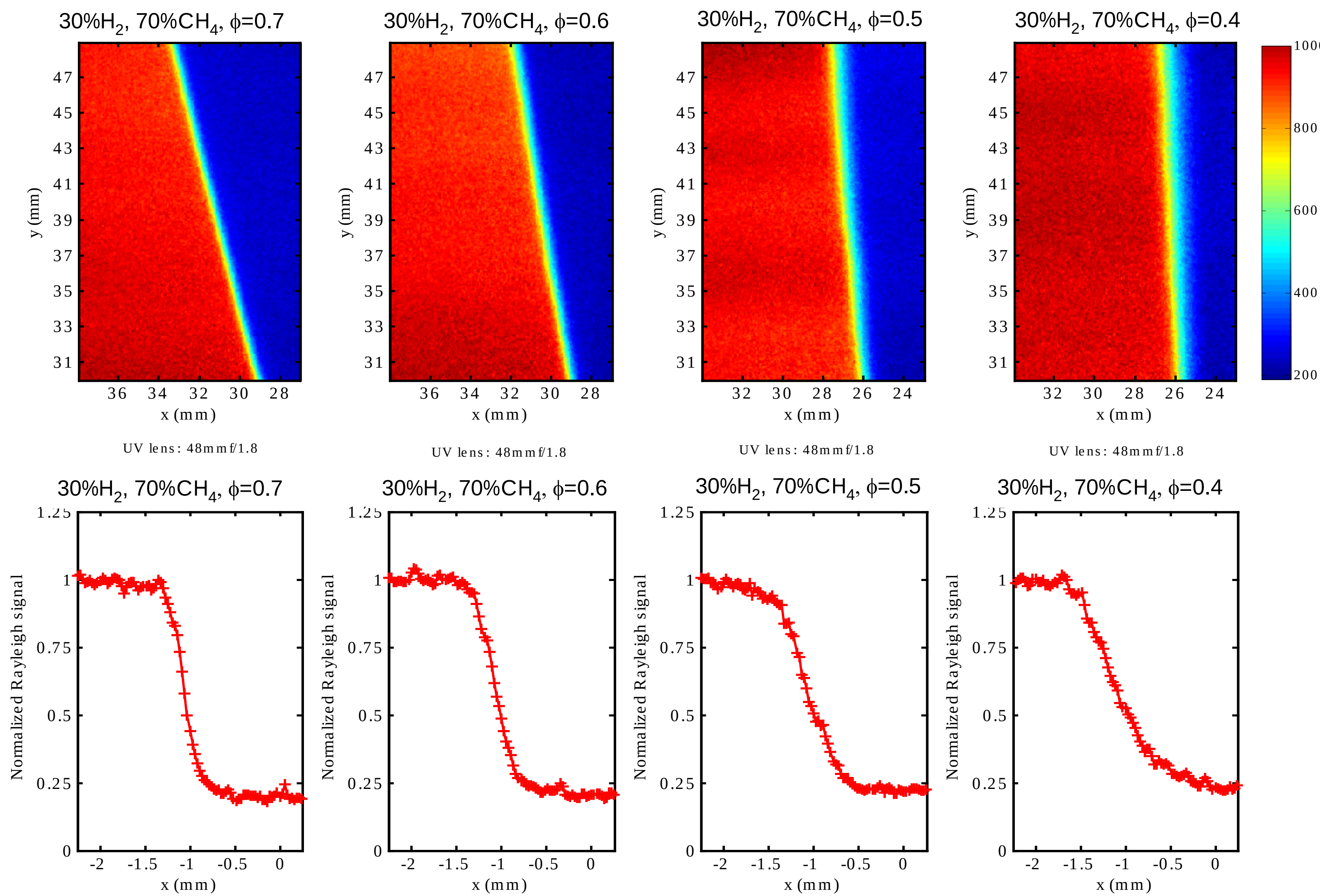
Flame thickness $\quad d_L = \dfrac{T_B - T_U}{(\nabla T)_{\max}}$

➔ conditioned by conduction and heat release fluxes

EXPERIMENTAL SET-UP

- Vertical open wind tunnel, mean flow velocity : 4m/s and u'=0.06m/s
- Rayleigh scattering, Nd-YAG laser 355nm, 230mJ/pulse
- ICCD camera Flamestar (LaVision), 384x286 pixel^2 , 12 bits
- Two different UV lenses : - 48 mm, f/1.8, CERCO, Spatial resolution 270µm
  - 92 mm, f/4.2, CERCO, Spatial resolution 167µm

Application : Laminar flame thickness



Application : Laminar flame thickness

UV lens	f number	Magnification ratio	Spatial resolution	Noise level
92 mm	1/4.2	30 pixels/mm	270 µm	High
48 mm	1/1.8	19 pixels/mm	167 µm	Low

Main role of noise and spatial resolution

48 mm UV lens :

If measured scale < 4.spatial resolution

→ Under-resolution phenomena

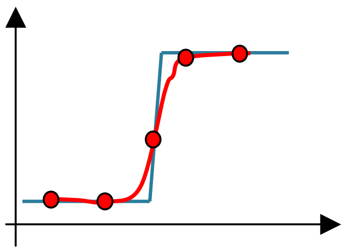
→ Over estimation of flame thickness

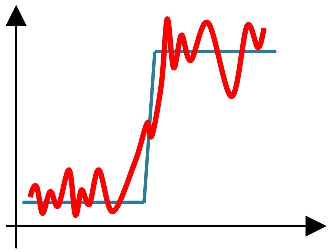
92 mm UV lens:

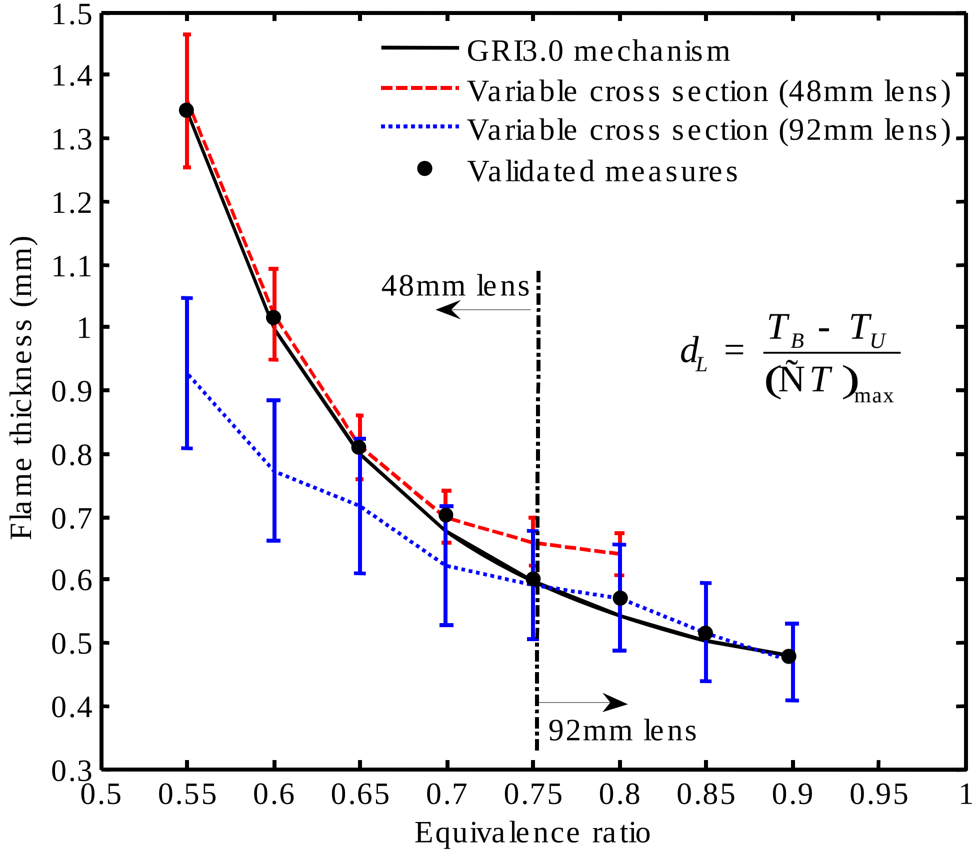
For low spatial gradient, main role of noise

→ Under estimation of flame thickness

→ Data filtering ?







Application : Quantitative measurements of molecular mixing (King *et al.*, 1997)

Interest :

- Numerous applications for combustion process since chemical reactions occurs when fuel and oxidant streams are mixed at the molecularly states

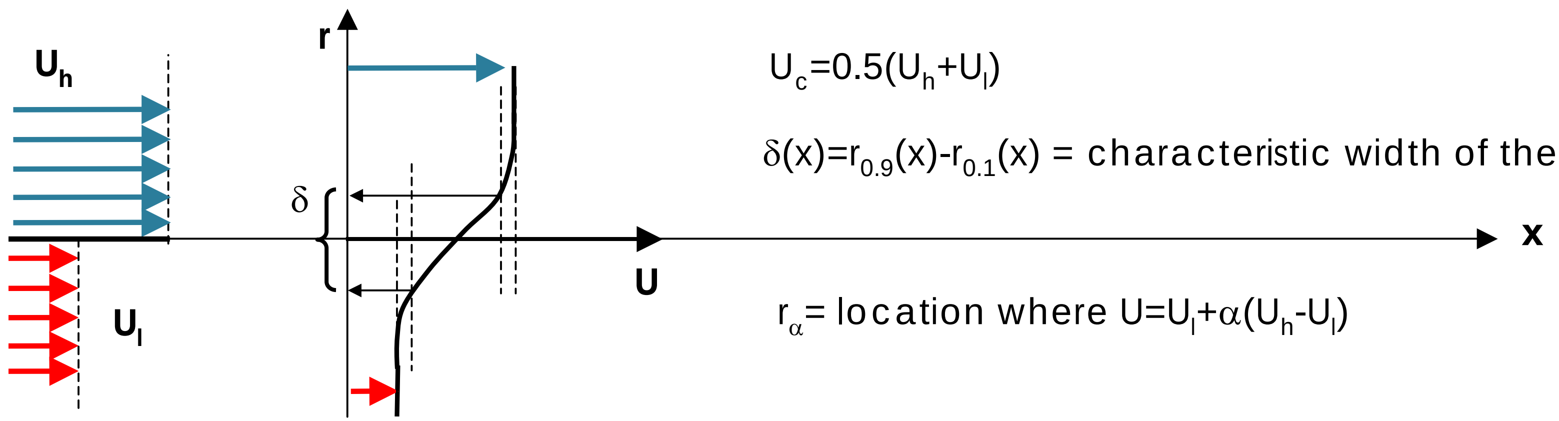
- Local composition of the flow : **mixture fraction field Z(x,t)** with $\varepsilon < Z < 1-\varepsilon$ representing mixed fluid for small values of ε.

- Statistics of mixed fluids PDF(Z)=f(x, Re, Sc, …)

- Measurements require full resolution of time/space scales

- How to quantify the molecular mixing with under-resolved technique ?

Application : Turbulent free shear layer



$U_c=0.5(U_h+U_l)$

$\delta(x)=r_{0.9}(x)-r_{0.1}(x)$ = characteristic width of the flow

r_α= location where $U=U_l+\alpha(U_h-U_l)$

Application : Quantitative measurements of molecular mixing

Statistics :

- Instantaneous mixture fraction field Z

- Pdf of Z, P(Z)

- Mixed fluid thickness fraction δ_m = average molecularly mixed fluid fraction across the mixing layer (mixing efficiency of the layer)

$$\frac{\delta_m(x, Sc, Re)}{\delta} = \int_0^{\infty} \int_{\varepsilon}^{1-\varepsilon} P(Z, x, r)\, dZ\, dr$$

Solutions :

-Flip experiment in reactive turbulent free shear layer (Koochesfahani *et al.*, 1985)

$\boxed{\text{-Dual tracer technique (King } et\ al.\text{, 1997; } Meyer\ et\ al.,\ 2002\text{)}}$

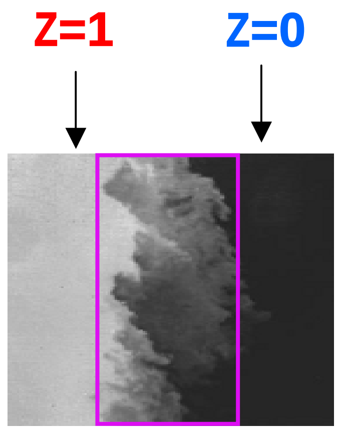
Application : Quantitative measurements of molecular mixing

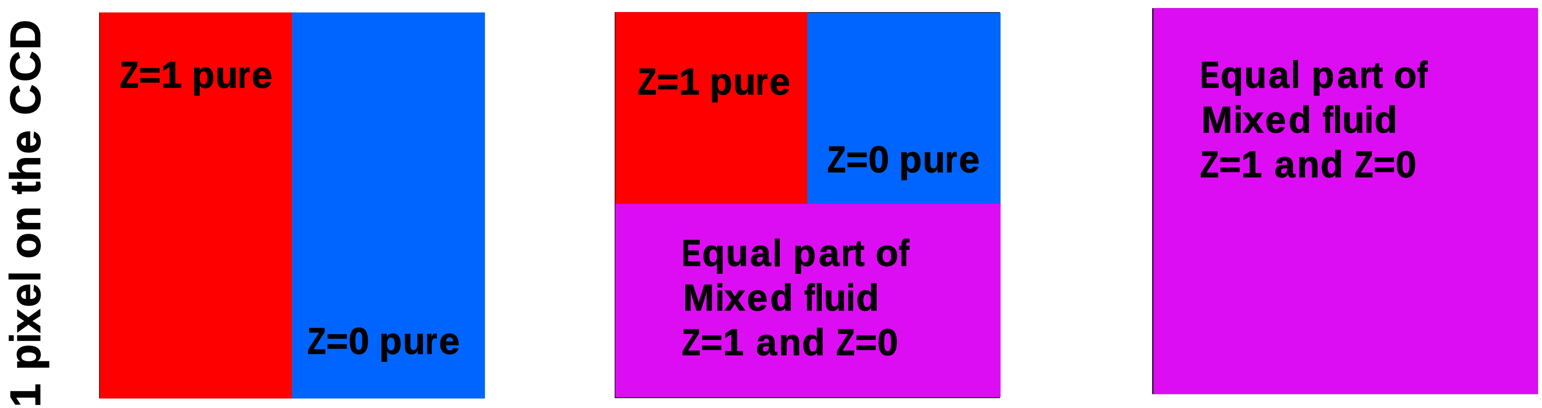
Problem position : Passive scalar

- Acetone PLIF measurements : $S_F(Z)$
- Mixing layer geometry : 2 fluids

(Z=0 air and Z=1 air + %acetone)

- Ideal spatial resolution of 1 pixel





$S_F(Z)=0,5$ $S_F(Z)=0,5$ $S_F(Z)=0,5$

Application : Quantitative measurements of molecular mixing

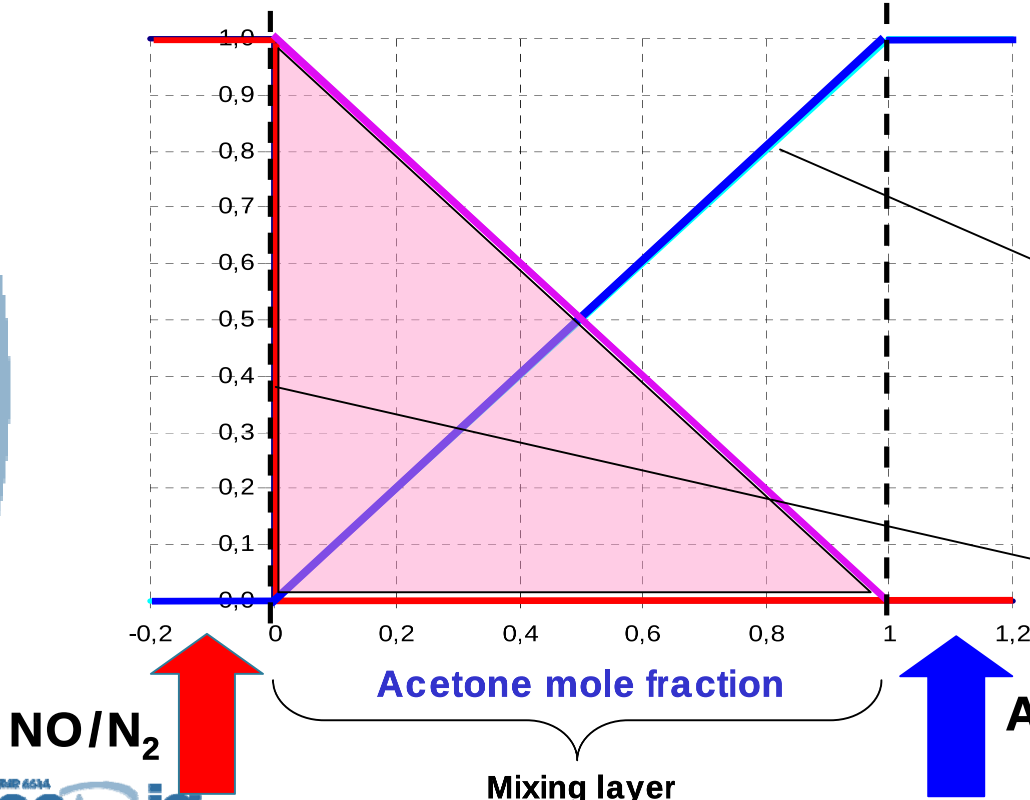
Solution : Dual tracer technique

- Highly quenched tracer PLIF : Nitric Oxide (NO), Q >> A+K

- No quenched tracer PLIF : Acetone, K >> A+Q

$$S_F(x,y) \propto Z \frac{A}{A+Q+K}$$

➔ **Mixing between 2 fluids : (NO/N_2) and (Acetone/air)**



Normalized fluorescence signal (Z_{Ac})

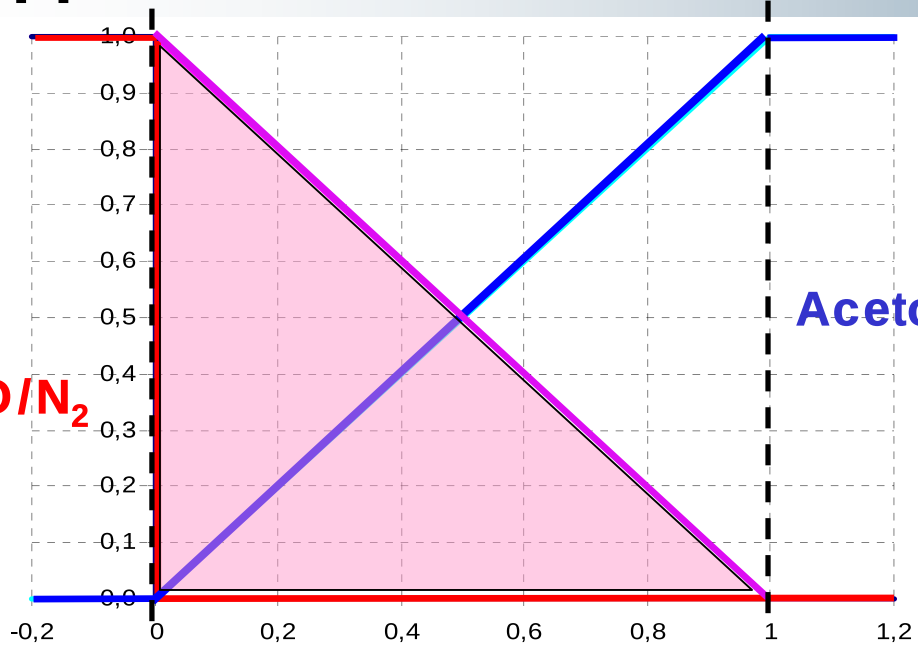
Normalized fluorescence signal (Z_{NO})

Normalized fluorescence signal for ($1- Z_{Ac}$)

$$\frac{S_{F(Ac,mix)}}{S_{F(Ac,pure)}} = Z_{Ac}$$

$$\frac{S_{F(NO,mix)}}{S_{F(NO,pure)}} = Z_{NO,pure}$$

Application : Quantitative measurements of molecular mixing



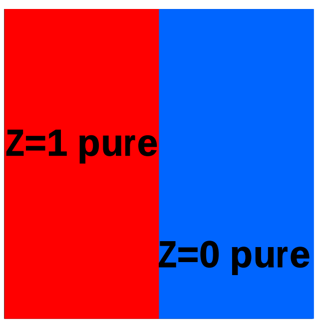
Mixed fluid fraction Z:

$$Z = 1 - Z_{Ac} - Z_{NO,pure}$$

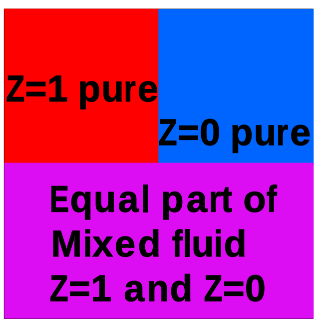
Mixing efficiency :

$$0 \le \eta_{mix} = \frac{Z}{1 - Z_{Ac}} \le 1$$

1 pixel on the CCD



$S_F(Ac)=0,5$
$S_F(NO)=0,5$
$Z=0$
$\eta_{NOmix}=0$



$S_F(Ac)=0,5$
$S_F(NO)=0,25$
$Z=0,25$
$\eta_{NOmix}=0,5$

$S_F(Ac)=0,5$
$S_F(NO)=0$
$Z=0.5$
$\eta_{NOmix}=1$

Application : Quantitative measurements of molecular mixing

Advantages :

- Towards a measurement of mixing state with sub-pixel resolution
- Differentiation between molecularly mixed state and small scale convection

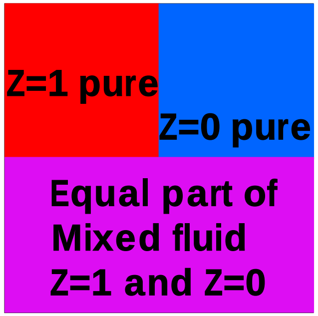
BUT : Drawbacks !

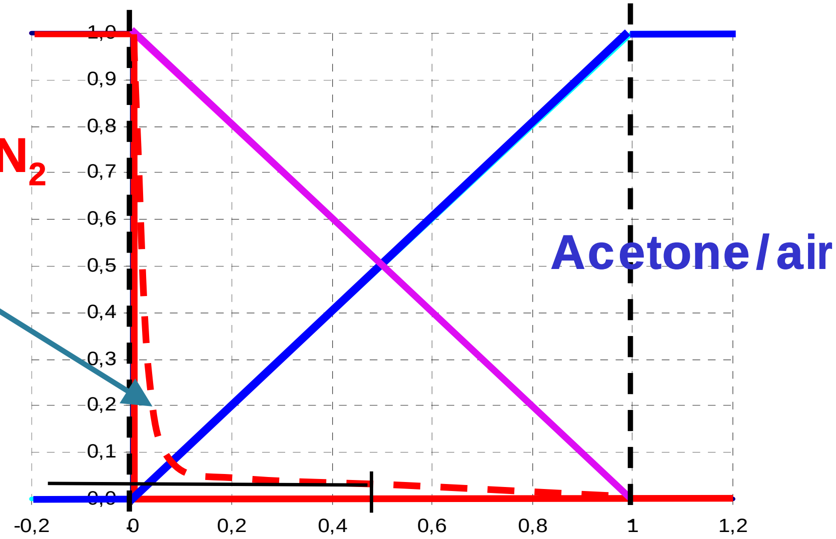
- Need high quality images without noise (difference operation for Z estimation)
- 2 limitations :
    - **Small local concentration of acetone mole fraction**
    - **Finite spatial resolution at high Re**

Application : Quantitative measurements of molecular mixing

Assumption of cold chemistry not fully true → Q_{NO} not infinite.

NO signal is not completely quenched even when molecularly mixed with the fluid 2





Cold chemistry fully valid :

$S_F(Ac)=0,5$
$S_F(NO)=0,25$
$Z=0,25$
$\eta_{NOmix}=0,5$

Correction :

$$Z = Z_{NO}\cdot\frac{Z_{NO}-Z_{NO,\exp}}{Z_{NO}-Z_{NO_2 Lev}}$$

What we really measure :

$S_F(Ac)=0,5$
$S_F(NO)=0,25+0.05=0.255$
$Z=0,245$ → 2% error (Higher for low acetone concentration)
$\eta_{NOmix}=0,49$

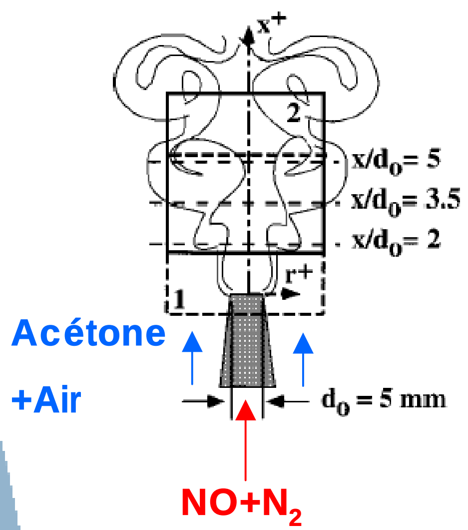
$$Z_{NO_{mix}} = 0,5.\frac{0,5-0,255}{0,5-0,01} = 0,25$$

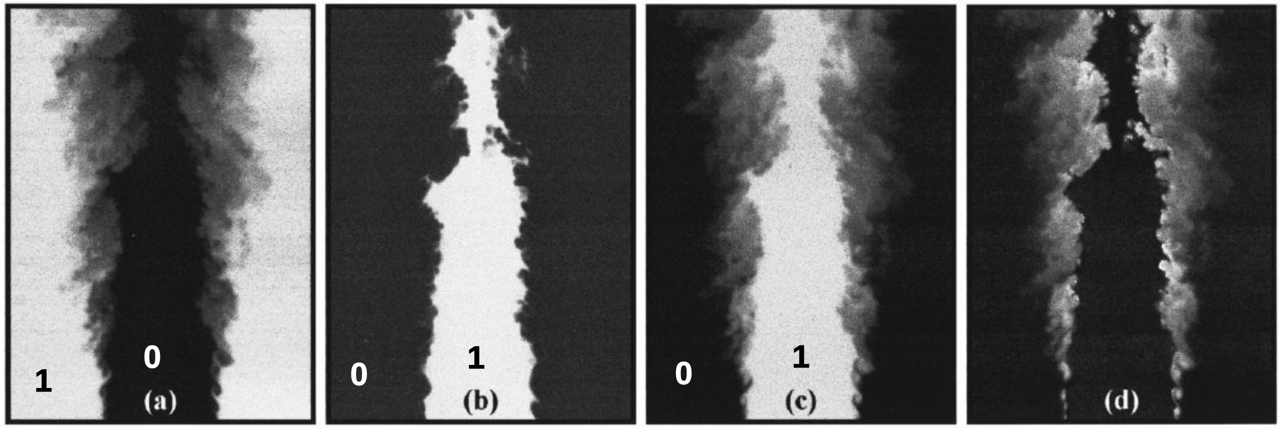
$$\eta_{mix} = \frac{0,25}{0,5} = 50\%$$

Application : Quantitative measurements of molecular mixing

Turbulent jet : near field study (King et al., 1999)

Re_D = 10.000





Normalized S_F(Acetone) = f_{tcf}

Normalized S_F(NO) = f_{pjet}

1 - Normalized S_F(Acetone)= f_{tjet}

1 - Normalized S_F(Acetone) – Normalized S_F(NO) = Z

f_{tcf} = total co-flow fluid fraction

f_{pjet} = pure jet fluid fraction

f_{tjet}= Total jet fluid fraction

Z = f_{mjet} = molecularly mixed fluid fraction = quantitative measurement of averaged molecularly mixed jet fluid fraction throughout the measurement volume imaged by a pixel

Mixing efficiency η_{mix}= f_{mjet} /f_{tjet}

→ Observation of small amount of sub-resolution stirring detected

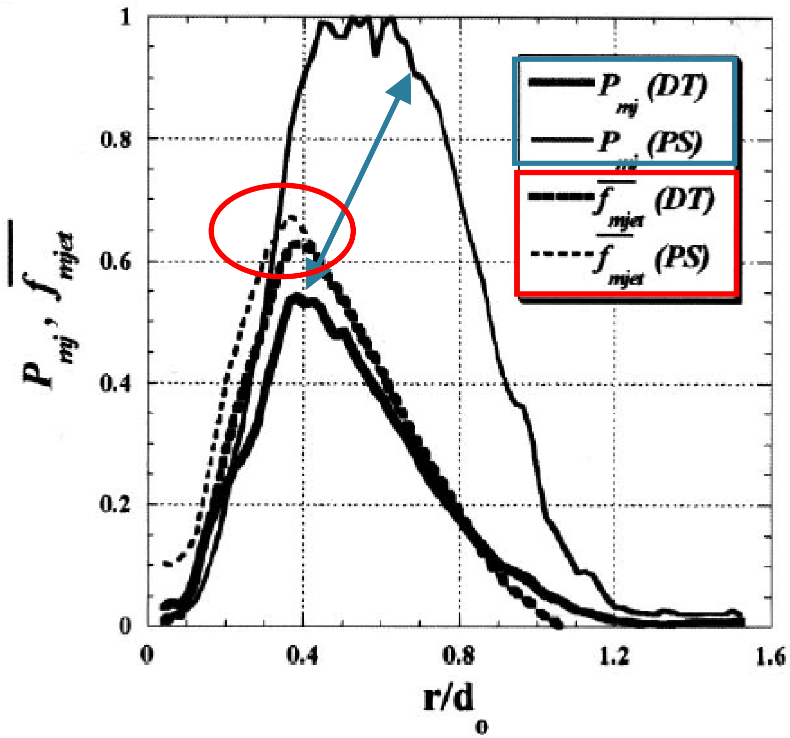
Application : Quantitative measurements of molecular mixing

Interest of dual-tracer technique :

- Radial profiles of averaged mixed jet fluid fraction : f_{mjet}

→Very small difference between the 2 methods

→ Measurement of **averaged** fluid properties quite accurate



- Radial profiles of probability of mixed jet fluid (**instantaneous information**)

→ Strong over-estimation of this PDF by passive scalar technique

→ Consequence on the mixed fluid thickness fraction δ_m

• Passive scalar measurements give the probability that mixed jet fluid at any concentration will occur in the measurement volume

• Dual tracer technique may be possible the extraction of fluid element molecularly mixed in the volume element.

Application : Estimation of strain tensor by DPSPIV

(Mullin *et al.*, 2006a)

DPSPIV = Dual Plane Stereoscopic PIV

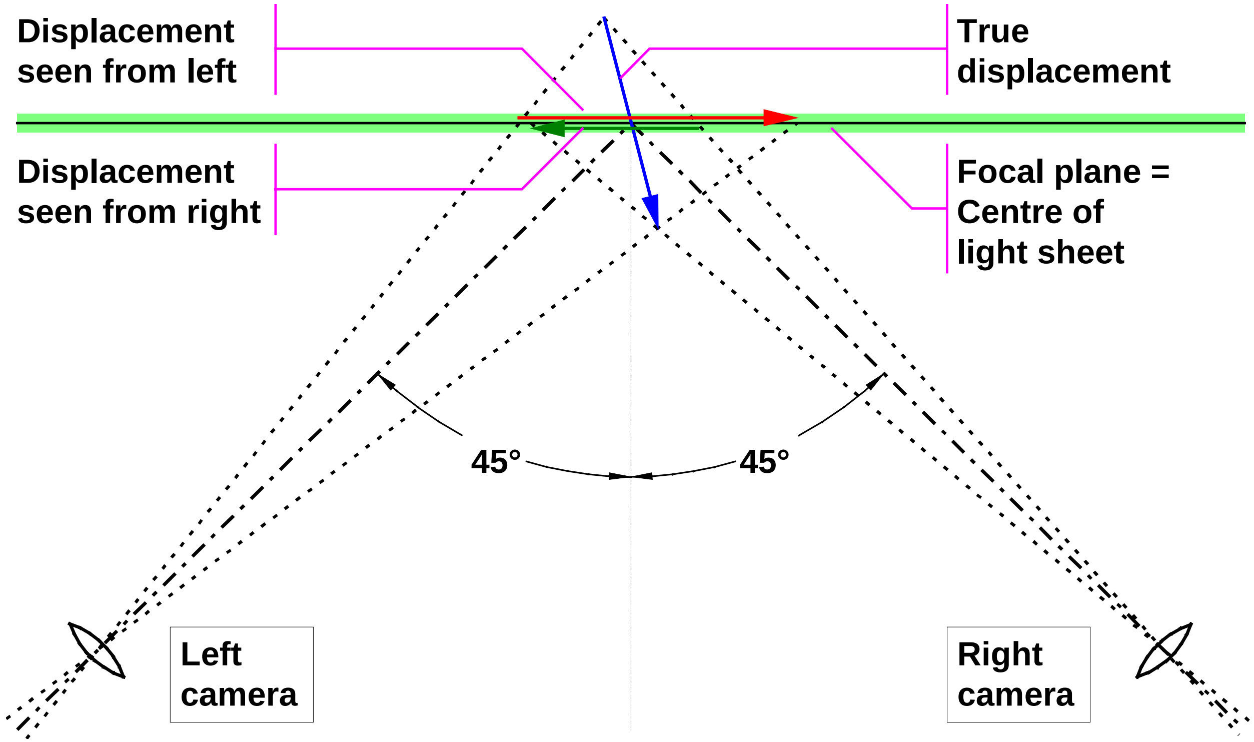
→ 3 velocity components for two planes separated by Δz

→ Estimation of full strain rate tensor without assumptions

Technique	Velocity Components	∇u Components	Dynamical Quantities
PIV	u, v	$\frac{\partial u}{\partial x}, \frac{\partial u}{\partial y}$ $\frac{\partial v}{\partial x}, \frac{\partial v}{\partial y}$	$\varepsilon_{xx}, \varepsilon_{yy}$ ε_{xy} ω_z
Stereo PIV	u, v, w	$\frac{\partial u}{\partial x}, \frac{\partial u}{\partial y}$ $\frac{\partial v}{\partial x}, \frac{\partial v}{\partial y}$ $\frac{\partial w}{\partial x}, \frac{\partial w}{\partial y}$	$\varepsilon_{xx}, \varepsilon_{yy}$ ε_{xy} ω_z
Dual-Plane Stereo PIV	$u, v, w(\mathrm{x})$ $u, v, w(\mathrm{x} + d\mathrm{x})$	$\frac{\partial u}{\partial x}, \frac{\partial u}{\partial y}, \frac{\partial u}{\partial z}$ $\frac{\partial v}{\partial x}, \frac{\partial v}{\partial y}, \frac{\partial v}{\partial z}$ $\frac{\partial w}{\partial x}, \frac{\partial w}{\partial y}, \frac{\partial w}{\partial z}$	$\varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{zz}$ $\varepsilon_{xy}, \varepsilon_{yz}, \varepsilon_{zx}$ $\omega_x, \omega_y, \omega_z$ $\nabla \cdot \mathrm{u}(\mathrm{x}, t)$ $\omega_i \omega_i$ $\omega_i \varepsilon_{ij} \omega_j(\mathrm{x}, t)$ $2\nu\ \varepsilon_{ij}\varepsilon_{ij}(\mathrm{x}, t)$

Application : Estimation of strain tensor by DPSPIV

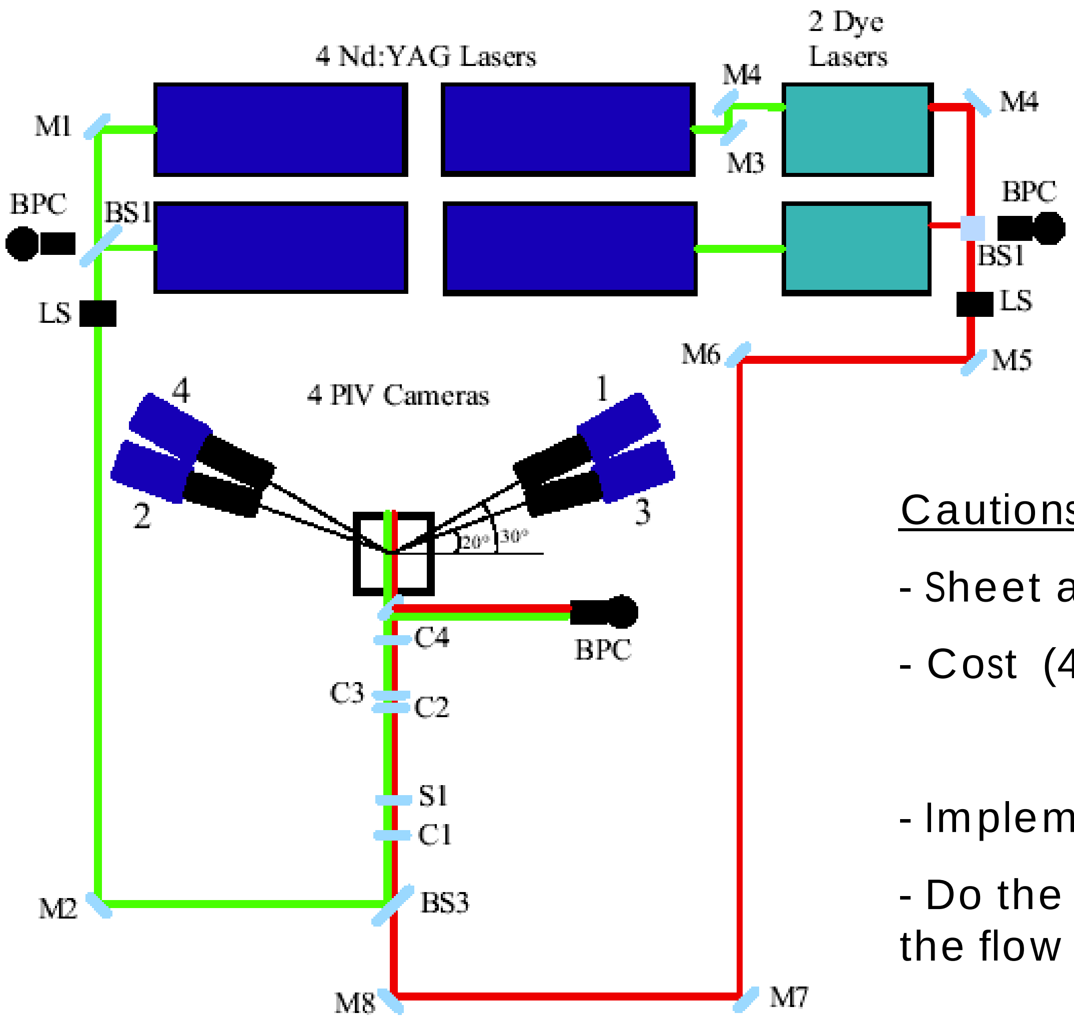
Stereoscopic PIV : principle



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

Application : Estimation of strain tensor by DPSPIV

Dual Plane Stereoscopic PIV : principle



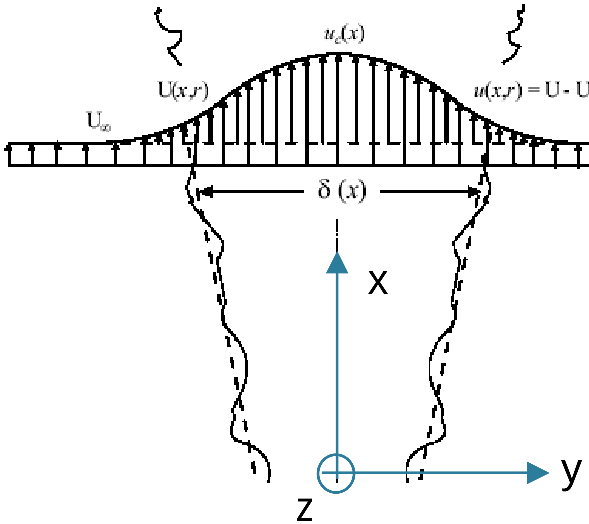
Cautions :

- Sheet alignment and accuracy on Δz
- Cost (4 lasers and 4 cameras .. !)

  → ≈ 450 k€
- Implementation not easy
- Do the results better help to understand the flow ? → appropriate use

Application : Estimation of strain tensor by DPSPIV

Strain tensor measurement in a low-turbulent jet (Mullin *et al.*, 2006a ; Mullin *et al.*, 2006b)

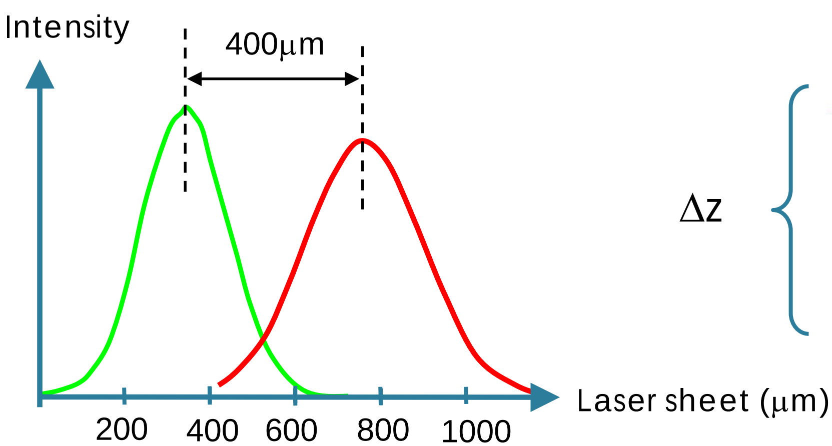


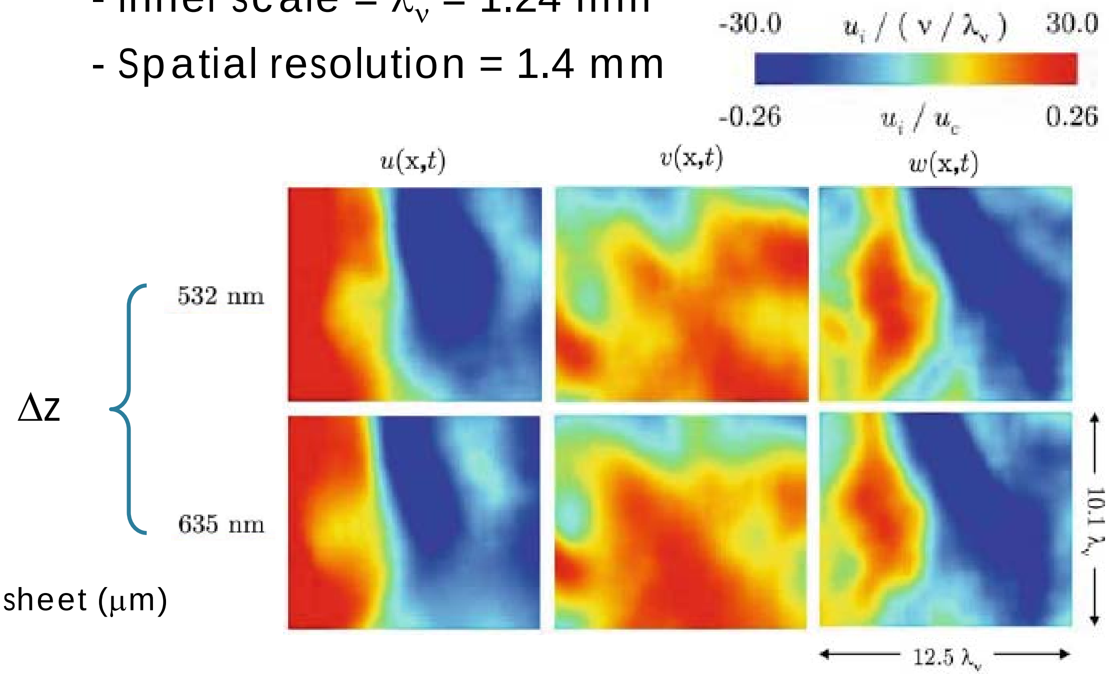
Operating conditions :

- Re_δ=6.000
- x= 17cm
- U_c=1.2m/s
- Field of view (15.5x12.5 mm²)
- Outer scale = δ(x)=7.4cm
- Inner scale = λ_ν = 1.24 mm
- Spatial resolution = 1.4 mm

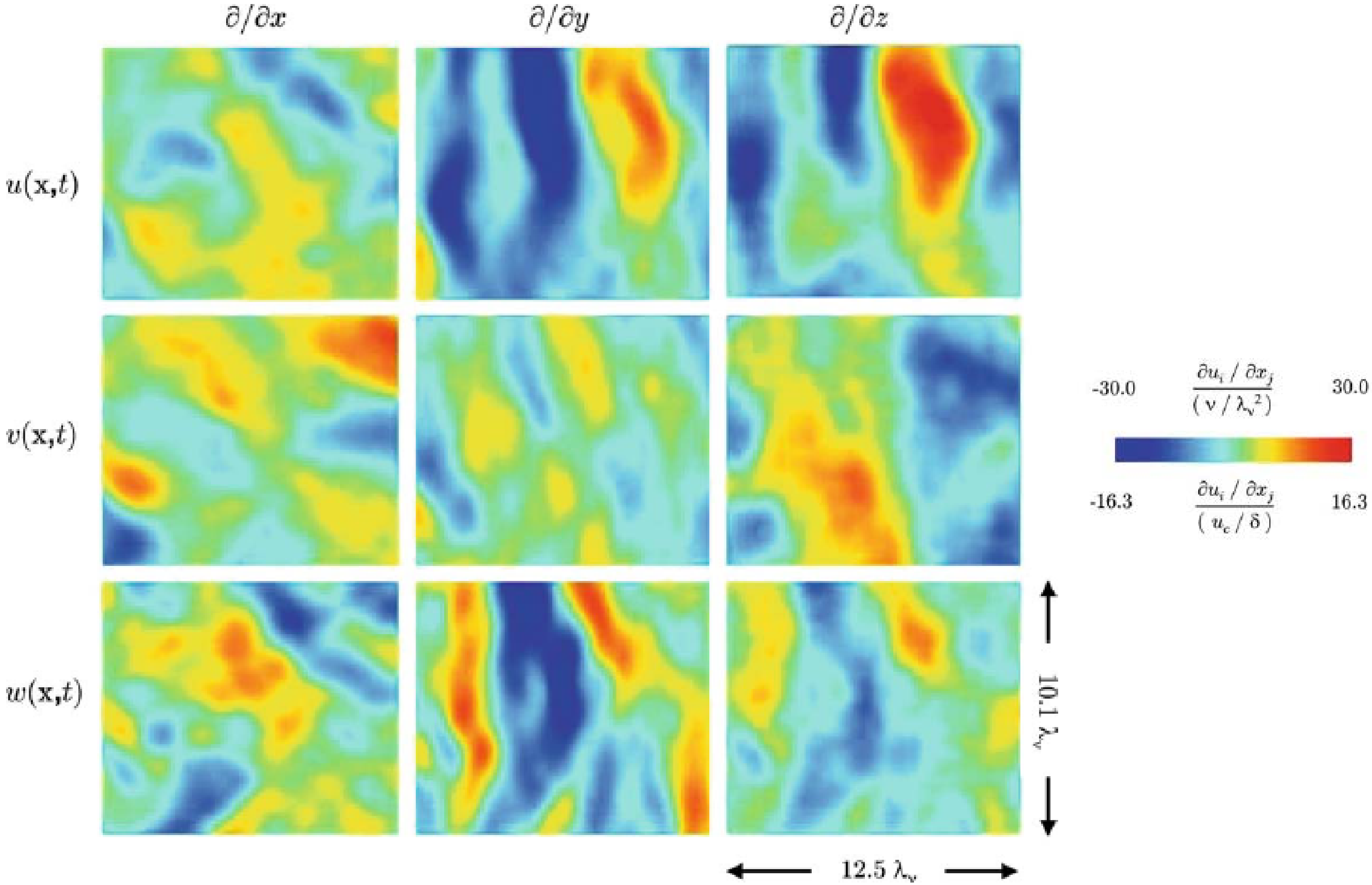
$$Re_\delta = \frac{U_c \delta}{\nu}$$

$$\lambda_\upsilon = \Lambda \delta \, Re_\delta^{-3/4}$$





Application : Estimation of strain tensor by DPSPIV



Conclusions

Optical diagnostics are powerful tools for flow understanding and analysis.

BUT, strong limitation by their limited band-width

Necessity to use with other measurement probes (1D) highly spatially or temporally resolved (HWA ...)

Acknowledgements

- Luminita Danaila
- Guillaume Boutin
- Yannick Lafay
- Jean-François Krawczynski

...

Bibliography

Particle Image Velocimetry

1) Scarano, F. and Riethmuller, M. L. (1999). "Iterative multigrid approach in PIV image processing with discrete window offset." *Experiments in Fluids,* **V26**, 6, pp.513-523.

2) Lecordier, B. (1997). "Etude de l'interaction de la propagation d'une flamme de prémélange avec le champ aréodynamique par association de la tomographie laser et de la PIV." PhD Thesis report, Université de Rouen, France,

3) Raffel, M., Willert, C. and Kompenhans, J. (2001). "Particle Image Velocimetry: A Practical Guide ", Springer, 253p.

4) Foucaut, J. M., Carlier, J. and Stanislas, M. (2004). "PIV optimization for the study of turbulent flow using spectral analysis." *Measurement Science and Technology,* **15**, 6, pp.1046-1058.

5) Stanislas, M., Okamoto, K., Kahler, C. J. and Westerweel, J. (2005). "Main results of the Second International PIV Challenge." *Experiments in Fluids,* **39**, 2, pp.170-191.

6) Foucaut, J. M. and Stanislas, M. (2002). "Some considerations on the accuracy and frequency response of some derivative filters applied to particle image velocimetry vector fields." *Measurement Science and Technology,* **13**, 7, pp.1058-1071.

7) Lecordier, B., Demare, D., Vervisch, L. M. J., Reveillon, J. and Trinite, M. (2001). "Estimation of the accuracy of PIV treatments for turbulent flow studies by direct numerical simulation of multi-phase flow." *Measurement Science and Technology,* **12**, 9, pp.1382-1391.

8) Stitou, A. and Riethmuller, M. L. (2001). "Extension of PIV to super resolution using PTV." *Measurement Science and Technology,* **12**, 9, pp.1398-1403.

Bibliography

Tracer PLIF and Rayleigh scattering

1) Schulz, C. and Sick, V. (2005). "Tracer-LIF diagnostics: Quantitative measurement of fuel concentration, temperature and fuel/air ratio in practical combustion systems." *Progress in Energy and Combustion Science,* **31**, 1, pp.75-121.

2) Kohse-Höinghaus, K. and Jeffries, J. B. (2002). "Applied combustion diagnostics." Taylor and Francis, New York, 705p.

3) Daily, J. W. (1997). "Laser induced fluorescence spectroscopy in flames." *Progress in Energy and Combustion Science,* **23**, 2, pp.133-199.

4) Lozano, A., Yip, B. and Hanson, R. K. (1992). "Acetone: a tracer for concentration measurements in gaseous flows by planar laser-induced fluorescence." *Experiments in Fluids,* **13**, 6, pp.369-376.

5) Miles, R. B., Lempert, W. R. and Forkey, J. N. (2001). "Laser Rayleigh scattering." *Measurement Science and Technology,* **12**, 5, pp.R33-R51.

6) Zhao, F.-Q. and Hiroyasu, H. (1993). "The applications of laser Rayleigh scattering to combustion diagnostics." *Progress in Energy and Combustion Science,* **19**, 6, pp.447-485.

7) Wang, G. H., Clemens, N. T., Barlow, R. S. and Varghese, P. L. (2007). "A system model for assessing scalar dissipation measurement accuracy in turbulent flows." *Measurement Science & Technology,* **18**, 5, pp.1287.

8) Krawczynski, J. F., Renou, B., Danaila, L. and Demoulin, F. X. (2006). "Small-scale measurements in a partially stirred reactor." *Experiments in Fluids,* **40**, 5, pp.667-682.

Bibliography

Applications

1) Buch, K. A. and Dahm, W. J. A. (1998). "Experimental study of the fine-scale structure of conserved scalar mixing in turbulent shear flows. Part 2. Sc approximately equals 1." *Journal of Fluid Mechanics,* **364**, pp.1-29

2) Su, L. K. and Clemens, N. T. (2003). "The structure of fine-scale scalar mixing in gas-phase planar turbulent jets." *Journal of Fluid Mechanics,* **488**, 488, pp.1-29.

3) Lafay, Y., Renou, B., Cabot, G and Boukhalfa, A.M. (2007). " Experimental and numerical investigation of H_2 enrichment effect on laminar methane-air flame thickness." Submitted to *Combustion and Flame.*

4) Degardin, O., Renou, B. and Boukhalfa, A. M. (2006). "Simultaneous measurement of temperature and fuel mole fraction using acetone planar induced fluorescence and Rayleigh scattering in stratified flames." *Experiments in Fluids*, **40**, 3, pp.452-463.

5) Koochesfahani, M. M., Dimotakis, P. E. and Broadwell, J. E. (1985). "'Flip' experiment in a chemically reacting turbulent mixing layer." *AIAA Journal,* **23**, 8, pp.1191-1194.

6) King, G. F., Lucht, R. P. and Dutton, C. J. (1997). "Quantitative dual-tracer planar laser-induced fluorescence measurements of molecular mixing." *Optics Letters,* **22**, 9, pp.633-635.

7) King, G. F., Dutton, J. C. and Lucht, R. P. (1999). "Instantaneous, quantitative measurements of molecular mixing in the axisymmetric jet near field." *Physics of Fluids,* **11**, 2, pp.403.

8) Meyer, T. R., King, G. F., Martin, G. C., Lucht, R. P., Schauer, F. R. and Dutton, J. C. (2002). "Accuracy and resolution issues in NO/acetone PLIF measurements of gas-phase molecular mixing." *Experiments in Fluids,* **32**, 6, pp.603-611.

9) Mullin, J. A. and Dahm, W. J. A. (2006). "Dual-plane stereo particle image velocimetry measurements of velocity gradient tensor fields in turbulent shear flow. I. Accuracy assessments." *Physics of Fluids,* **18**, 3, pp.035101.

10) Mullin, J. A. and Dahm, W. J. A. (2006). "Dual-plane stereo particle image velocimetry measurements of velocity gradient tensor fields in turbulent shear flow. II. Experimental results." *Physics of Fluids,* **18**, 3, pp.035102.