Particle Imaging Velocimetry: principles, limitations, errors

Joel Sommeria, LEGI-CNRS, Grenoble, France

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OVERVIEW

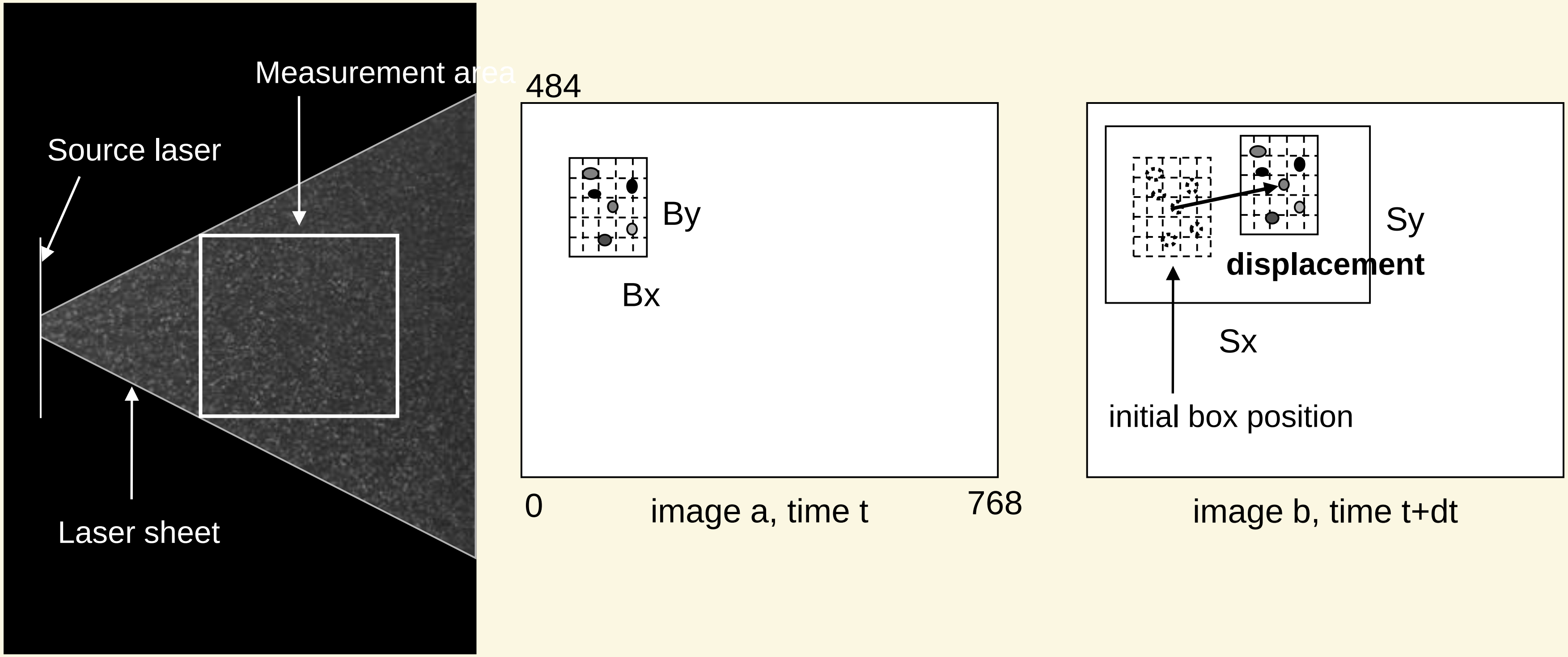
1-Basic principles of PIV

2-Error estimates

3-Hierarchical algorithms

4-3D generalisations

Principle of PIV



Correlation box: (Bx, By)

Search box (Sx, Sy)

Image inter-correlation

We first calculate the box intensity averages

$$\overline{I_a} = \frac{1}{B_x B_y} \sum_{k=1}^{B_x} \sum_{l=1}^{B_y} I_a(k,l)$$

$$\overline{I_b} = \frac{1}{B_x B_y} \sum_{k=1}^{B_x} \sum_{l=1}^{B_y} I_b(k+i,l+j)$$

Ve substract this average to each intensity, and calculate the ormalized by the variance, or covariance $c(i,j)$ as

$$c(i,j) = \frac{\sum_{k=1}^{B_x} \sum_{l=1}^{B_y} (I_a(k,l) - \overline{I_a})(I_b(k+i,l+j)}{[\sum_{k=1}^{B_x} \sum_{l=1}^{B_y} (I_a(k,l) - \overline{I_a})^2 \ \sum_{k=1}^{B_x} \sum_{l=1}^{B_y} (I_b(k+i,l}$$

or each displacement (i,j) allowed by the search box(3.2.2).

Calculation of c(i,j):

-Direct calculation

-FFT (faster for large correlation boxes, but edge effects)

-Optical Fourier transform (obsolete)

-Find the displacement (i,j) which maximizes the correlation c(i,j)

-Interpolate c(i,j) to get sub-pixel resolution

PIV/CIV vs particle tracking (PTV)

Particle tracking:

Detect individual particles (luminosity maximum)

Follow particle positions by continuity

- Tracking suitable for rare particles
- PIV (CIV) suitable for large particle concentration (pattern matching)

typically > 5 particles / (correlation box)

The art of particle seeding

-Density close to fluid (avoid sedimentation)

-Good optical reflectivity, spherical shape optimal

-Minimum visible size to reduce sedimentation and laser absorbsion

-Optimal seeding density is about 0.05 particle/px.

-Avoid coagulation (use soap)

Illumination

-Laser sheet generally used to isolate a plane:

two methods of sheet generation:

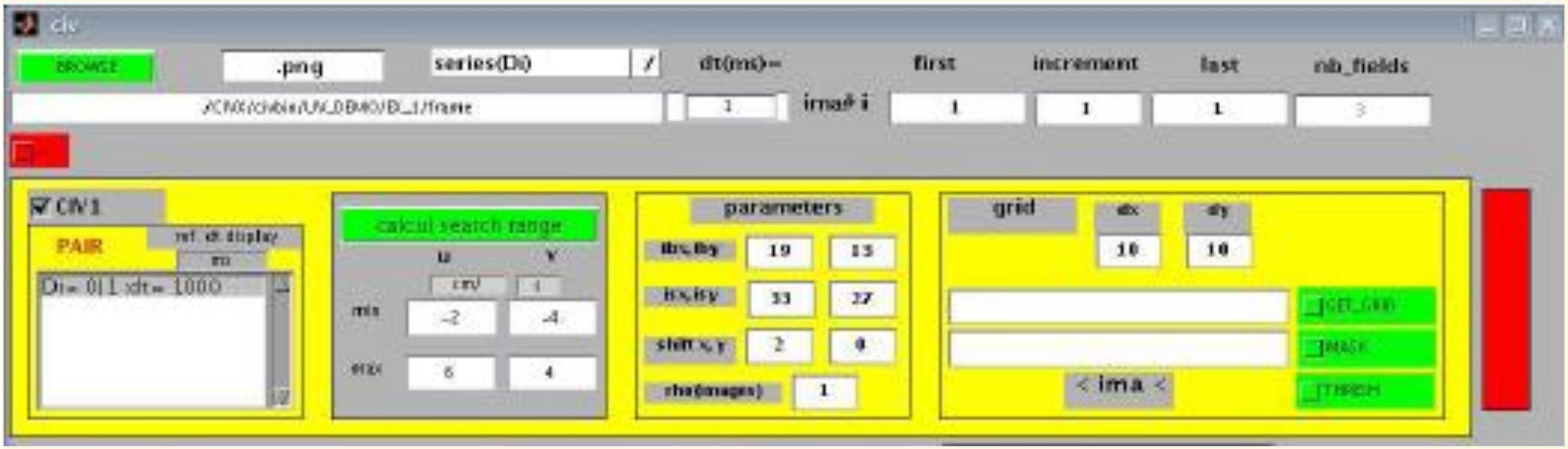
- oscillating mirror (better quality)
- cylindrical lens (static)

-Adapt the laser sheet thickness depending on normal velocity component

-Double-pulse laser (Yag) for large speeds. Synchronisation with suitable camera.

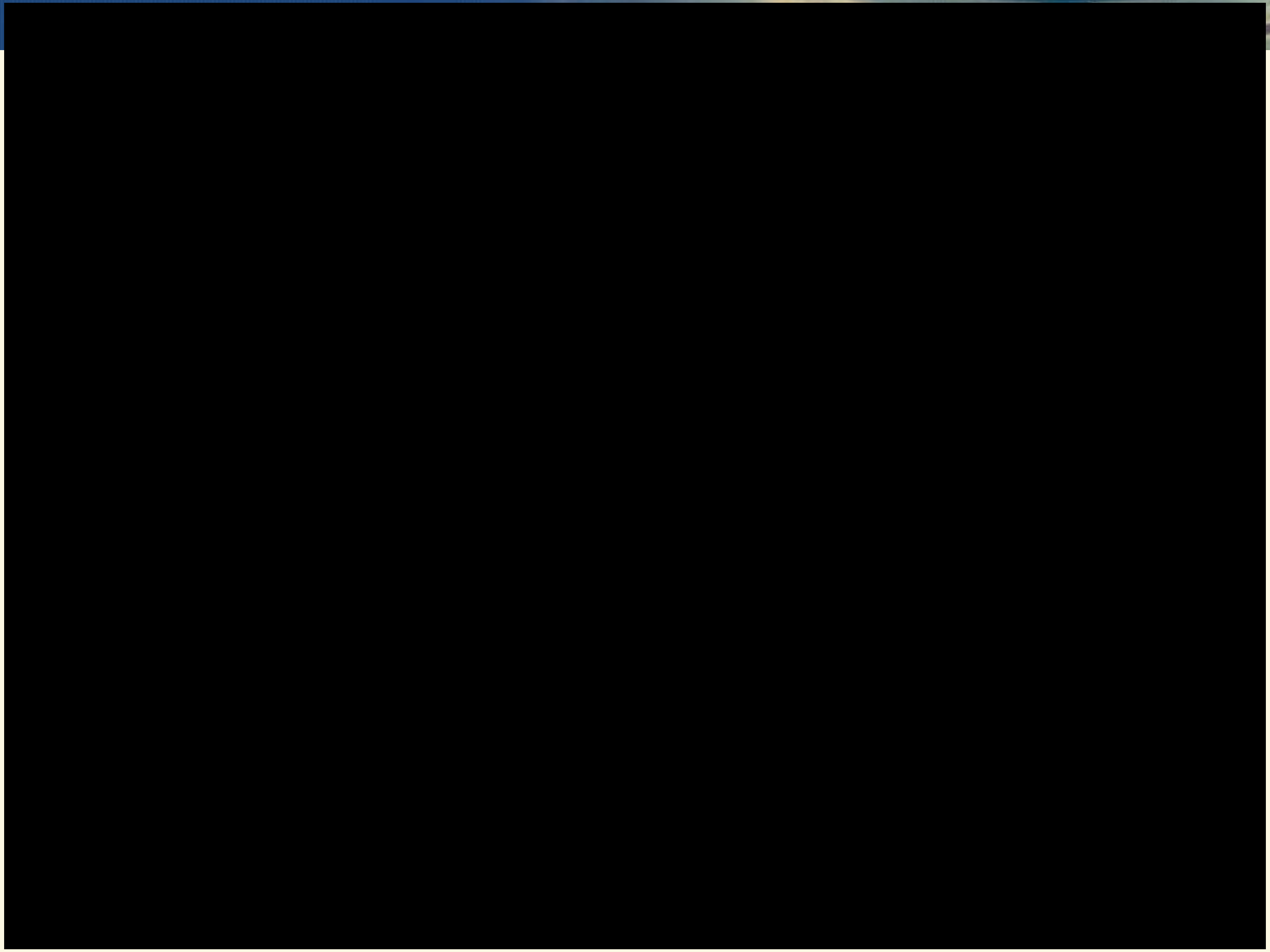
Beware of fixed background (use function ‘sub_background’)

PIV parameters

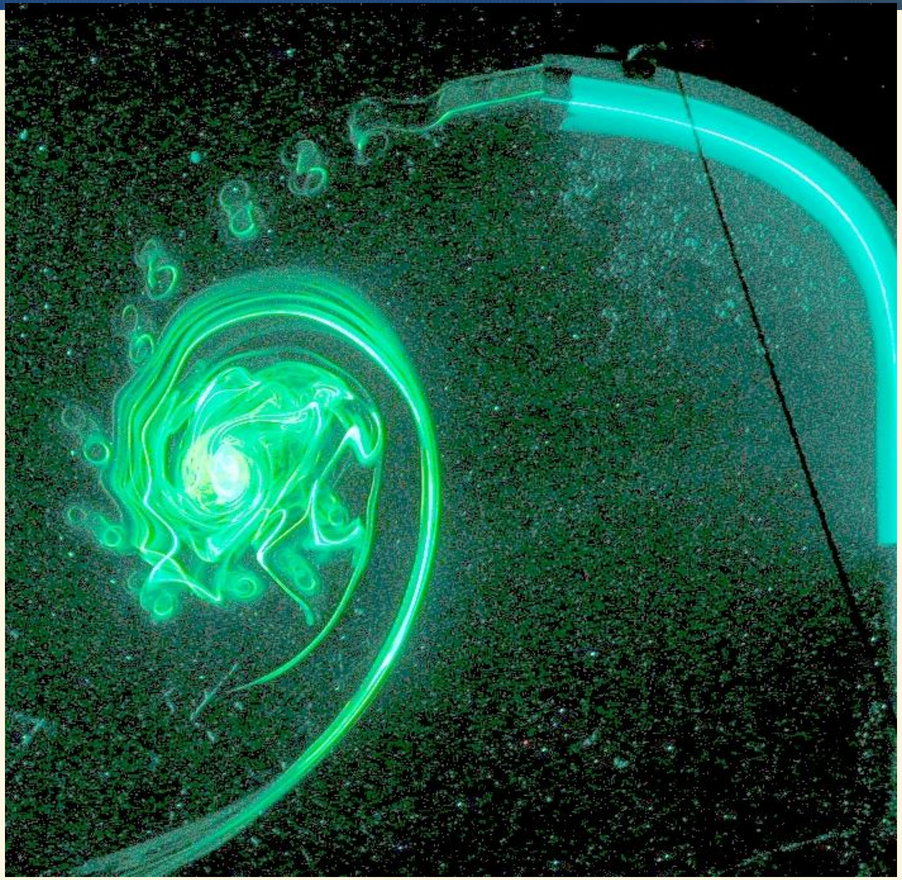


Choose dt such that the displacement ~ 5-20 pixels

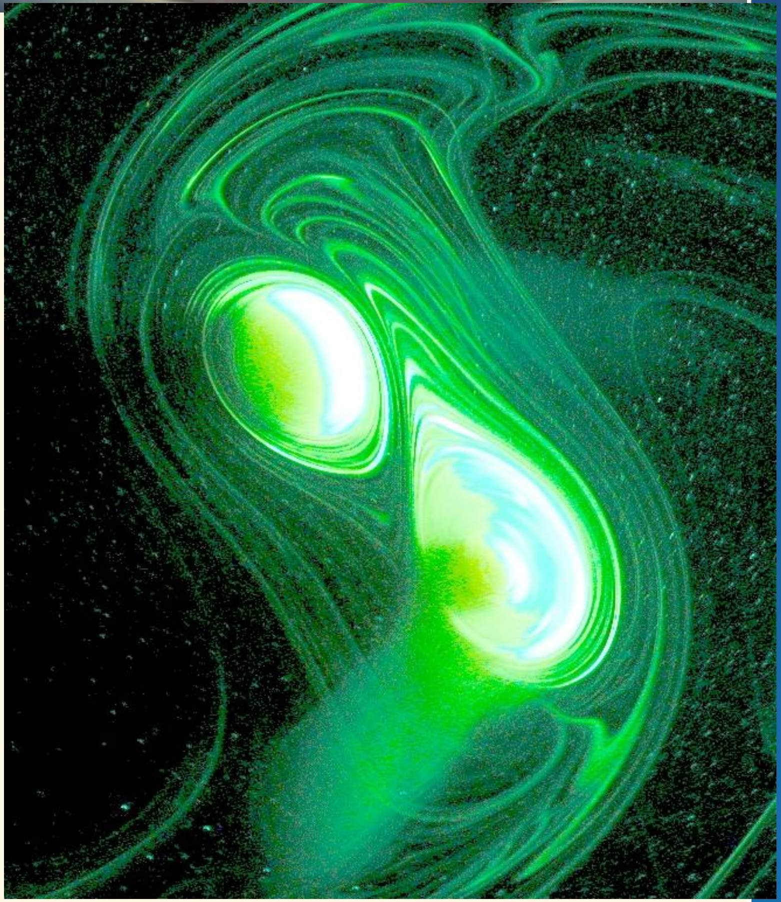
Choose grid mesh (dx, dy) ~ correlation box



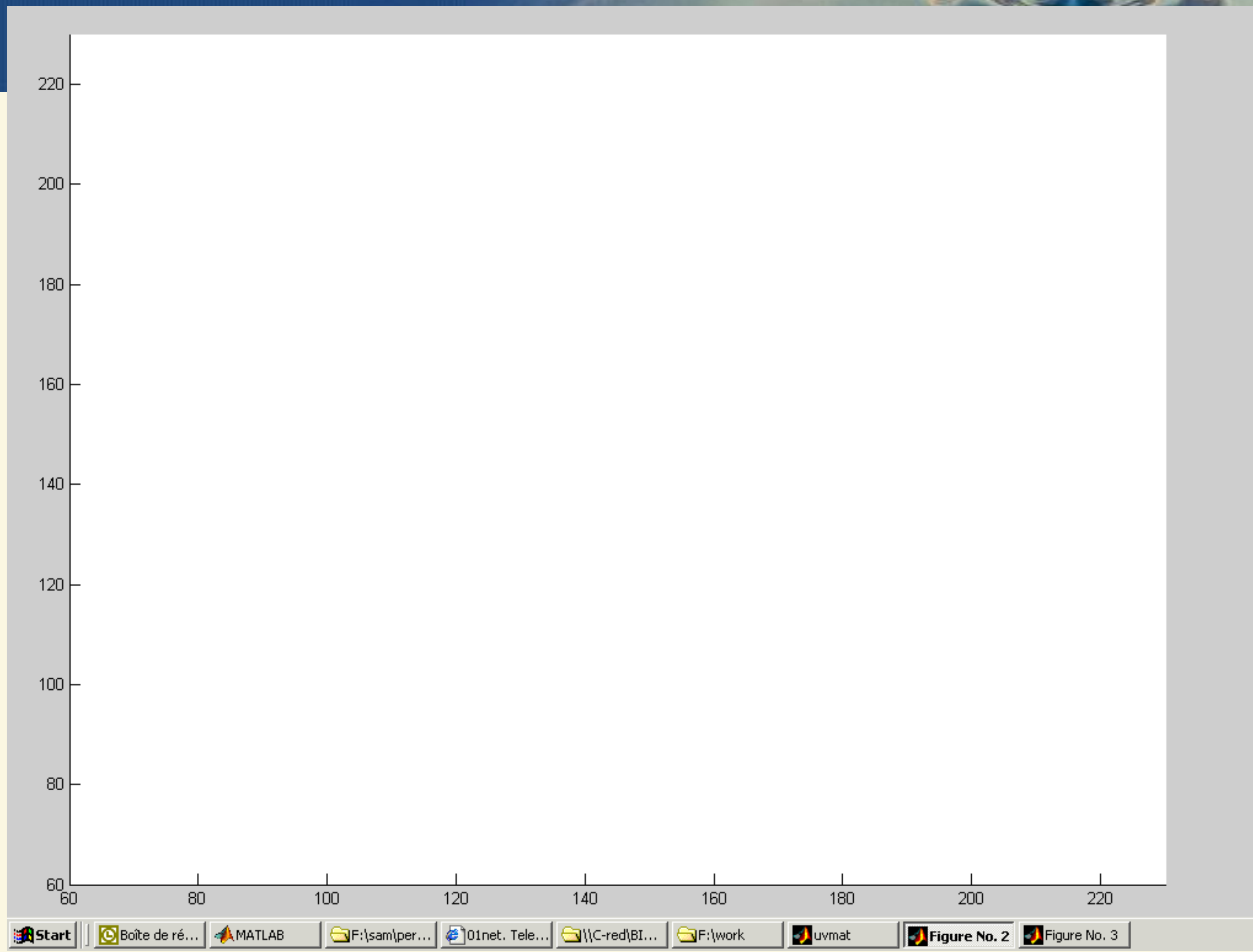
Generation of a cyclone by a flap



fusion of 2 cyclones

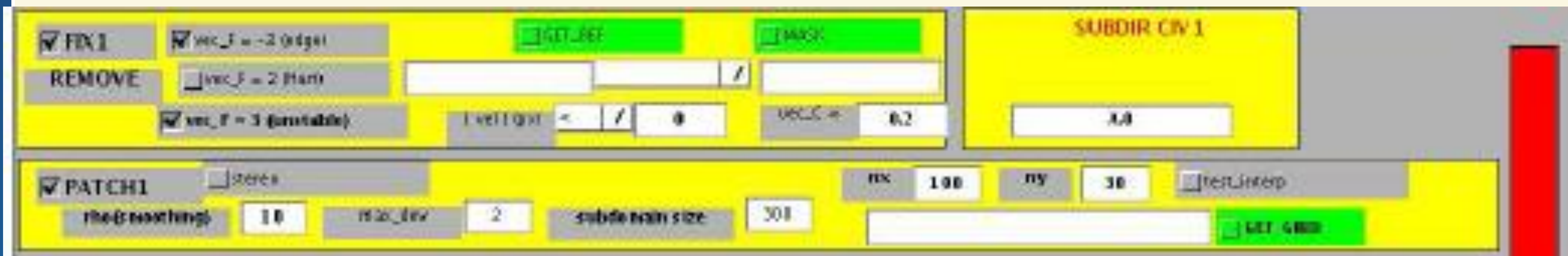


B. CARITEAU; J.B. FLOR 2004



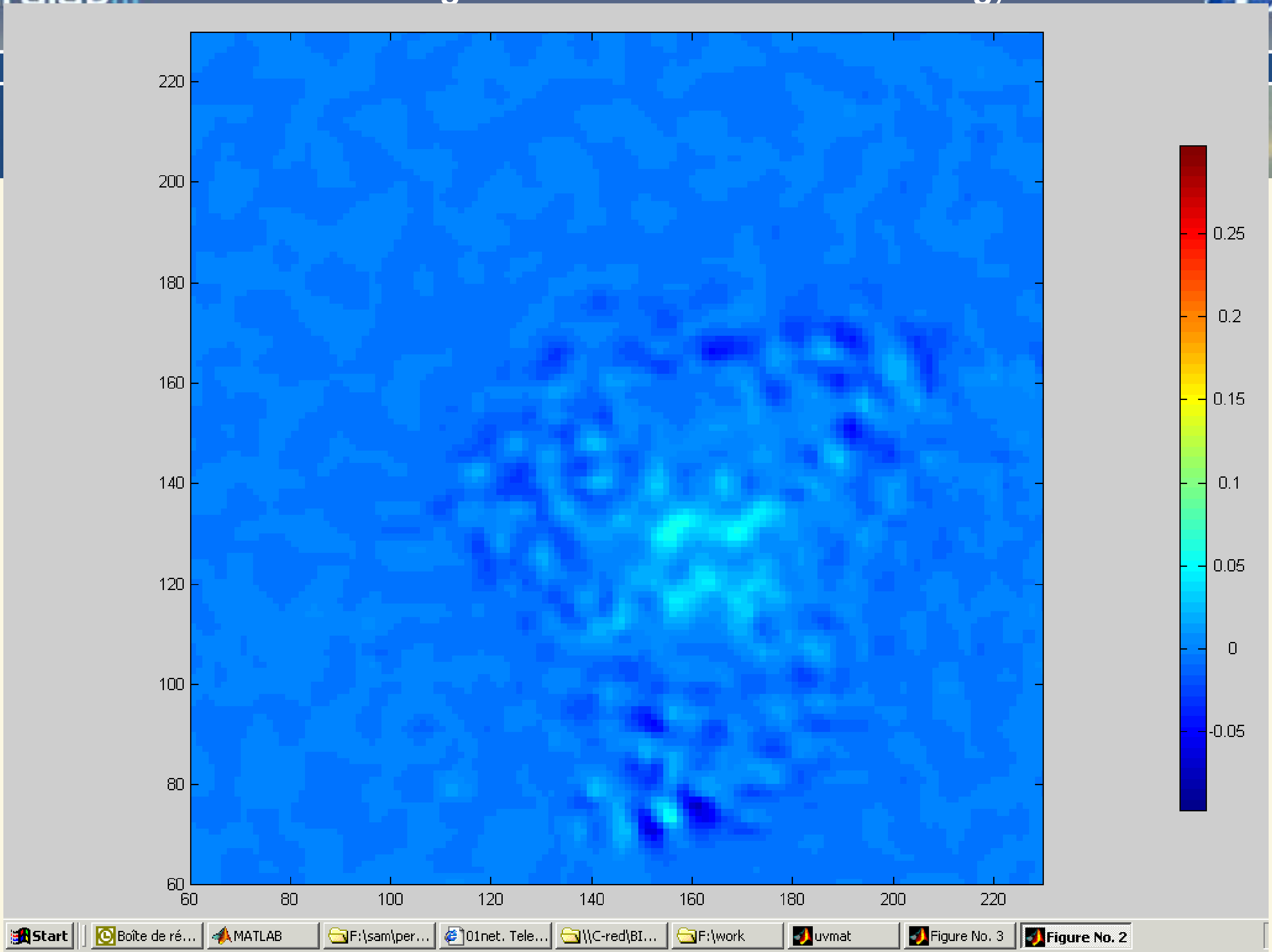
Velocity fields from PIV. Vector colors indicate the velocity modulus (accelerated 60 times)

Fix and patch



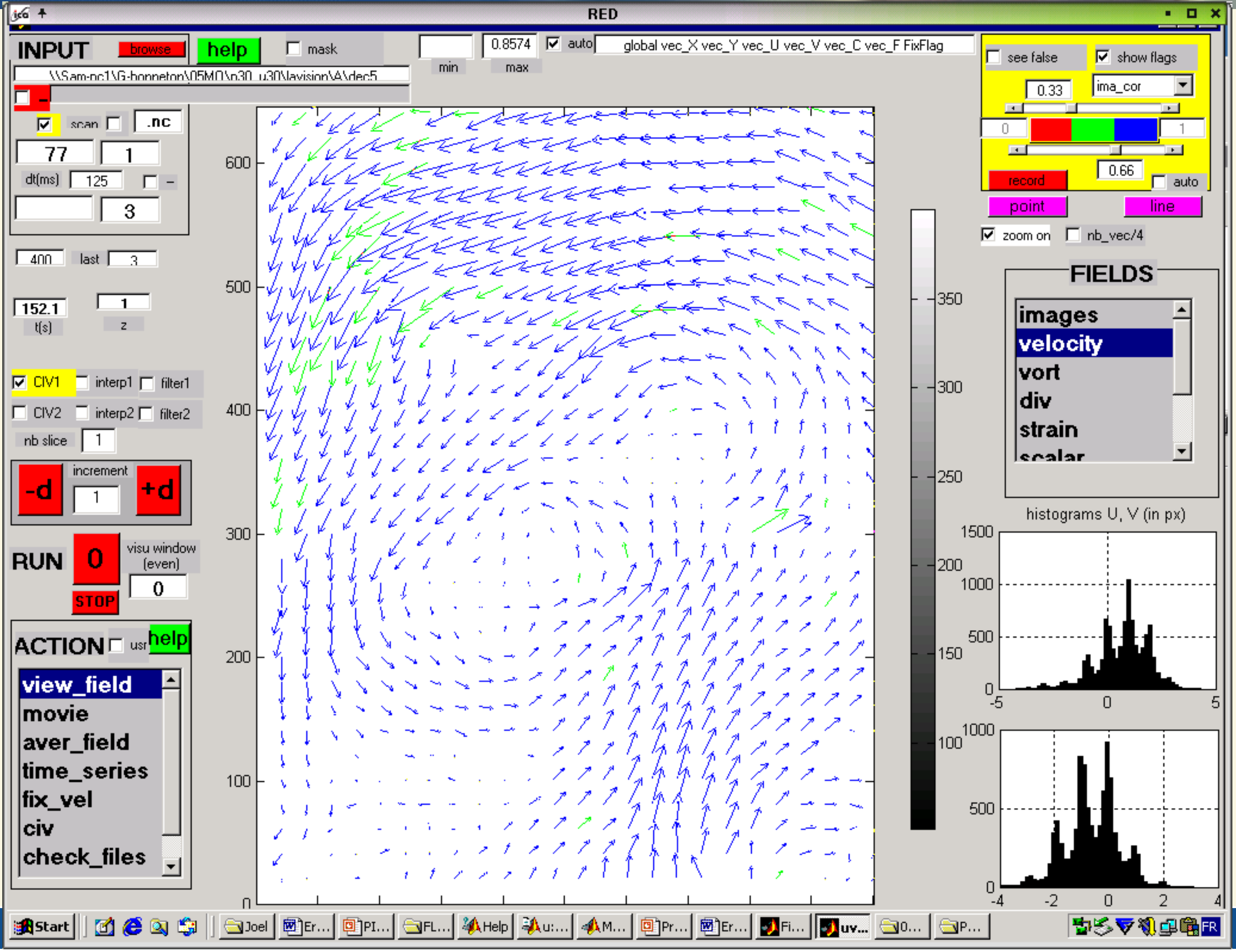
Fix: removes false velocity vectors: correlation max at the edge of the search box, thresholds, continuity, mask …

Patch: interpolates velocity on a regular grid and calculates spatial derivatives (vort, div). We use thin shelf spline, which minimizes a combination of curvature and distance to values.

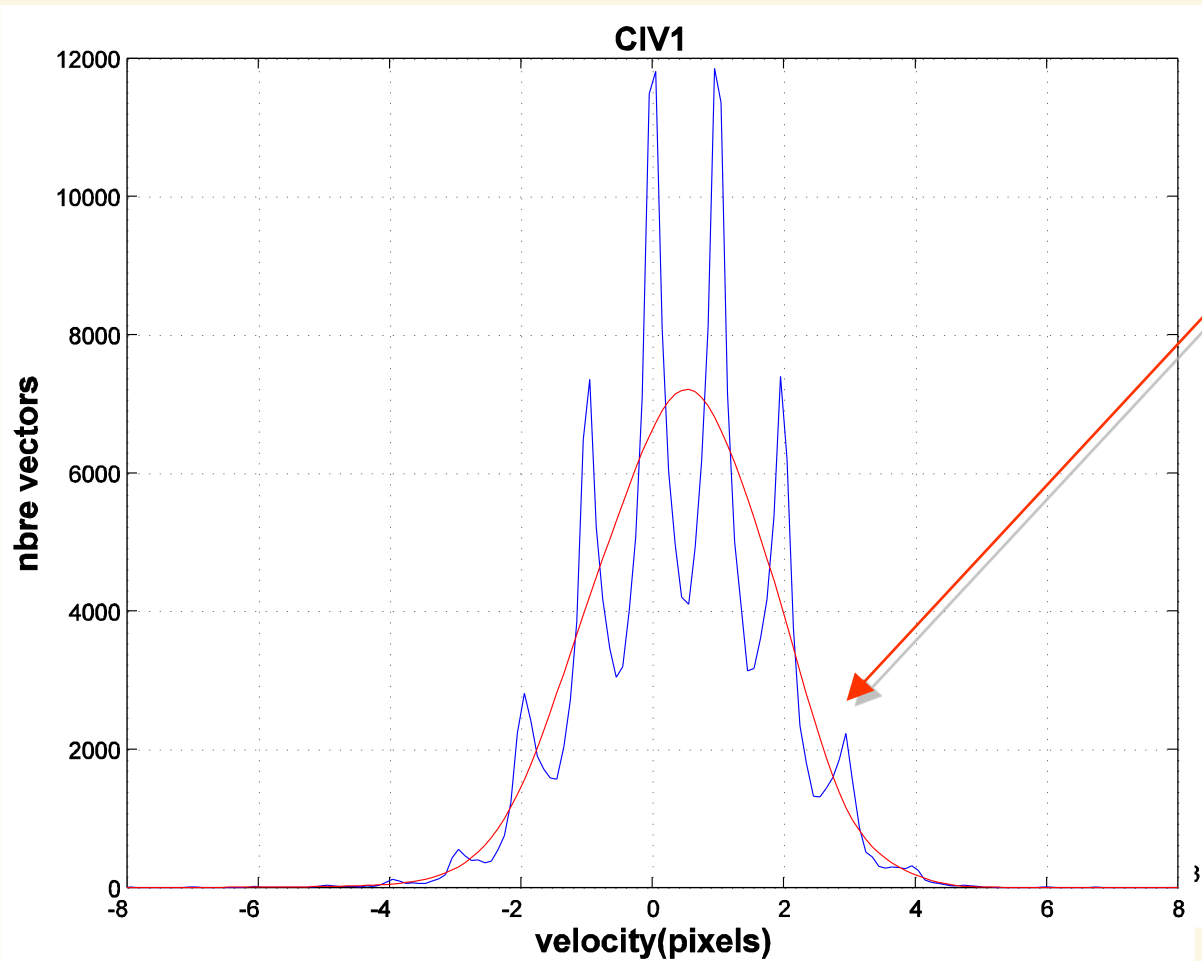


Vorticity field obtained by differentiation of the velocity field (accelerated 60 times)

Peaklocking error



Histogram of velocity (mean on 25 fields of 100 x 100 vectors)



Spline *f* de log(*p*) tel que

$$\int_{n-1/2}^{n+1/2} p(x)dx = \int_{n-1/2}^{n+1/2} f(y)dy$$

MESURE DE L'ERREUR SYSTEMATIQUE DE PEACKLOCKING

$y=x+e(x)$, où l'erreur $e(x)$ est de période 1.

soit $x=G(y)$.

densités de probabilité:

$f(y)dy=p(x)dx$. $(dx/dy=G'(y))$

$$G'(y) = \frac{f(y)}{p(G(y))}$$

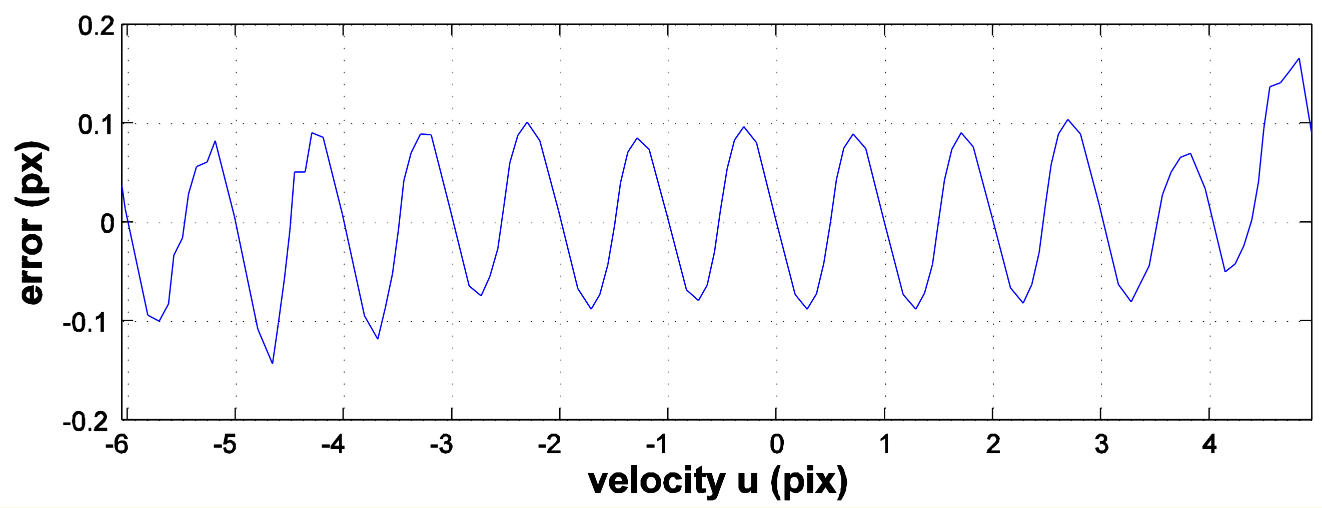
f(y) interpolation spline

p(x) histogramme mesuré

Equation résolue par une méthode itérative

(G(y)=y à l'ordre 0)

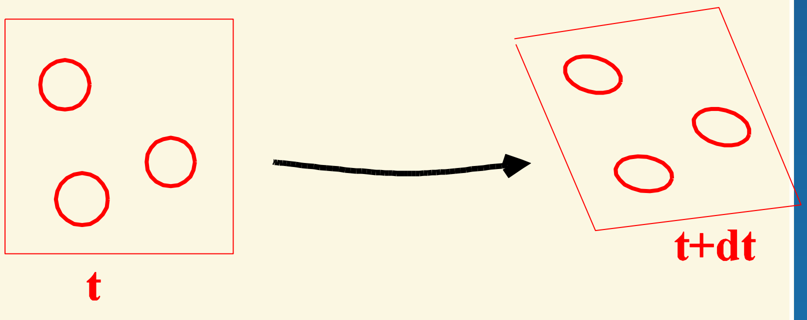
Systematic error (peaklocking)



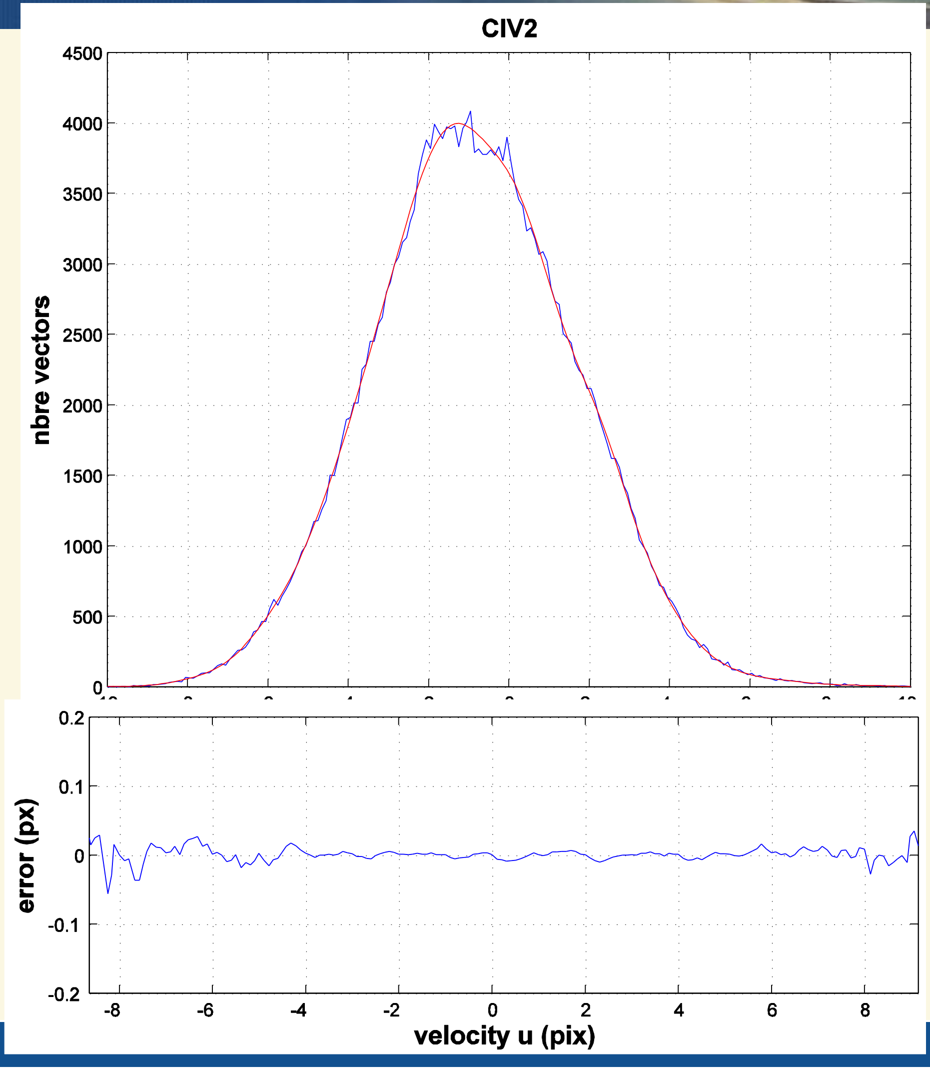
Hierarchical algorithm (CIV2)

(Fincham et Delerce, Exp. Fluids 2000)

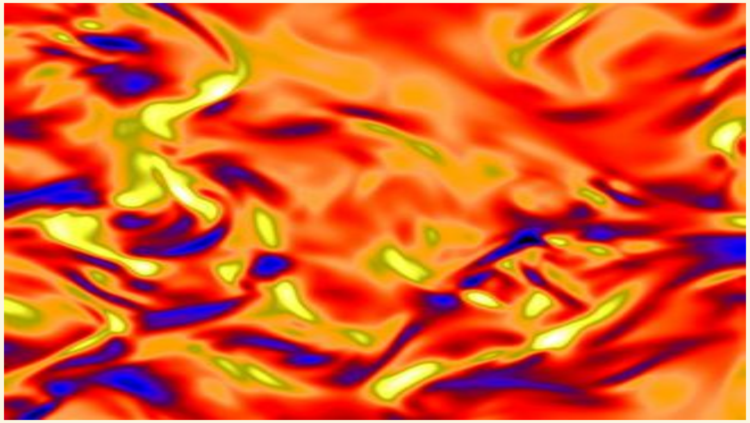
- **CIV1** --> *u, v*
  first estimate
- **FIX1** --> *remove false vectors*
- **PATCH1** --> *interpolate, smooth (spline thin shell)*
  spatial derivatives
- **CIV2:**
  'decimal shift' (image interpolation)
  deformation' (strain, rotation)
  ' --> ***improved u and v***



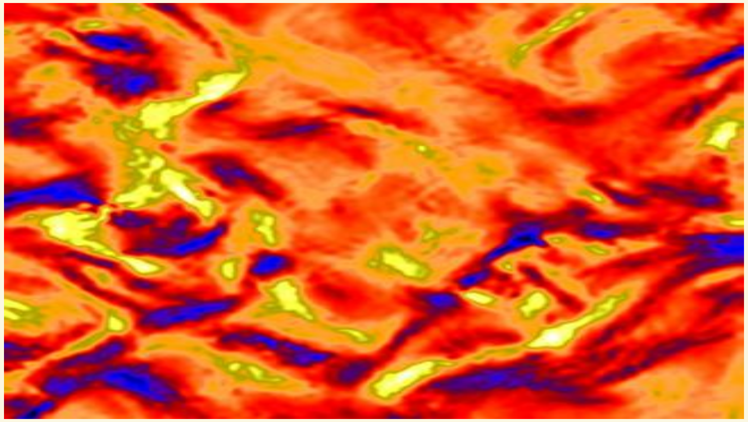
Peaklocking error CIV2



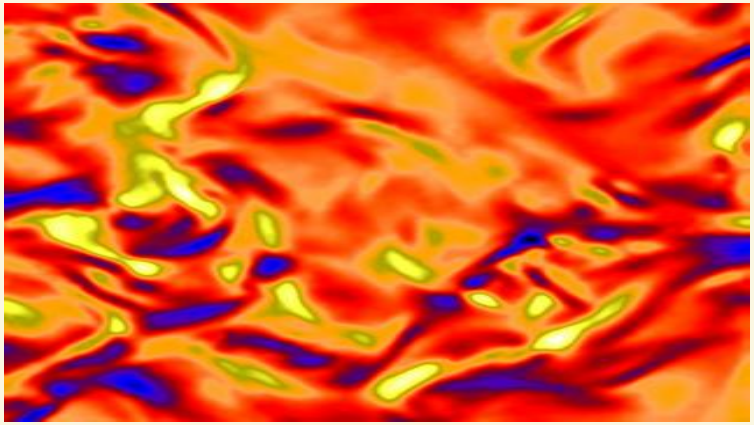
Test with numerical fields (vorticity)



DNS (reference)



CIV 1



CIV 2

(ref: Fincham & Delerce 2000)

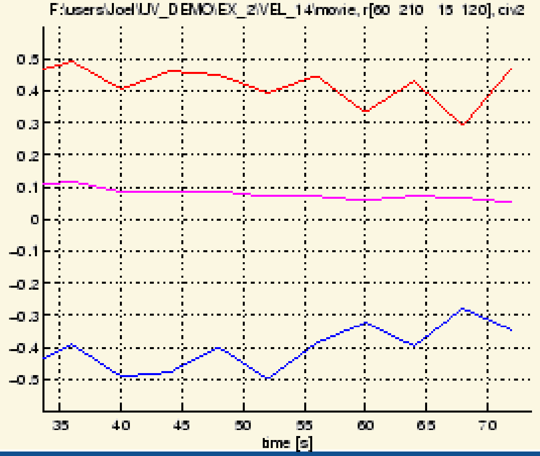
Experimental estimate of random error

We compare measurements from two image pairs, close in time (bursts), with time intervals τ_1 *et* $\tau_2=\alpha\tau_1$. We assume that the error probability p_d on displacement is independent for the two pairs, with the same probability law.

$$\text{Pair 1: } p_1(u_1)= \tau_1 p_d(u_1\tau_1)$$
$$\text{Pair 2: } p_2(u_2)= \tau_2 p_d(u_2\tau_2)$$

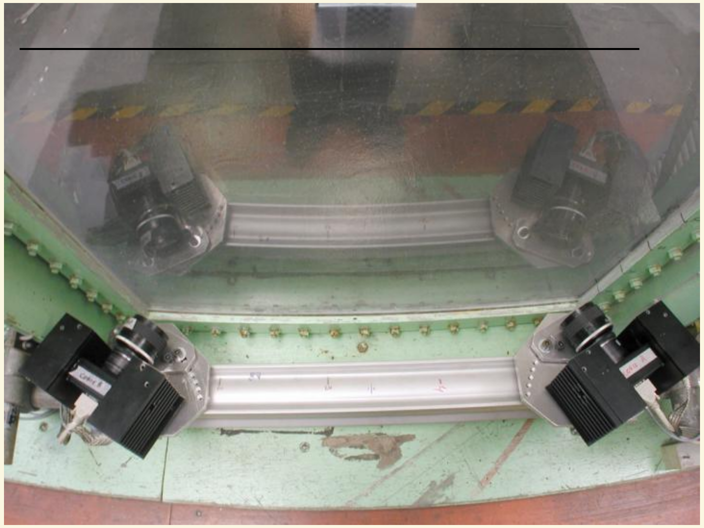
Independency -->

$$<u^2>=<(u_1-u_2)^2>=<u_1^2>+<u_2^2>=(1+\alpha^2)<u_1^2>$$



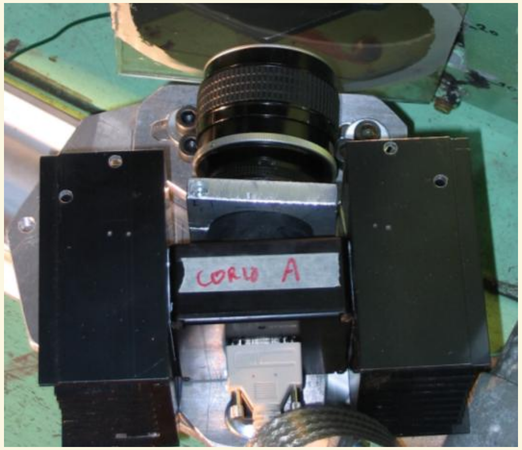
DISTRIBUTION DE PROBABILITE DE L'ERREUR

Stereoscopic PIV (2D3C)



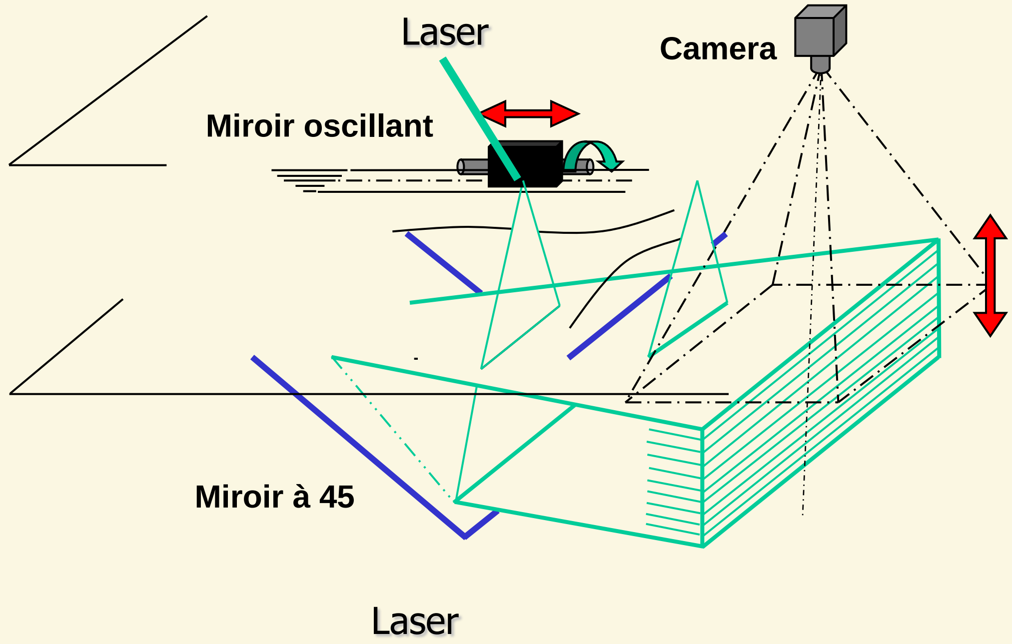
Système de calibration avec des mires

PIV 3 composantes dans le plan laser

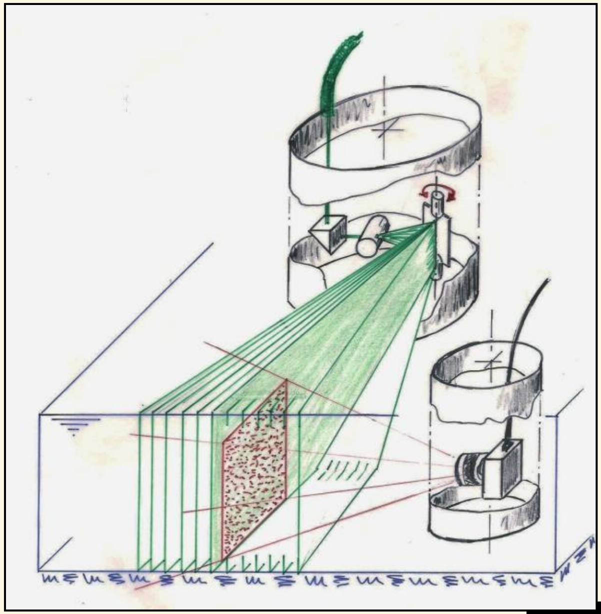


Decentered optic

Volume sweeping systems

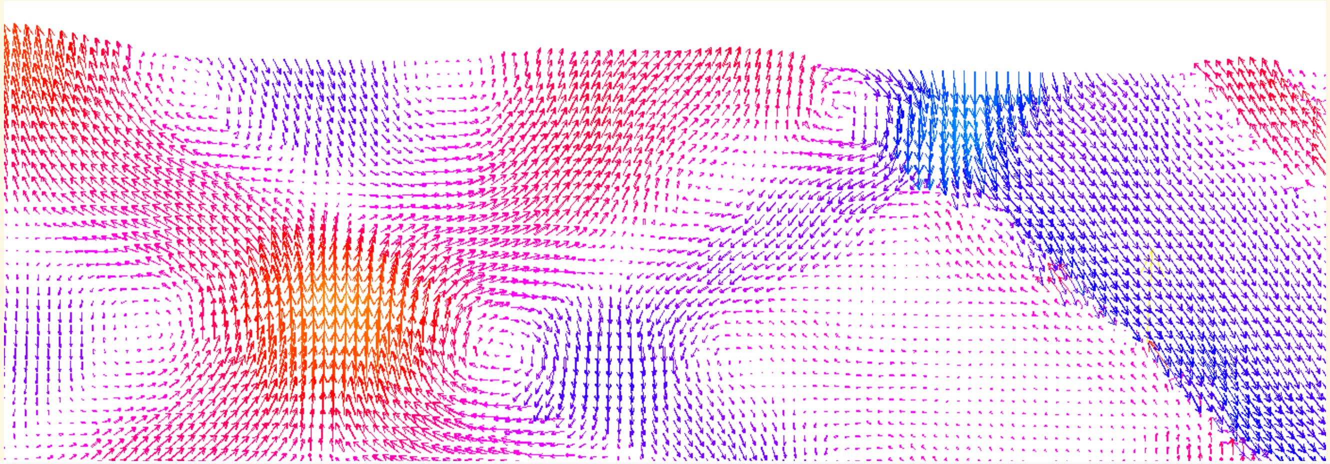


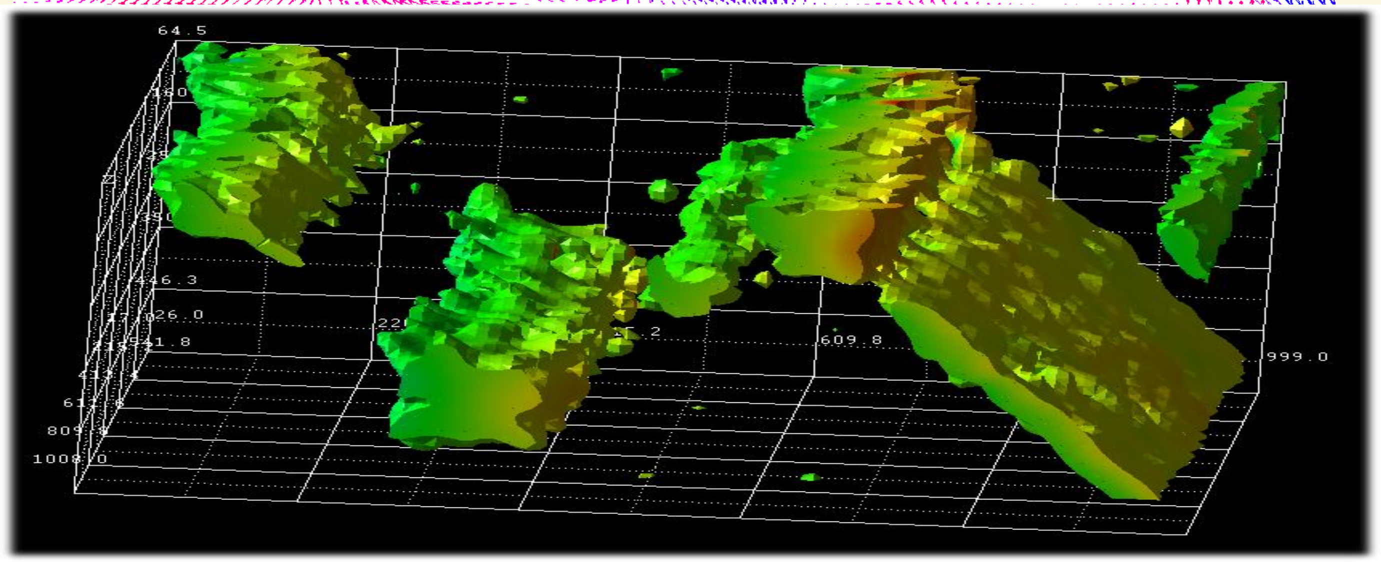
Parallel sweeping (convenient but not fast)



Angular sweeping

Example internal gravity wave





References

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