Mesoscopic wave physics in fish shoals

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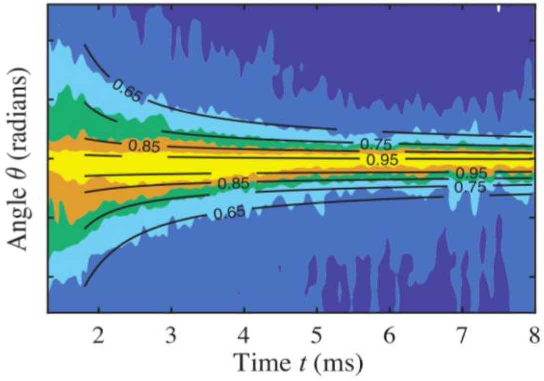
ISTerre Institut des Sciences de la Terre   iXblue   CARRTEL   LPMMC laboratoire de physique et de modélisation des milieux condensés   cnrs

Outline

- Shoals biomass estimation
  - Counting methods for low fish densities
  - Multiple scattering issues
  - Open sea cages

Cannes aquafrais

- Mesoscopic wave physics for biomass assessment
  - Spatial correlations and intensity probability density
  - Coherent backscattering (CBS)

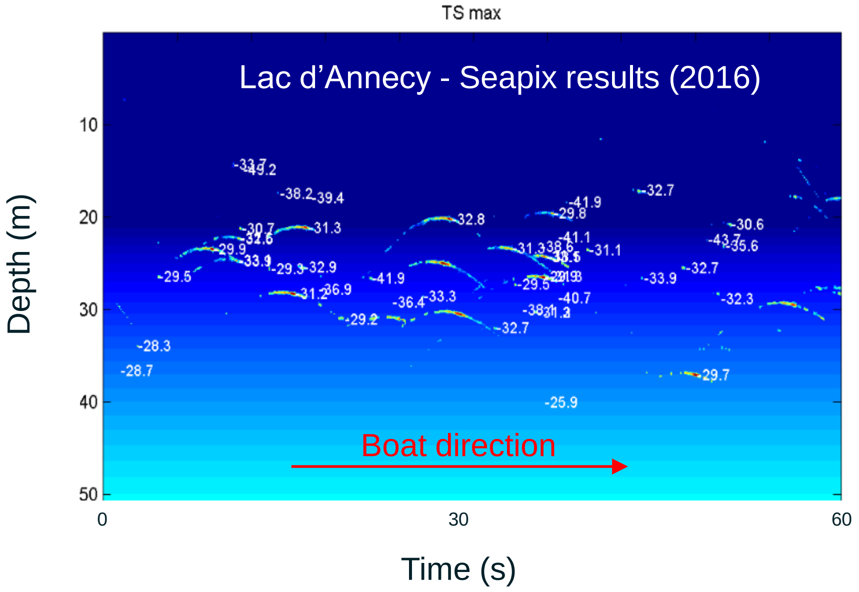


Dynamic CBS profile

Shoal biomass estimation : low density

- Well separated targets

  ⇒ Echo-counting



$$T_S \propto \log L$$

Target Strength

Fish length

J. Simmonds and D. N. MacLennan, *Fisheries Acoustics* (2008)

- Diluted shoals

  ⇒ Echo-integration

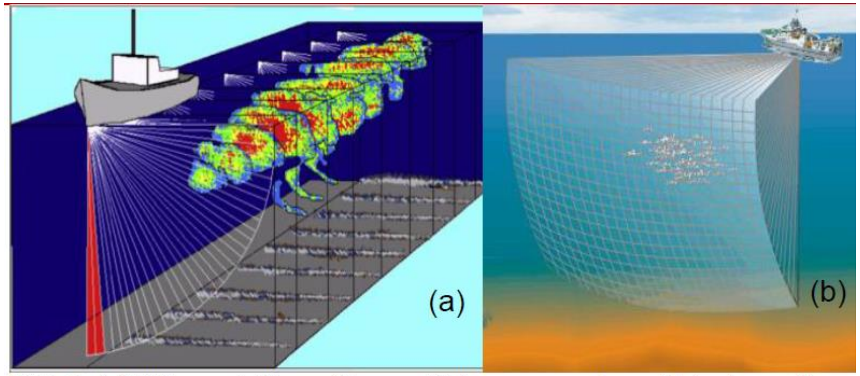


Fig. 1: (a) 3D acquisition with a multi-beam sounder with juxtaposition of 2D images formed along the plan perpendicular to the vessel route; in red, zone sampled by a vertical sonar. (b) Geometry of the acquisition with 3D sounders (from Simrad Compagny).

Backscattered energy

$$E \propto N \times T_S$$

Target Strength

Number of fish

K. G. Foote, *J. Acoust. Soc. Am.* **73**, 1932 (1983)

Single scattering approximation

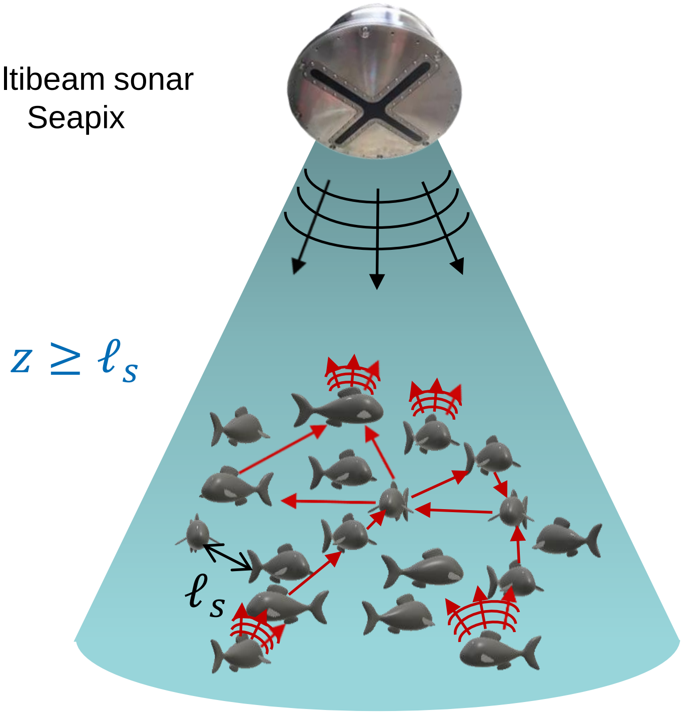
Shoal biomass estimation : high density

High fish density:

- Gregarious species
- Aquaculture

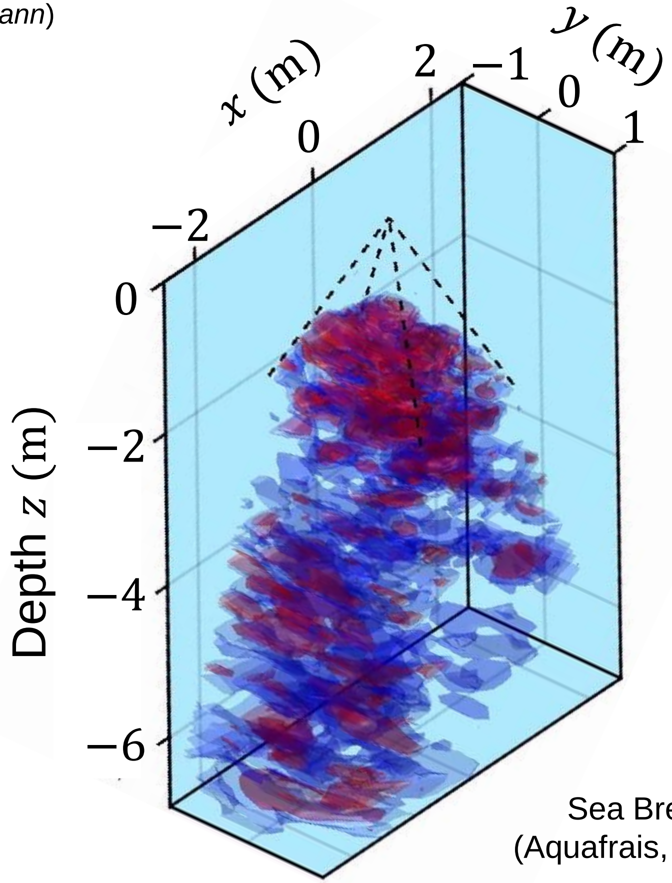
Herrings
(*C. Swann*)

Cannes aquaculture
(*S. Pasta*)



Multibeam sonar
Seapix

Multiple scattering regime
⇒ Biased biomass estimation



Sea Breams
(Aquafrais, Cannes)

Shoal biomass estimation : impact of multiple scattering

Effects of multiple scattering:

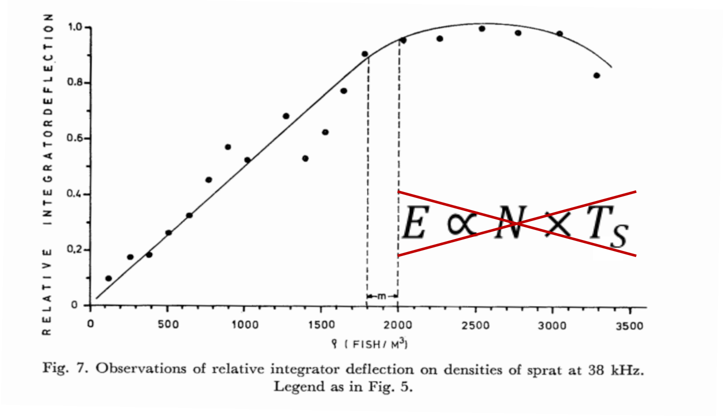
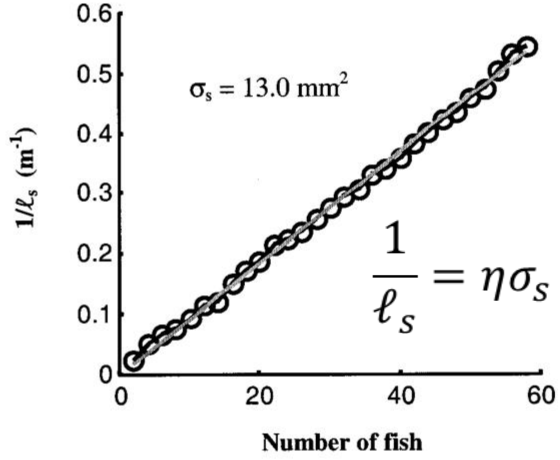


Fig. 7. Observations of relative integrator deflection on densities of sprat at 38 kHz. Legend as in Fig. 5.

I. Røttingen, *FiskDir. Skr. Ser.* **16**, 301 (1976)

Reverberating cavities

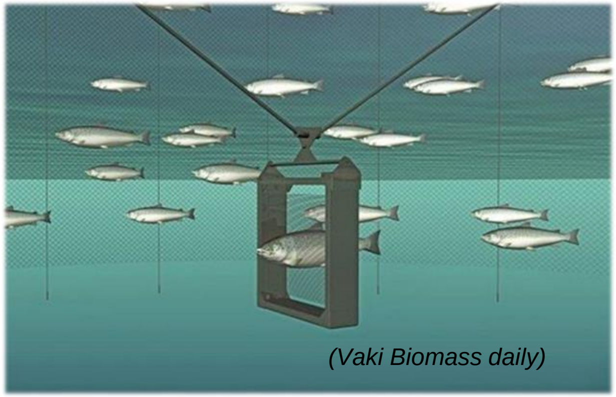


J. De Rosny and P. Roux, *J. Acoust. Soc. Am.* **109**, 2587 (2001)

Solutions :

Manual counting
(invasive)

Cannes aquafrais



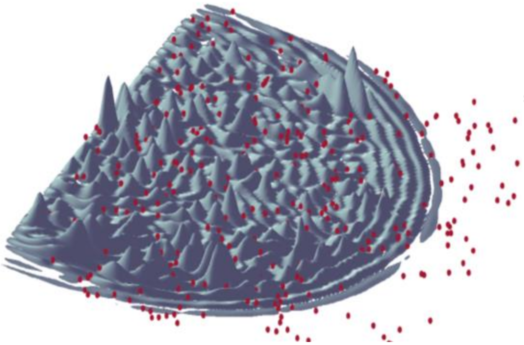
(Vaki Biomass daily)

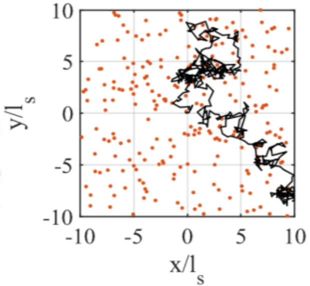
Counting by doors
(local)

Mesoscopic wave physics for biomass assessment

Microscopic description (scale $\sim \lambda$):

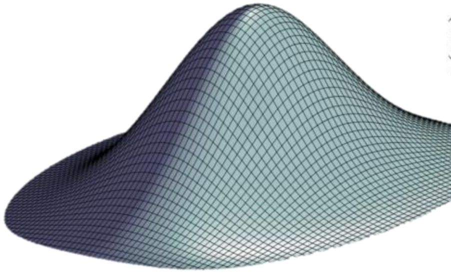
Macroscopic description (scale $\gg \lambda$):

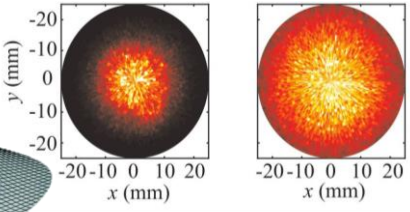




Random walk of propagation direction

Random walk transport



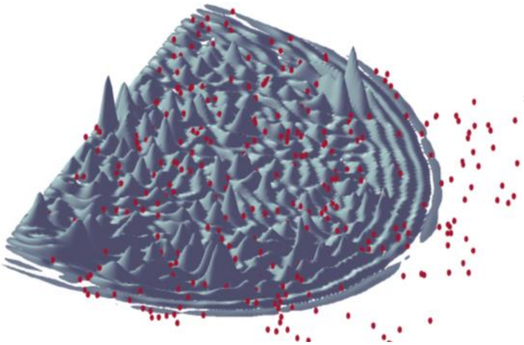


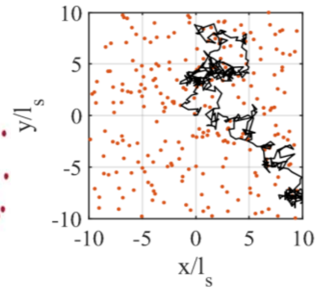
Diffusion of an acoustic point source

Diffusive transport

Mesoscopic wave physics for biomass assessment

Microscopic description (scale $\sim \lambda$):

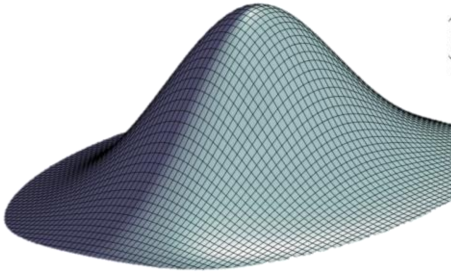


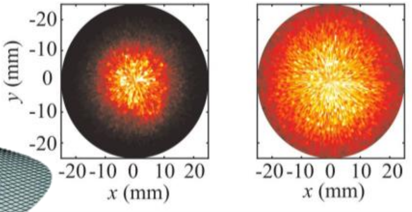


Random walk of propagation direction

Random walk transport

Macroscopic description (scale $\gg \lambda$):



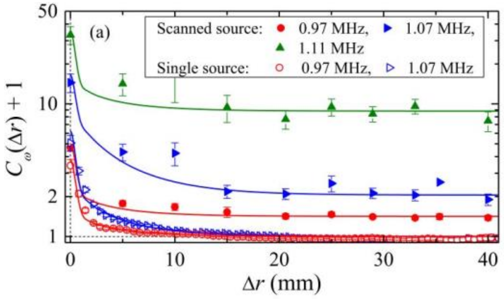


Diffusion of an acoustic point source

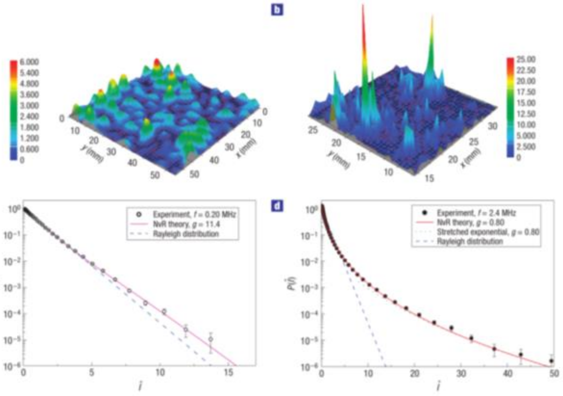
Diffusive transport

Mesoscopic wave phenomena ($\ell_s \sim \lambda$):

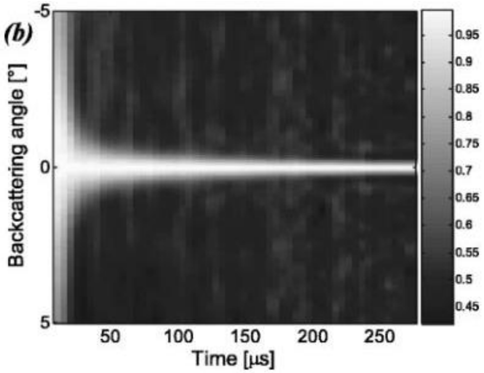
impact of microscopic interferences of the macroscopic description



Long range correlations
(K. Hildebrand *et al.*,
Phys. *Rev. Lett.* **112**, 2014)

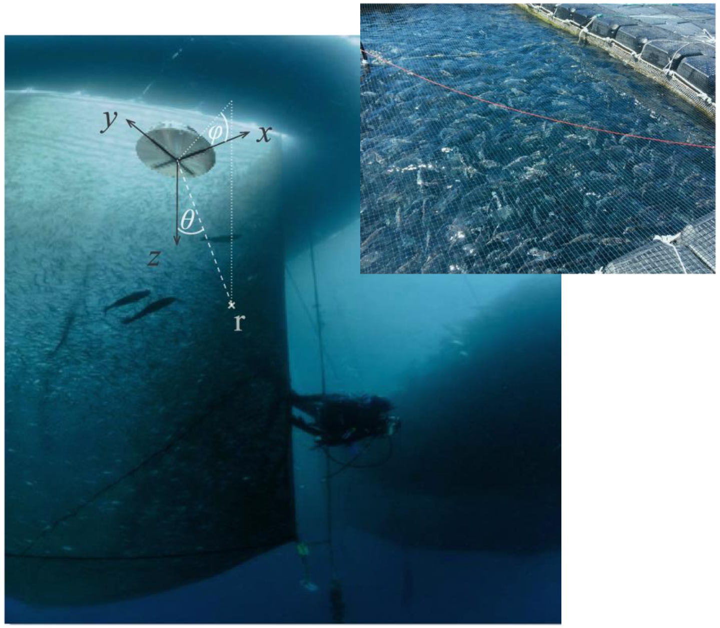


Non Rayleigh distribution of ultrasonic speckle
(H. Hu *et al.*, *Nat. Phys.* **4**, 2008)



Coherent backscattering
(A. Aubry *et al.*, *JASA* **121**, 2007)

Multiple scattering in open sea cages



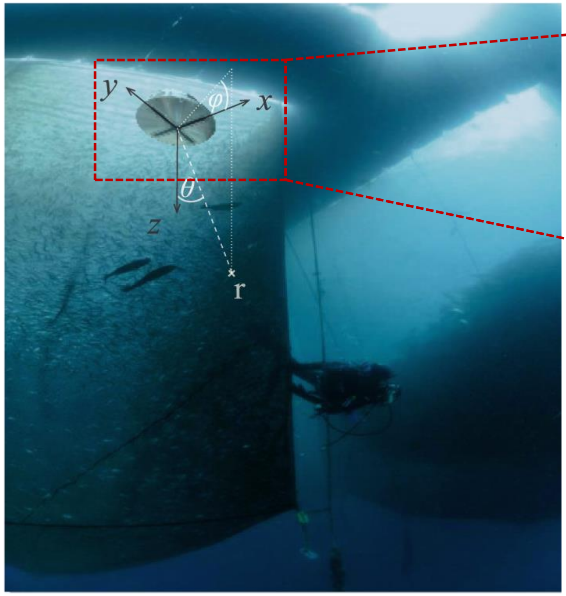
Sea breams cage (Cannes aquafrais)

Organic certified farm:

- Fish raised under conditions close to their natural environment (selected species, densities, size…).
- Necessity of developing non-invasive monitoring methods.

	N	W	η (kg/m^3)	V (m^3)
C1 (sea breams, fry)	75,000	10	6	125
C2 (sea breams, adults)	5,000	500	7	343
C3 (sea breams, adults)	10,080	284	23	125
C4 (sea breams, adults)	6,000	320	15	125
C5 (croakers, adults)	13,900	886	24	512

Multiple scattering in open sea cages



Sea breams cage (Cannes aquafrais)

SeapiX (iXblue):

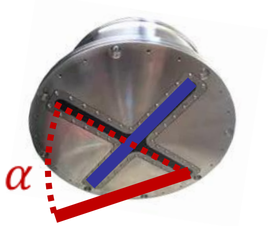
- Mills cross shaped antenna
- 64+64 ultrasonic transducers ($\emptyset = \lambda/2$)
- $f = 150\ \mathrm{kHz}\ (\lambda = 1\ \mathrm{cm})$
- Acquisition sequence repeated every 30 ms

3 acquisition sequences:

Point source

Plane wave

Scan

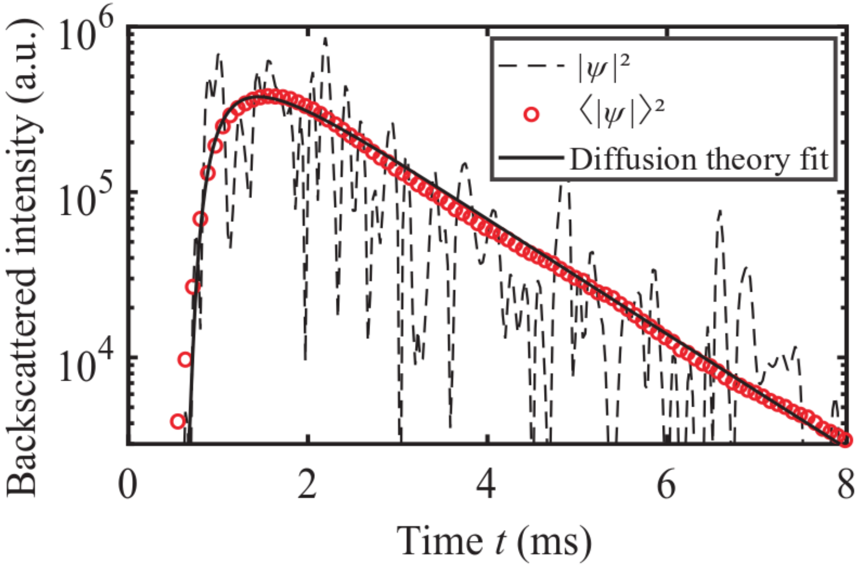


🟥 Emission

🟦 Reception

Mesoscopic wave physics for biomass assessment

Average intensity:



Diffusion theory:

$$\langle I(t)\rangle = \frac{I_0}{2\pi}\int_{-\infty}^{+\infty}\frac{z_0 e^{-\gamma_0 z'}}{D(1+\gamma_0 z_0)}e^{-i\Omega t}d\Omega$$

with:

$$\gamma_0^2(\Omega) = \frac{-i\Omega}{D} + \frac{1}{D\tau_a}$$

$$z_0 = \frac{2}{3} + \frac{1+R}{1-R}\ell^*$$

D: diffusivity

τ_a: absorption time

R: reflection coefficient (water/air)

ℓ^*: transport mean free path

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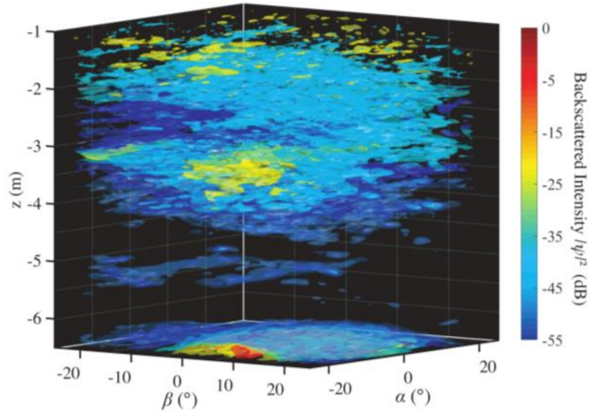
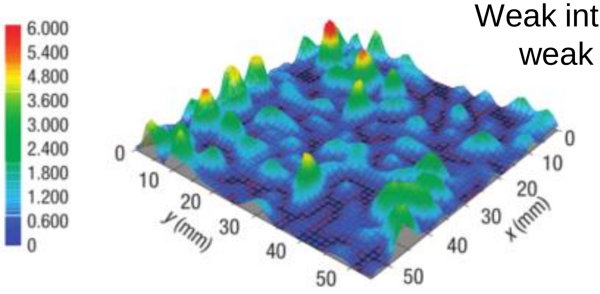
Mesoscopic wave physics for biomass assessment

Acoustic intensity distribution : the « conductance » g





Weak interferences = weak variance

H. Hu *et al.*, *Nat. Phys.* **4**, 2008

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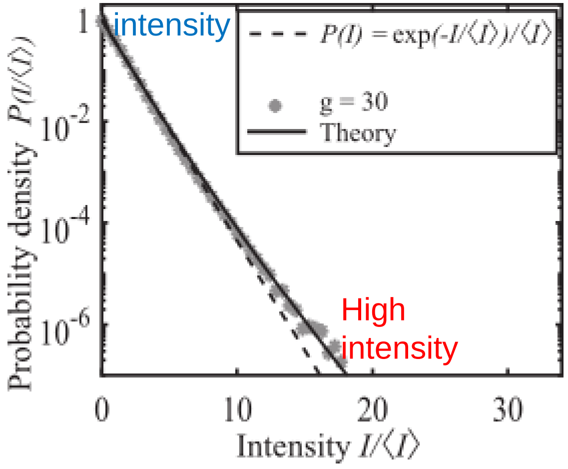
$g = 30$



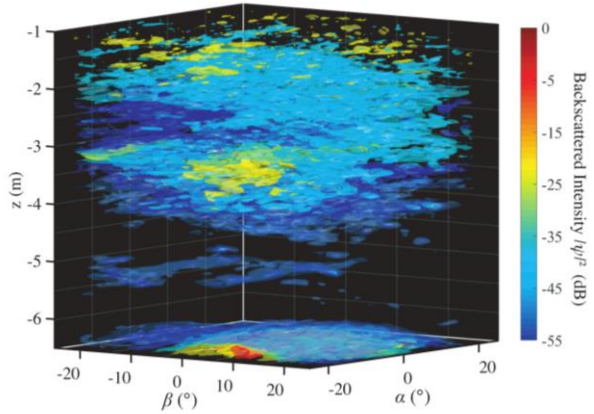
Weak intensity

High intensity

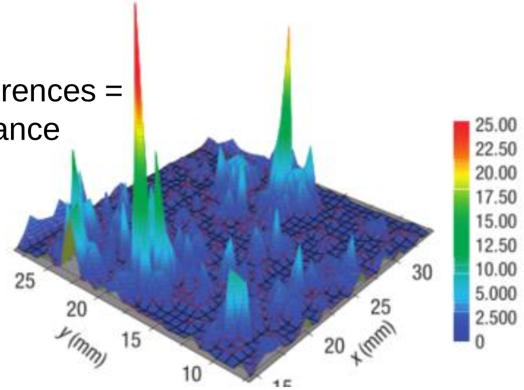
B. Tallon, P. Roux, G . Matte, J. Guillard, S. E. Skipetrov *AIP Adv.* **10**, 055208 (2020)

Mesoscopic wave physics for biomass assessment

Acoustic intensity distribution : the « conductance » g



Strong interferences = high variance



H. Hu *et al.*, *Nat. Phys.* **4**, 2008

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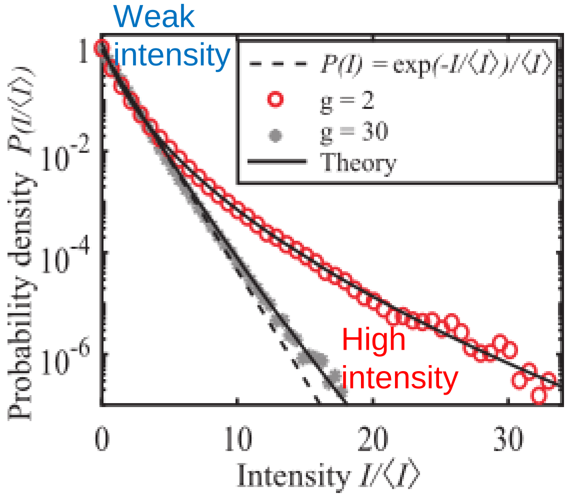
$g = 30$

$g = 2$



B. Tallon, P. Roux, G . Matte, J. Guillard, S. E. Skipetrov *AIP Adv.* **10**, 055208 (2020)

Th.M. Nieuwenhuizen and M.C.W. van Rossum, *Phys. Rev. Lett.* **74**, 2674 (1995)

$$P(I/\langle I\rangle) = \int_0^{\infty} \frac{\mathrm{d}v}{v} \int_{-\mathrm{i}\infty}^{\mathrm{i}\infty} \frac{\mathrm{d}x}{2\pi\mathrm{i}}\, e^{\frac{I}{\langle I\rangle} + xv - f(\boldsymbol{g})}$$

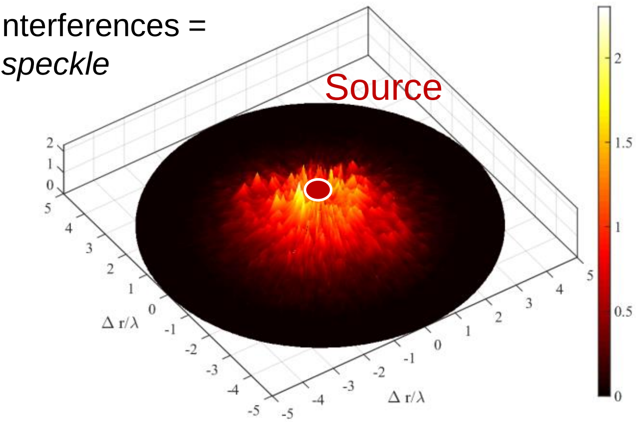
Mesoscopic wave physics for biomass assessment

Spatial correlations

● Source

$$C(\Delta r) = \frac{\langle \delta(0)\delta I(\Delta r)\rangle}{\langle I(0)\rangle^{2}}$$

Weak interferences = *speckle*



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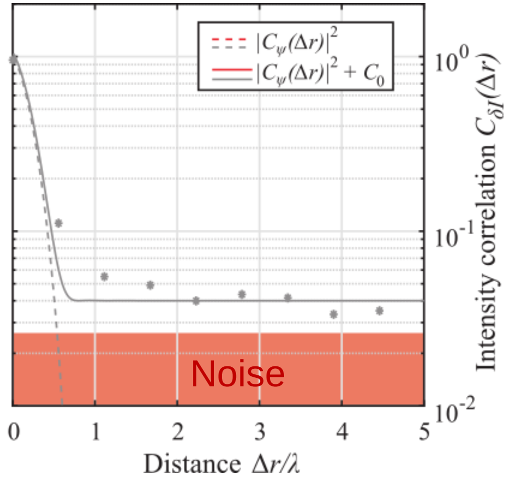
C_0 = 0,04



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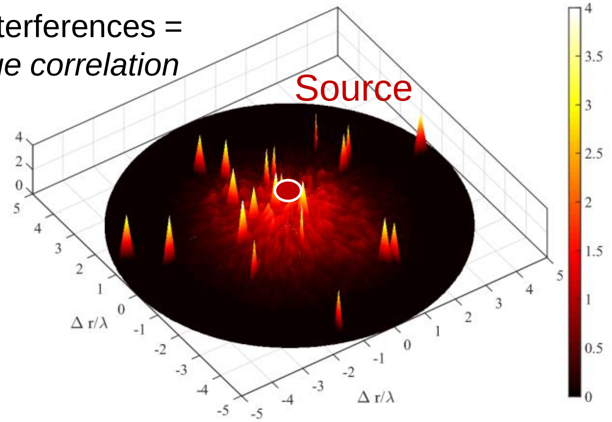
Mesoscopic wave physics for biomass assessment

Spatial correlations

● Source

$$C(\Delta r) = \frac{\langle \delta(0)\delta I(\Delta r)\rangle}{\langle I(0)\rangle^2}$$

Strong interferences =
long range correlation



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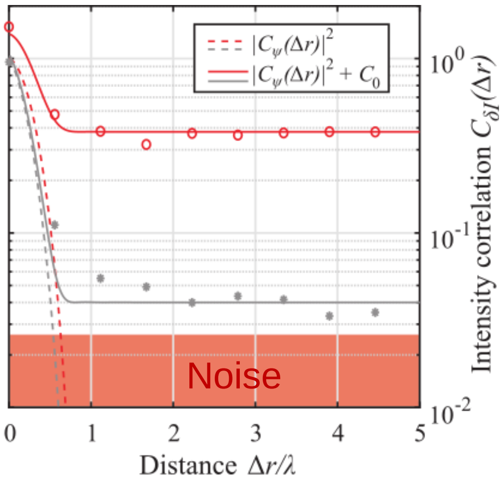
C_0 = 0,04

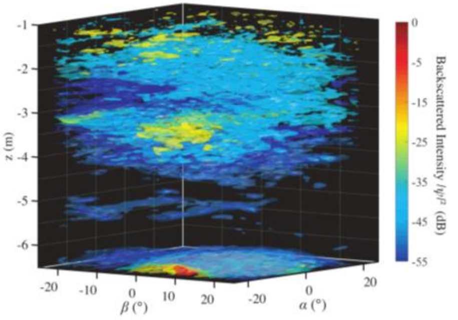
C_0 = 0,4

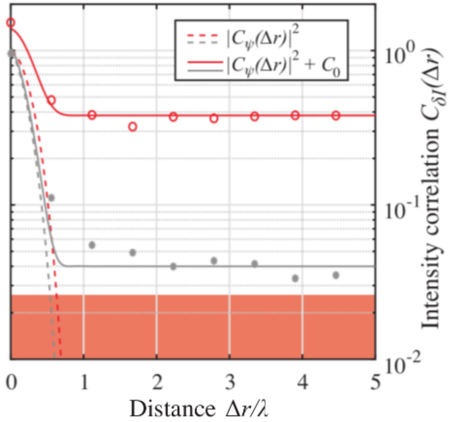


B. Tallon, P. Roux, G . Matte, J. Guillard, S. E. Skipetrov *AIP Adv.* **10**, 055208 (2020)

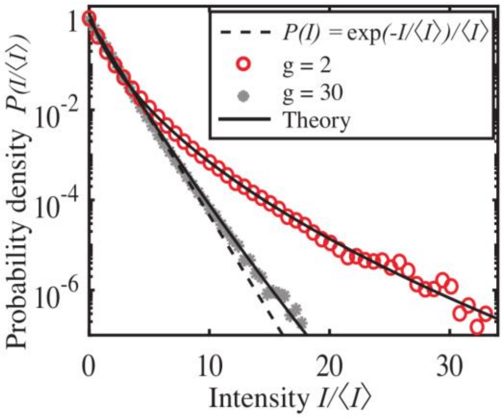
Mesoscopic wave physics for biomass assessment

Spatial correlations and Intensity distribution:





$$C_{\delta I} = |C_\psi|^2 + C_0$$



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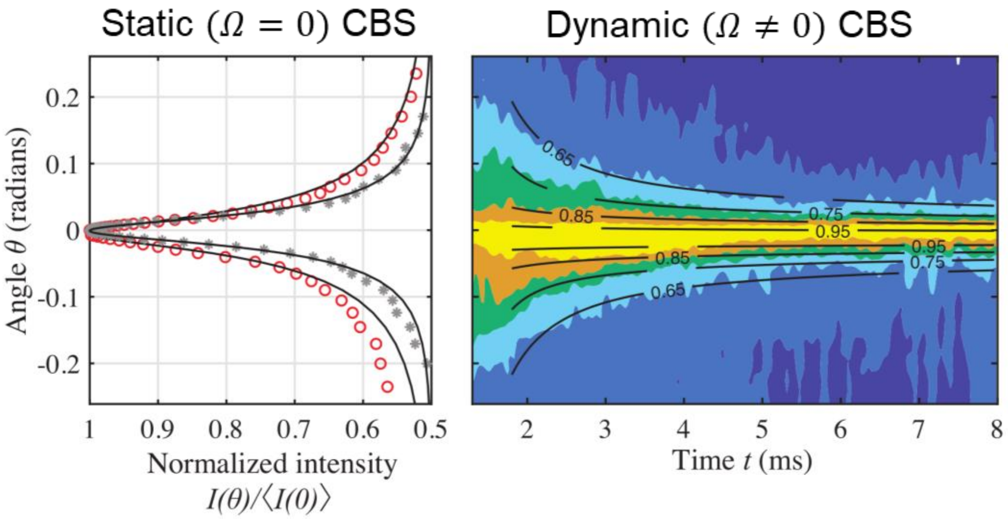
$C_0 = 0.04, g = 30$

$C_0 = 0.4, g = 2$

High fish density
⇒ long range correlation +
low conductance

Mesoscopic wave physics for biomass assessment

Coherent backscattering (CBS):



Static ($\Omega = 0$) CBS

Dynamic ($\Omega \neq 0$) CBS

Plane wave

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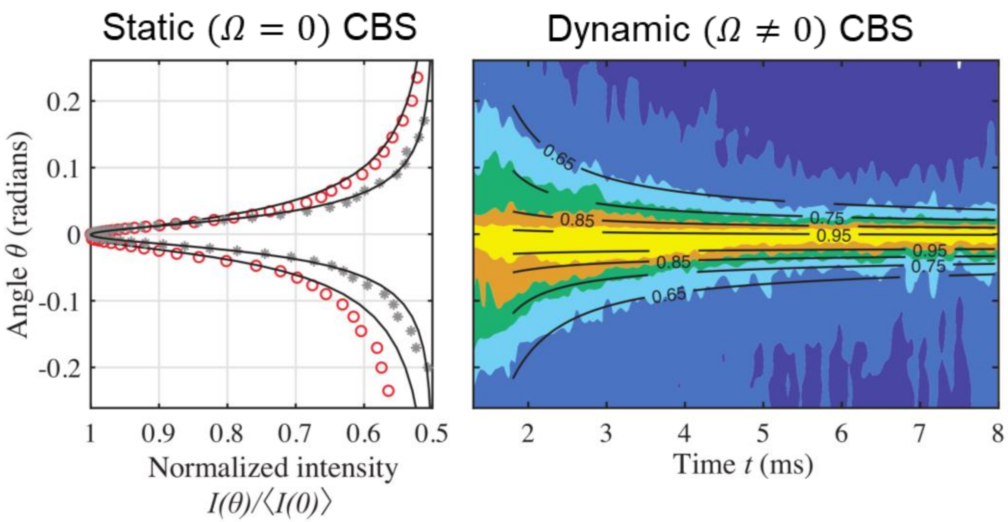
Mesoscopic wave physics for biomass assessment

Coherent backscattering (CBS):



In the frequency domain:

$$\tilde{R}(\theta,\Omega) = \frac{e^{-\gamma_0 z'}}{1+\gamma_0 z_0} + \frac{e^{-\gamma z'}}{1+\gamma z_0}$$

z': source depth

$$\gamma = \sqrt{\frac{-i\Omega}{D} + k_0^2 \sin^2(\theta) + \frac{3}{\ell^* \ell_a}}$$

$\gamma_0 = \gamma(\theta = 0)$

ℓ_a: absorption length

ℓ^*: transport mean free path

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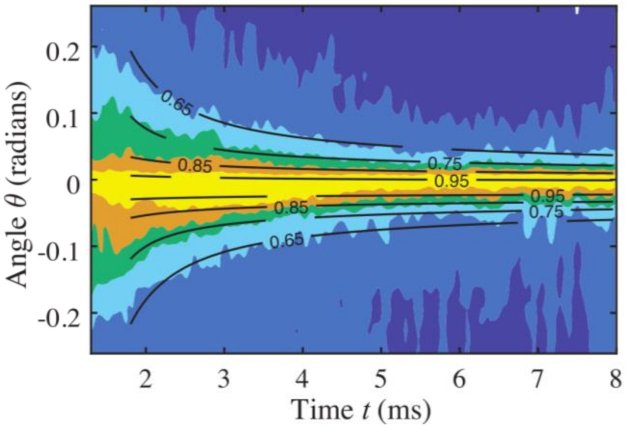
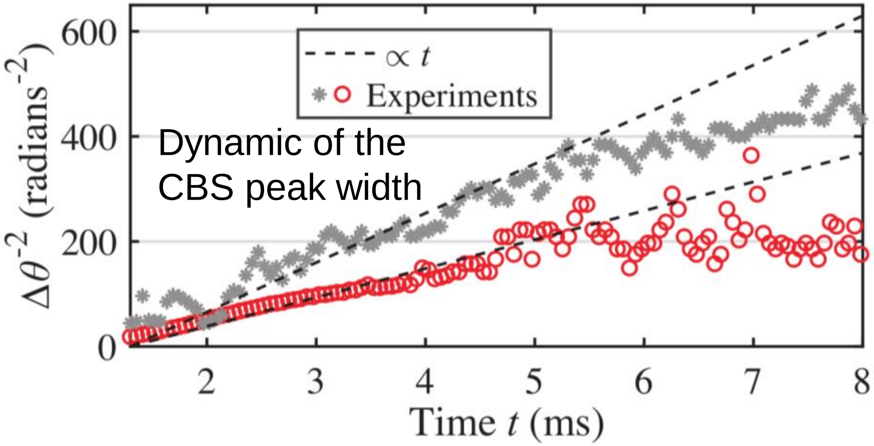
$\ell^* = 1.7\lambda$

$\ell^* = 0.7\lambda$

Mesoscopic wave physics for biomass assessment

Coherent backscattering (CBS):





Dynamic of the CBS peak width

Sub-diffusion of acoustic waves

Diffusivity D can be estimated from the *dynamic* CBS profile

$$\Delta\theta^{-2} \propto Dt$$

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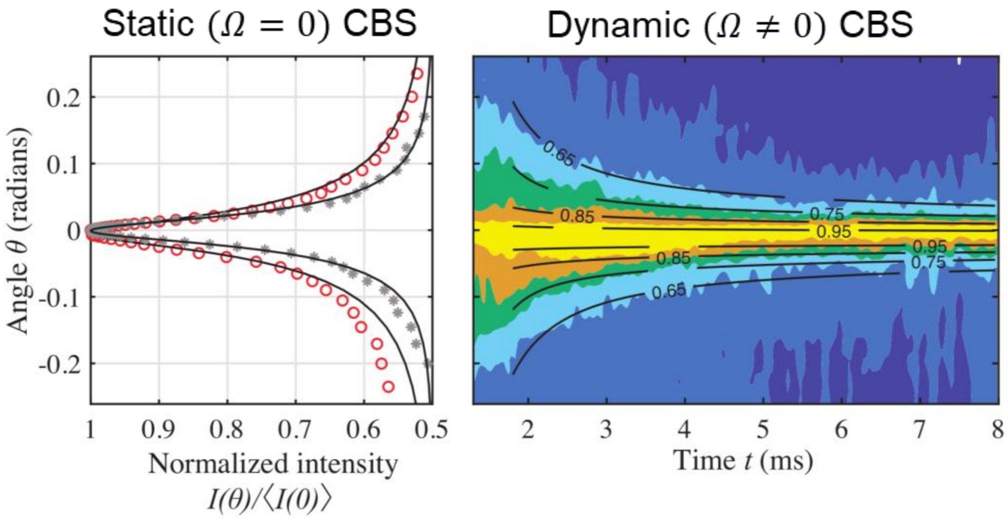
$$\ell^* = 1.7\lambda, D = 0.2\ \mathrm{m}^2/\mathrm{s}$$

$$\ell^* = 0.7\lambda, D = 0.07\ \mathrm{m}^2/\mathrm{s}$$

Mesoscopic wave physics for biomass assessment

Coherent backscattering (CBS):



Energy velocity of diffusive waves:

$$\ell^* = 1.7\lambda, D = 0.2\ \mathrm{m}^2/s$$
$$\Rightarrow v_e = \frac{3D}{\ell^*} = 35\ \mathrm{m}/s$$

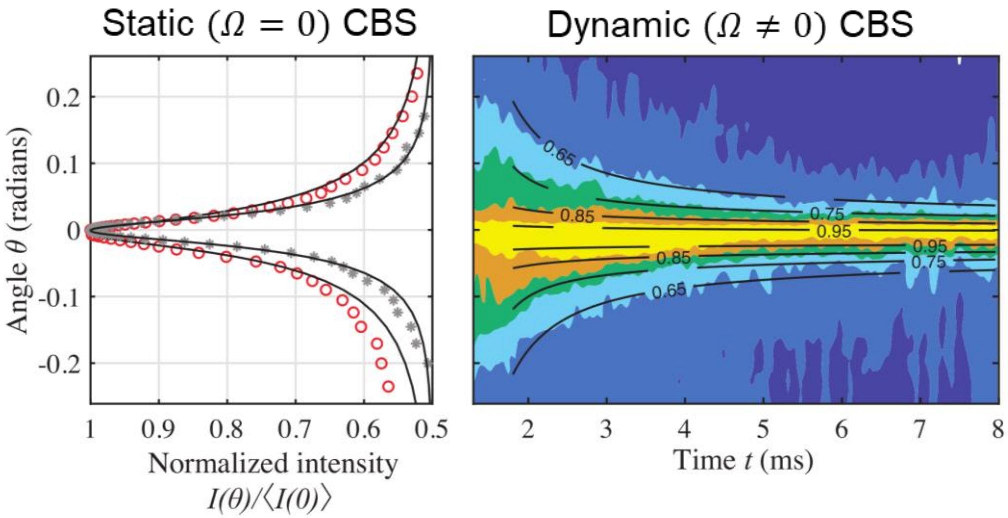
$$\ell^* = 0.7\lambda, D = 0.07\ \mathrm{m}^2/s$$
$$\Rightarrow v_e = \frac{3D}{\ell^*} = 30\ \mathrm{m}/s$$

Ultra-low transport velocity

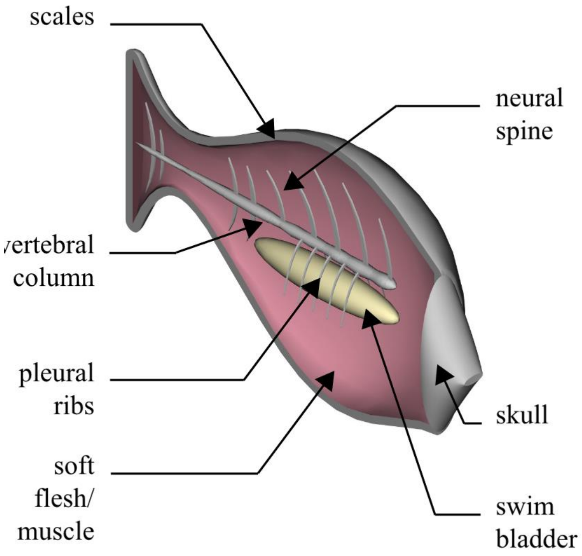
	N	W	η (kg/m^3)	V (m^3)
C1 (sea breams, fry)	75,000	10	6	125
C2 (sea breams, adults)	5,000	500	7	343
C3 (sea breams, adults)	10,080	284	23	125
C4 (sea breams, adults)	6,000	320	15	125
C5 (croakers, adults)	13,900	886	24	512

Mesoscopic wave physics for biomass assessment

Coherent backscattering (CBS):



Fish structure model : elastic medium



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C5 (croakers, adults)	13,900	886	24	512

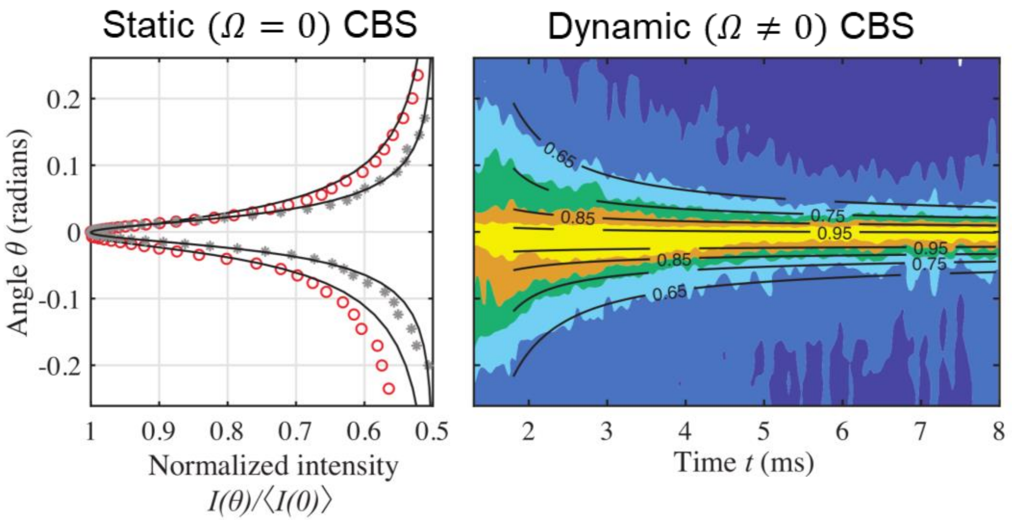
(1) Swim bladder: ~ air

(2) fish flesh: $v_{l2} = 1600\ \mathrm{m/s}$
$\boldsymbol{v_{t2} = 10\ \mathrm{m/s}}$

(3) fish bones: $v_{l1} = 2340\ \mathrm{m/s}$
$v_{t1} = 1040\ \mathrm{m/s}$

Mesoscopic wave physics for biomass assessment

Coherent backscattering (CBS):



Static ($\Omega = 0$) CBS

Dynamic ($\Omega \neq 0$) CBS

	N	W	η (kg/m^3)	V (m^3)
C1 (sea breams, fry)	75,000	10	6	125
C2 (sea breams, adults)	5,000	500	7	343
C3 (sea breams, adults)	10,080	284	23	125
C4 (sea breams, adults)	6,000	320	15	125
C5 (croakers, adults)	13,900	886	24	512

Energy velocity of diffusive waves:

→ Assuming energy equipartition

$(E_t/E_l = 2v_l^3/2v_t^3 \gg 1)$,

shear waves dominate in the fish.

$$\Rightarrow v_{fish} \sim v_t = 10\ \mathrm{m/s}$$

$v_{water} \sim v_0$ = 1500 m/s

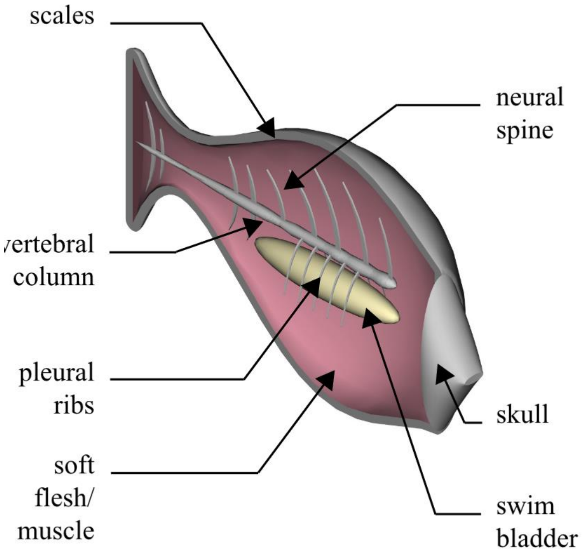
ϕ fish volume fraction

$$v_e = \frac{1 + (\phi/(1-\phi))^{1/3}}{1/v_0 + (\phi/(1-\phi))^{1/3}/v_t}$$

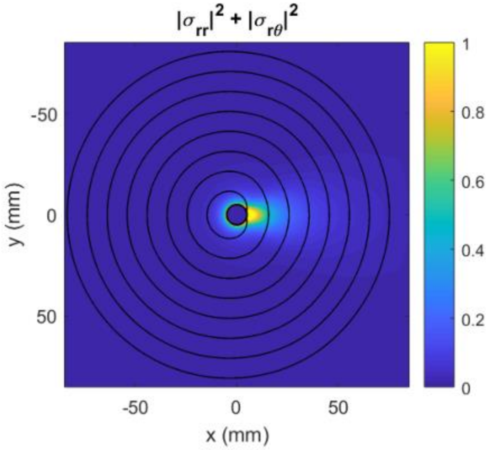
$$v_e \sim 30\ \mathrm{m/s}$$

Mesoscopic wave physics for biomass assessment

Energy velocity of diffusive waves:



(0) sea water:
$v_{l0} = 1480 \text{ m/s}$
$\rho_0 = 1 \text{ g/cm}^3$



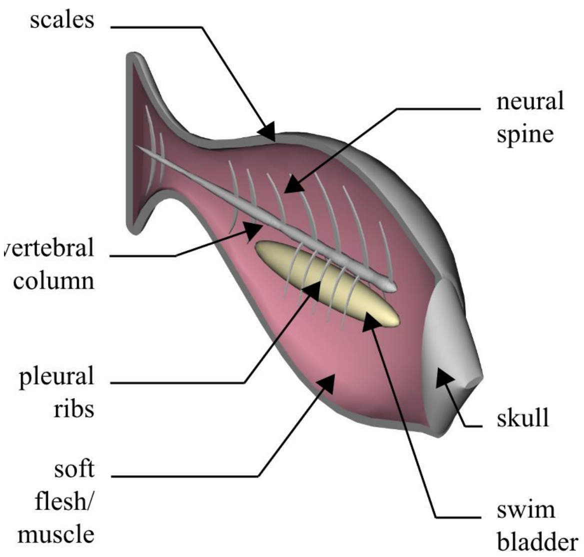
Map of scattered intensity

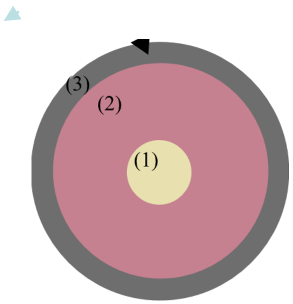
$v = 1500 \text{ m/s}$

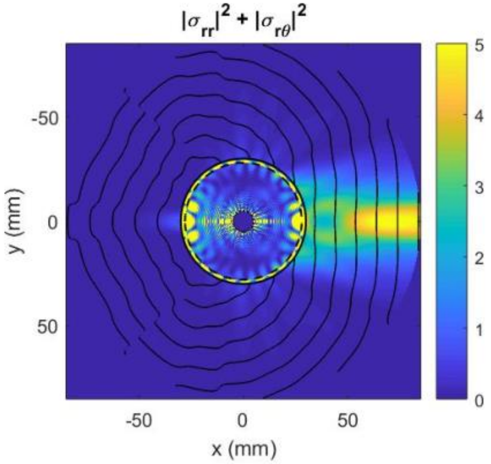
(1) Swim bladder:
$v_{l1} = 340 \text{ m/s}$
$\rho_1 = 0.001 \text{ g/cm}^3$
$R_1 = 5 \text{ mm}$

Mesoscopic wave physics for biomass assessment

Energy velocity of diffusive waves:







Map of scattered intensity

$$v = 50\ \mathrm{m/s}$$

(0) sea water:

$$v_{l0} = 1480\ \mathrm{m/s}$$
$$\rho_0 = 1\ \mathrm{g/cm^3}$$

(2) fish flesh:

$$v_{l2} = 1600\ \mathrm{m/s}$$
$$\boldsymbol{v_{t2} = 100\ \mathrm{m/s}}$$
$$\rho_2 = 1.1 \mathrm{g/cm^3}$$
$$R_1 = 30\ \mathrm{mm}$$

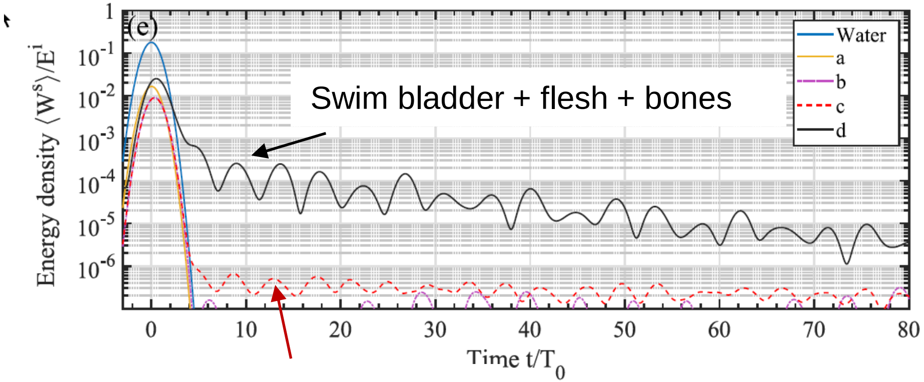
(3) fish bones:

$$v_{l1} = 2340\ \mathrm{m/s}$$
$$v_{t1} = 1040\ \mathrm{m/s}$$
$$\rho_1 = 1.4\ \mathrm{g/cm^3}$$
$$R_1 = 31\ \mathrm{mm}$$

(1) Swim bladder:

$$v_{l1} = 340\ \mathrm{m/s}$$
$$\rho_1 = 0.001\ \mathrm{g/cm^3}$$
$$R_1 = 5\ \mathrm{mm}$$

Scattering delay



Swim bladder + flesh + bones

Swim bladder + flesh

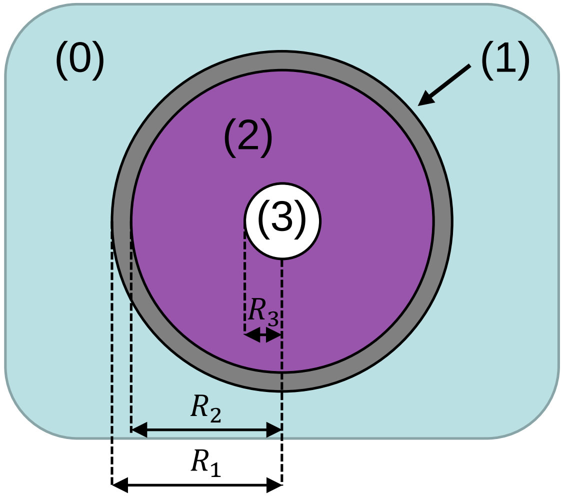
Conclusions

- Conclusions
  - Observation of mesoscopic wave phenomena in fish shoals
  - Potential new tools for biomass assessment

- Perspectives
  - Long time range experiments (fish growth monitoring)

Mesoscopic wave physics for biomass assessment

Energy velocity of diffusive waves:



(0) sea water:
$v_{l0} = 1480\ \mathrm{m/s}$
$\rho_0 = 1\ \mathrm{g/cm^3}$

(1) fish bones:
$v_{l1} = 2340\ \mathrm{m/s}$
$v_{t1} = 1040\ \mathrm{m/s}$
$\rho_1 = 1.4\ \mathrm{g/cm^3}$
$R_1 = 31\ \mathrm{mm}$

(2) fish flesh:
$v_{l2} = 1600\ \mathrm{m/s}$
$\boldsymbol{v_{t2} = 100\ \mathrm{m/s}}$
$\rho_2 = 1.1\mathrm{g/cm^3}$
$R_1 = 30\ \mathrm{mm}$

(3) Swim bladder:
~ vacuum
$R_1 = 5\ \mathrm{mm}$

$$k^2 = \frac{\omega}{v_{\mathrm{ph}}} + \frac{\mathrm{j}}{2\ell_s}$$

$$= k_0^2 + 4\pi \int_R \eta_R f_R(0)\mathrm{d}a$$

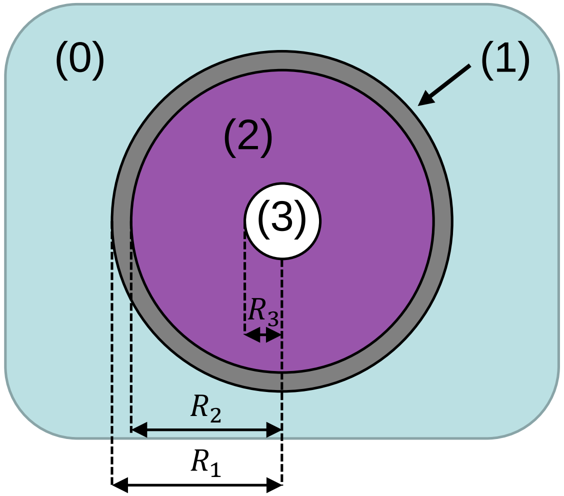
$$v_{\mathrm{gr}} = \frac{v_0^2/v_{\mathrm{ph}}}{1+\Delta_{\mathrm{gr}}} \qquad \boldsymbol{\Delta}_{\mathbf{gr}} = 2\pi \int_R \eta_R \frac{v_0^2}{\omega}\frac{\partial \mathrm{Re} f_R(0)}{\partial\omega}\mathrm{dR}$$

$$v_e = \frac{v_0^2/v_{\mathrm{ph}}}{1+\Delta_1+\Delta_2} \qquad \boldsymbol{\Delta}_{\mathbf{1}} = \frac{v_{\mathrm{ph}}}{v_0^2} v_{\mathrm{gr}}\, \boldsymbol{\Delta}_{\mathbf{gr}}$$

$$\boldsymbol{\Delta}_{\mathbf{2}} = 2\pi v_{\mathrm{gr}} \int_R \int_\theta \mathrm{dRd}\theta\,\eta_{\mathrm{R}}\sin\theta\,|f_R(\theta)|^2 \frac{\partial\varphi_R(\theta)}{\partial\omega}$$

Mesoscopic wave physics for biomass assessment

Energy velocity of diffusive waves:



(0) sea water:
$v_{l0} = 1480\ \mathrm{m/s}$
$\rho_0 = 1\ \mathrm{g/cm^3}$

(1) fish bones:
$v_{l1} = 2340\ \mathrm{m/s}$
$v_{t1} = 1040\ \mathrm{m/s}$
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(2) fish flesh:
$v_{l2} = 1600\ \mathrm{m/s}$
$\boldsymbol{v_{t2} = 100\ \mathrm{m/s}}$
$\rho_2 = 1.1\mathrm{g/cm^3}$
$R_1 = 30\ \mathrm{mm}$

(3) Swim bladder:
$\sim$ vacuum
$R_1 = 5\ \mathrm{mm}$

$$k^2(\omega) = k_0^2(\omega) + 4\pi \int_a \eta_a f_a(0)\mathrm{d}a$$

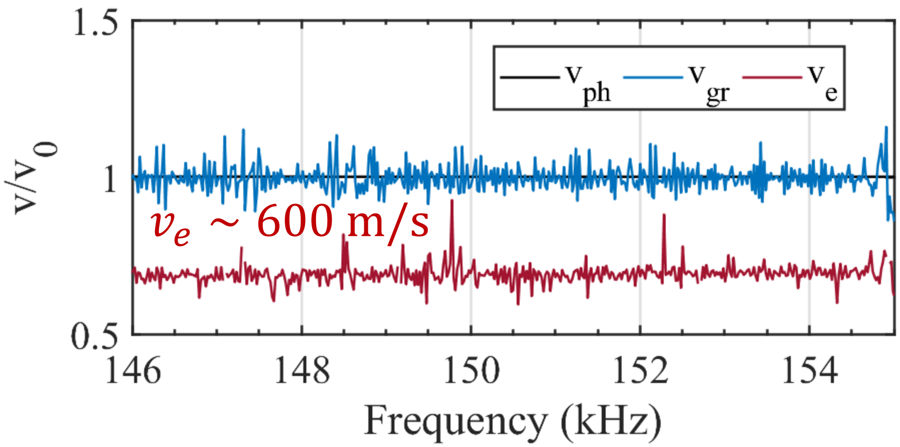
$$v_{\mathrm{gr}} = \frac{v_0^2/v_{\mathrm{ph}}}{1+\Delta_{\mathrm{gr}}}$$

$$\boldsymbol{\Delta_{\mathrm{gr}}} = 2\pi \int_R \eta_R \frac{v_0^2}{\omega}\frac{\partial \mathrm{Re} f_R(0)}{\partial \omega}\mathrm{dR}$$

$$v_e = \frac{v_0^2/v_{\mathrm{ph}}}{1+\Delta_1+\Delta_2}$$

$$\boldsymbol{\Delta_1} = \frac{v_{\mathrm{ph}}}{v_0^2} v_{\mathrm{gr}}\, \boldsymbol{\Delta_{\mathrm{gr}}}$$

$$\boldsymbol{\Delta_2} = 2\pi v_{\mathrm{gr}} \int_R \int_\theta \mathrm{dR}\mathrm{d}\theta\, \eta_{\mathrm{R}} \sin\theta |f_R(\theta)|^2 \frac{\partial \varphi_R(\theta)}{\partial \omega}$$

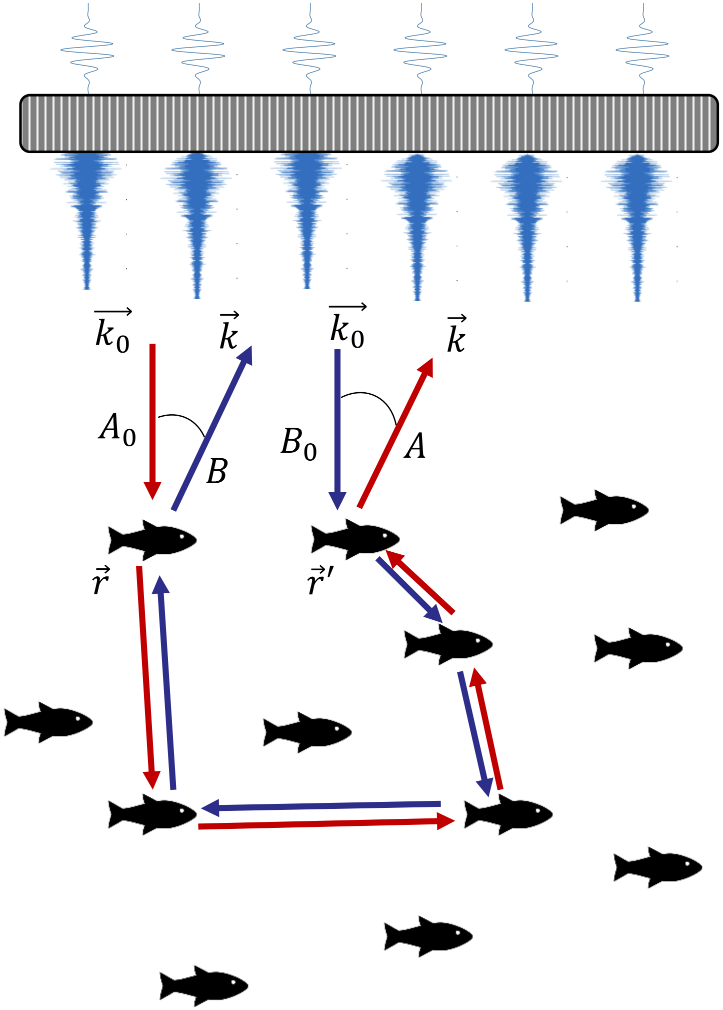


$v_e \sim 600\ \mathrm{m/s}$

Vibea

P. Sheng, *Introduction to wave scattering, Localization, and Mesoscopic phenomena* (2006)

Effet de rétrodiffusion cohérente : vers une estimation directe de la biomasse

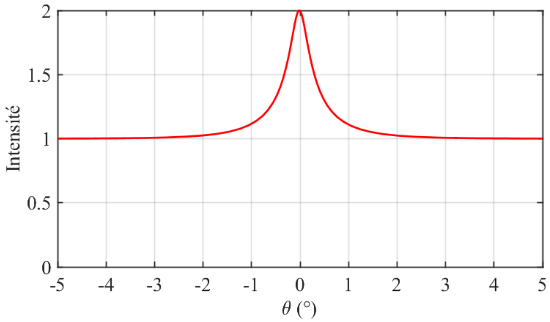


Seapix

Avec boucles d'interférence

$$|A+B|^2 = 2|A|^2\{1+\cos[(\overrightarrow{k_0}+\vec{k}).(\vec{r}-\vec{r}')]\}$$

Facteur 2 sur l'intensité dans la direction $\vec{k} = -\overrightarrow{k_0}$.



Gloires optiques :

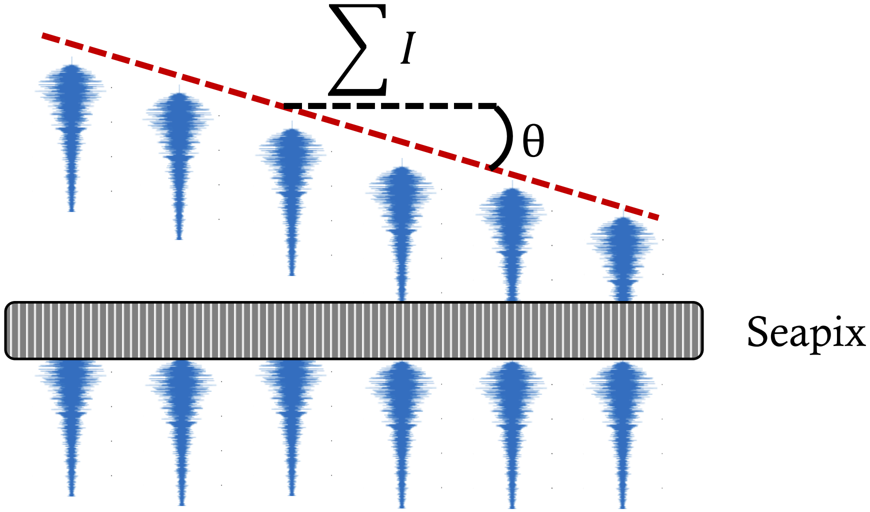
Linfo.re

earthsky.org

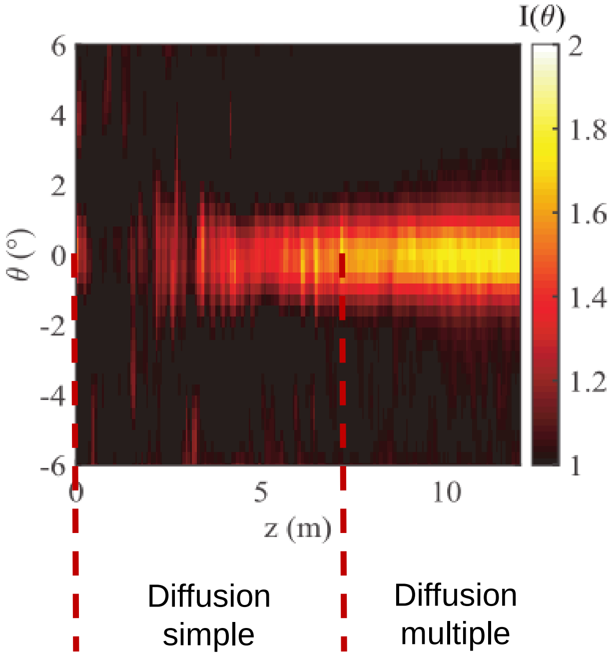
Vibea

Effet de rétrodiffusion cohérente : vers une estimation directe de la biomasse

Déphasage sur chaque élément



Mesure du cône de rétrodiffusion dans des bancs de saumons :

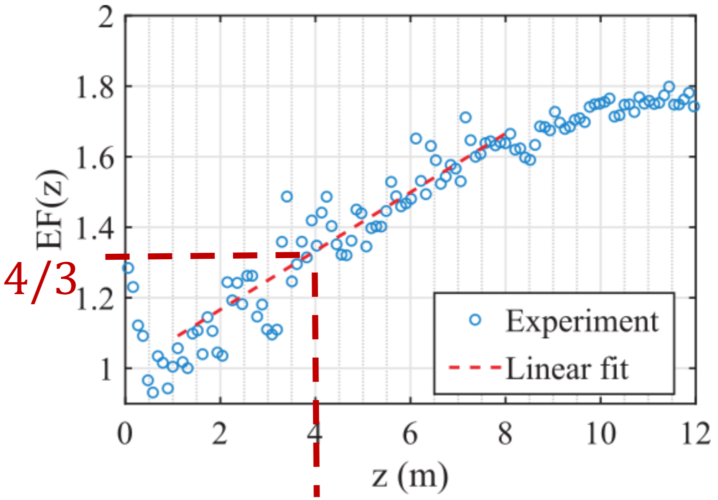


B. Tallon, P. Roux, G . Matte, J. Guillard, S. E. Skipetrov *J. Acoust. Soc. Am.* **148**, EL234 (2020)

Vibea

Effet de rétrodiffusion cohérente : vers une estimation directe de la biomasse

<u>Amplitude du cône :</u>

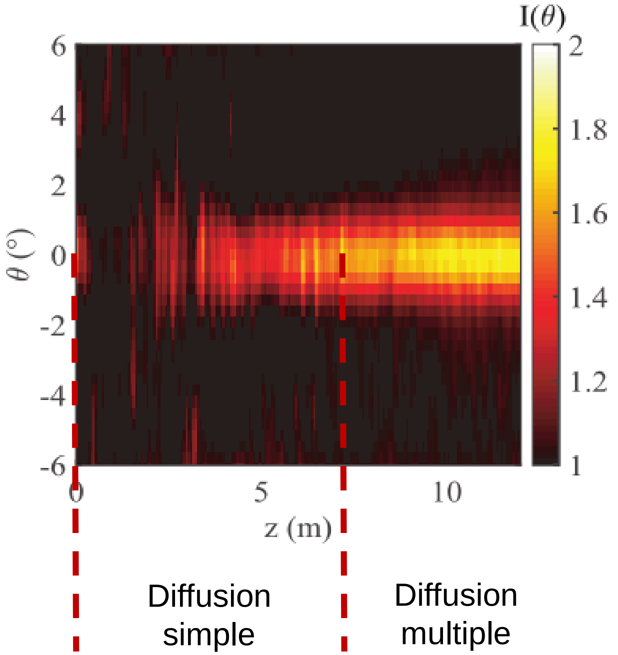


$\ell_s = (4 \pm 0{,}3)$ m

$$EF = \frac{I(0)}{I(\theta)} = \frac{2I_{DS}(0) + 2I_{DM}(0)}{2I_{DS}(\theta) + I_{DM}(\theta)}$$

B. Tallon, P. Roux, G . Matte, J. Guillard, S. E. Skipetrov *J. Acoust. Soc. Am.* **148**, EL234 (2020)

<u>Mesure du cône de rétrodiffusion dans des bancs de saumons :</u>



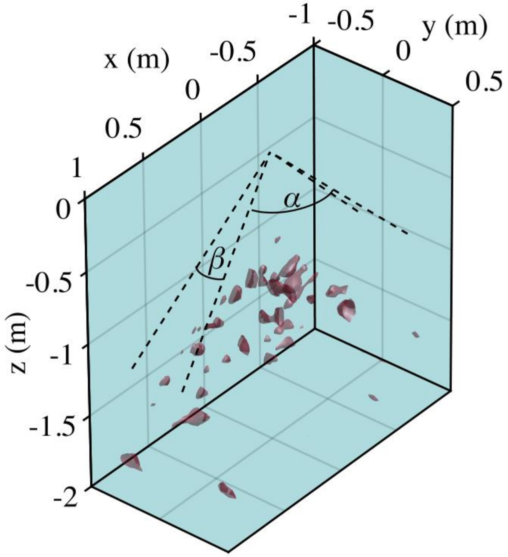
Diffusion simple

Diffusion multiple

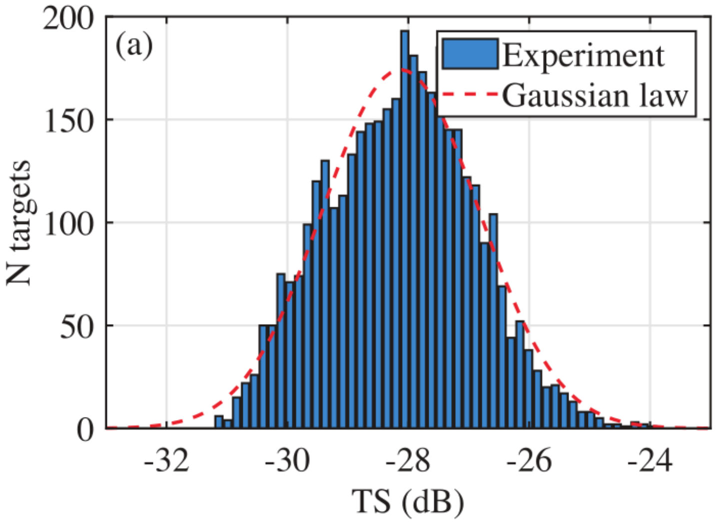
Vibea

Effet de rétrodiffusion cohérente : vers une estimation directe de la biomasse

Scan superficiel du banc (diffusion simple):



Distribution de TS:



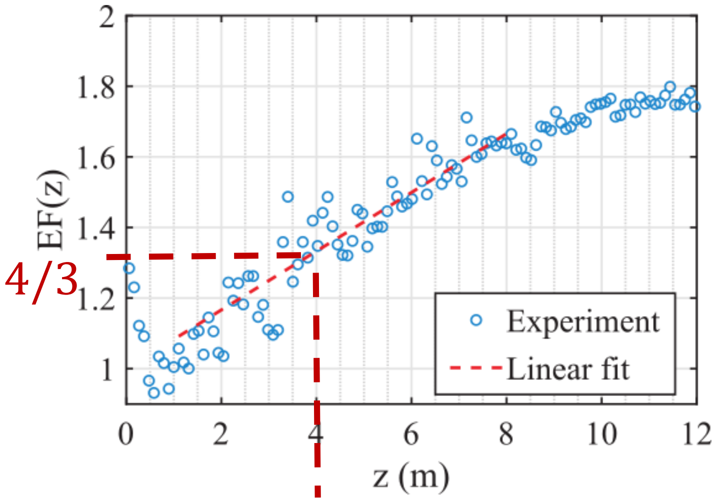
$TS = (-28 \pm 1)$ dB

B. Tallon, P. Roux, G . Matte, J. Guillard, S. E. Skipetrov *J. Acoust. Soc. Am.* **148**, EL234 (2020)

Vibea

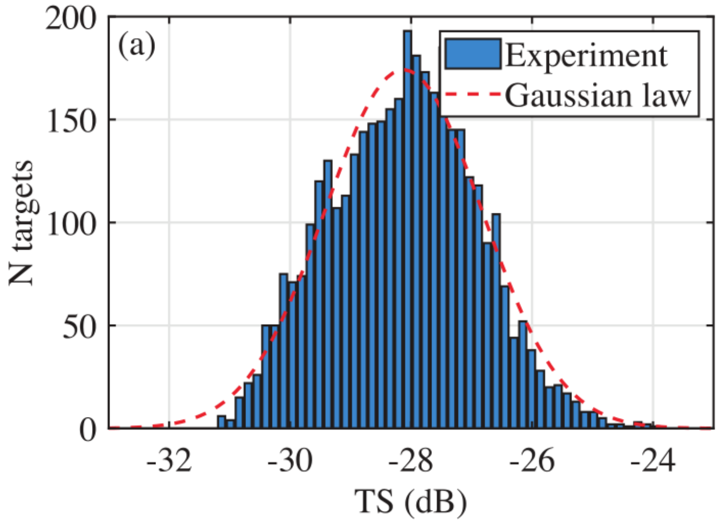
Effet de rétrodiffusion cohérente : vers une estimation directe de la biomasse

Amplitude du cône :



$\ell_s = (4 \pm 0{,}3)$ m

Distribution de TS:



$TS = (-28 \pm 1)$ dB

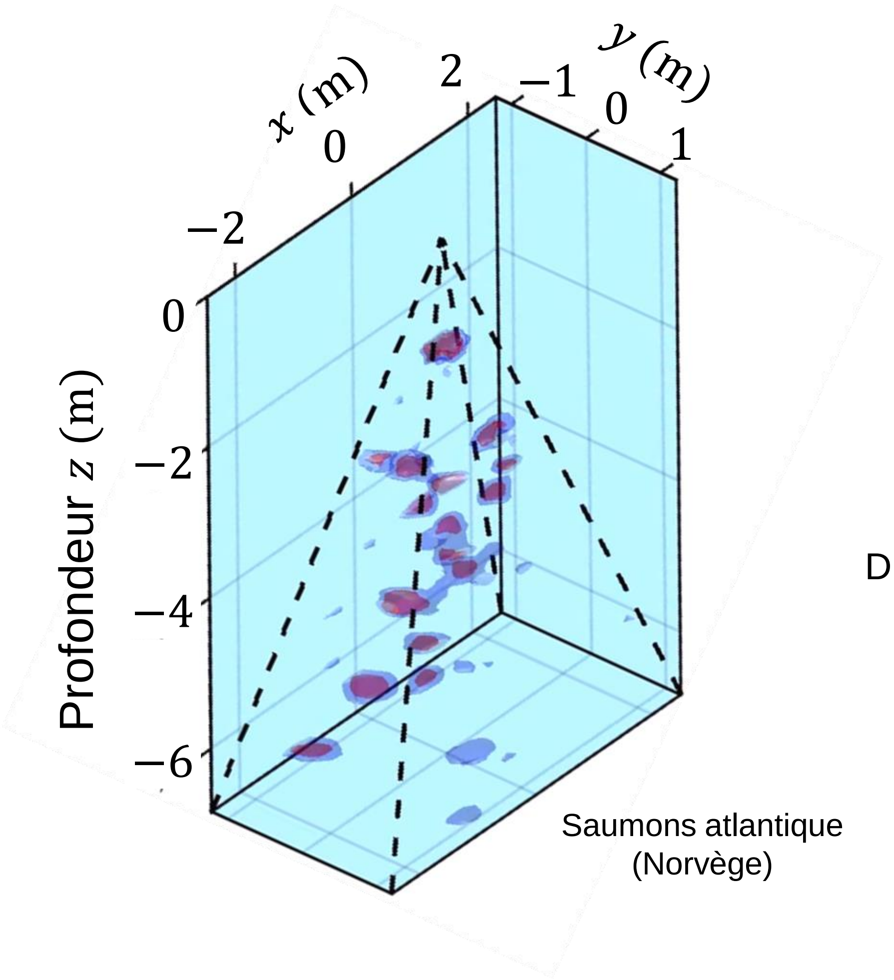
$$\eta \propto \frac{1}{10^{-TS/10} \times \ell_s}$$

$$\eta = (7 \pm 1)\ \text{poissons/m}^3$$

B. Tallon, P. Roux, G . Matte, J. Guillard, S. E. Skipetrov *J. Acoust. Soc. Am.* **148**, EL234 (2020)

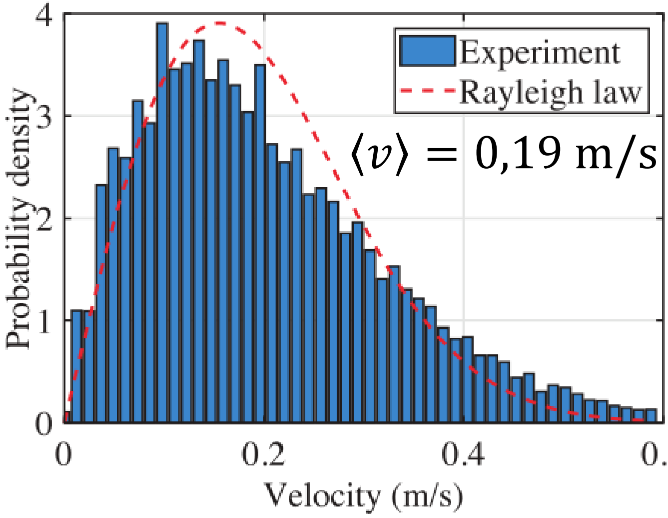
Vibea

Suivi de l’activité du banc

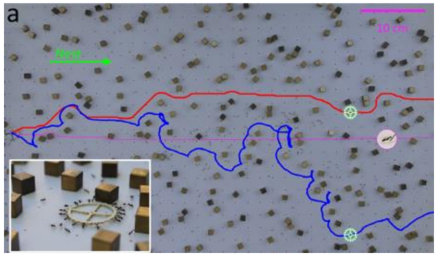


Saumons atlantique
(Norvège)

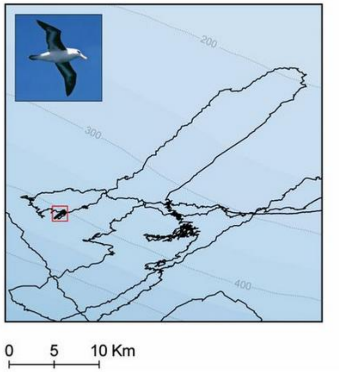
Distribution de Vitesses :



Distribution de Rayleigh = pas de corrélations de vitesses



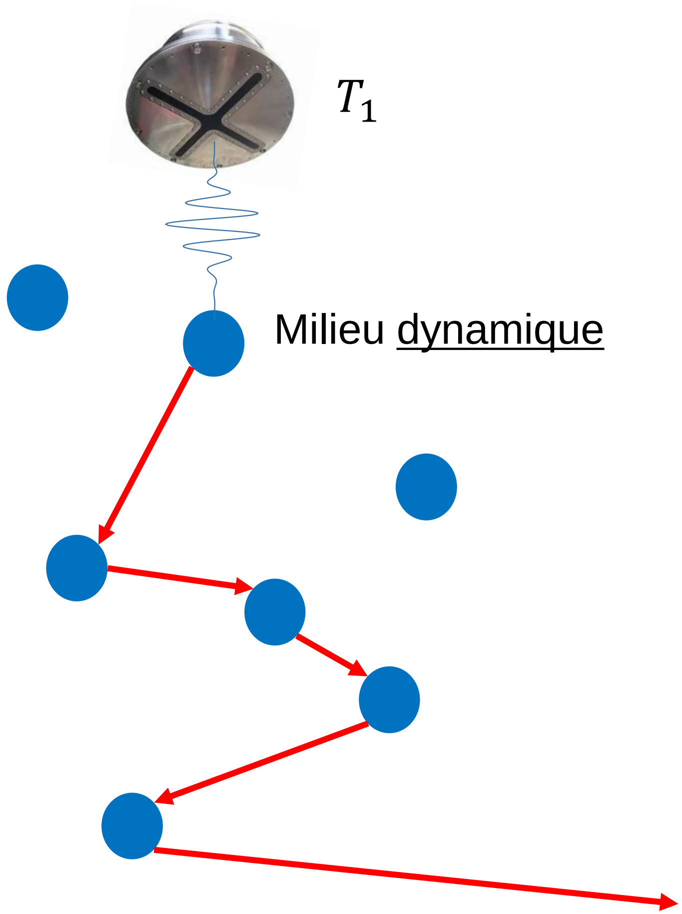
A. Gelblum *et al.* *eLife* **9** (2020)



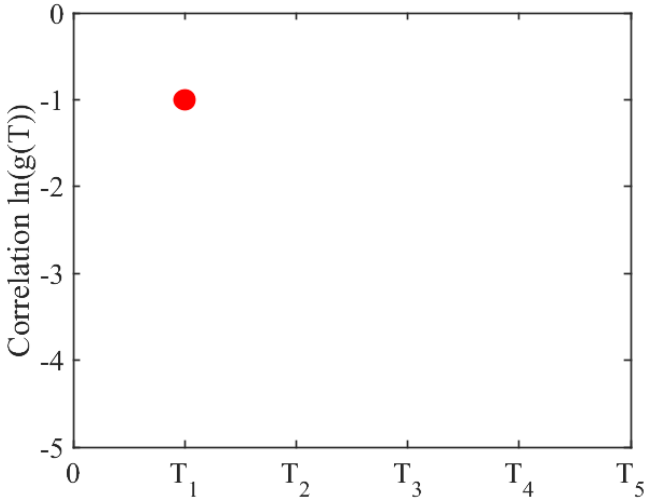
S. Ornes, *PNAS* **110** (2013)

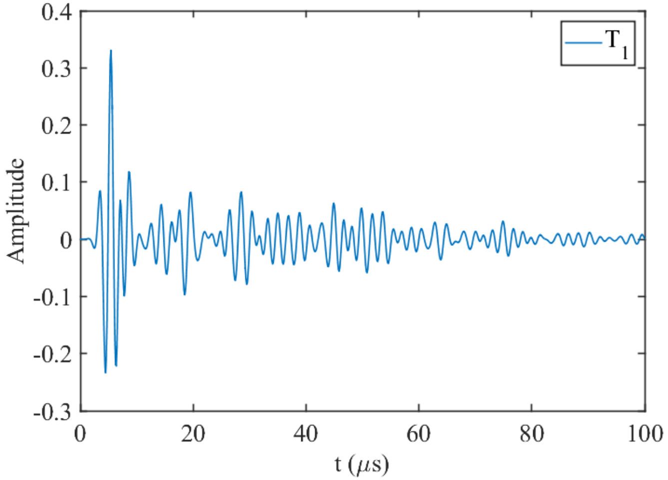
Vibea

DWS: *Diffusing wave spectroscopy*



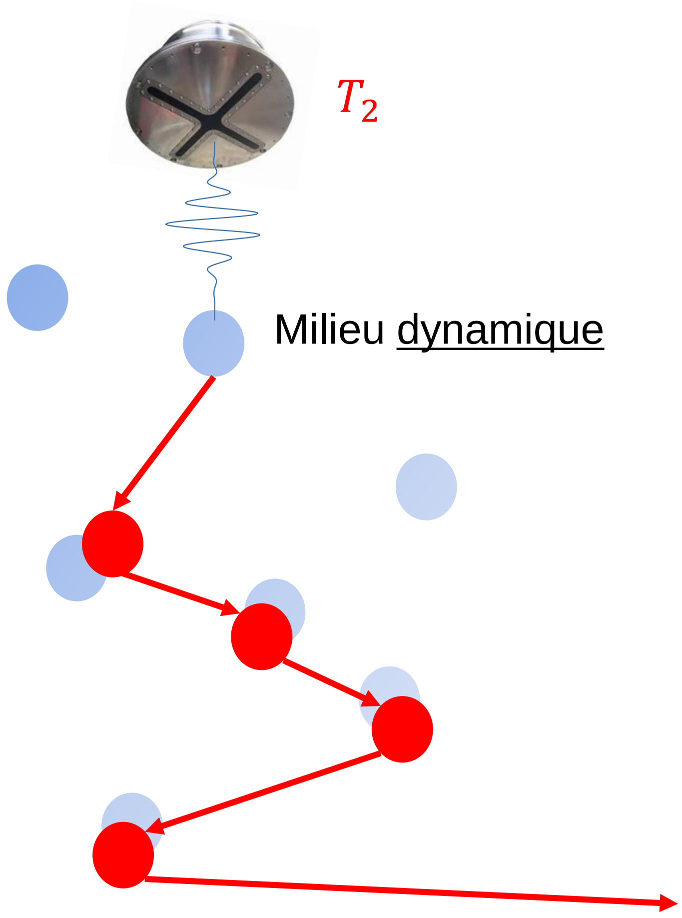
Milieu dynamique



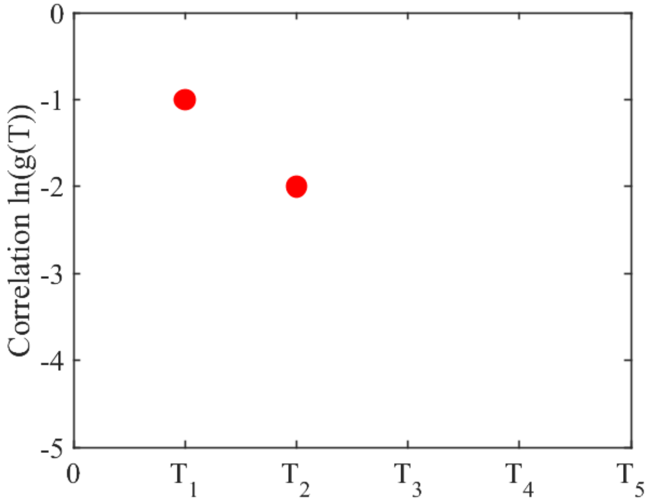


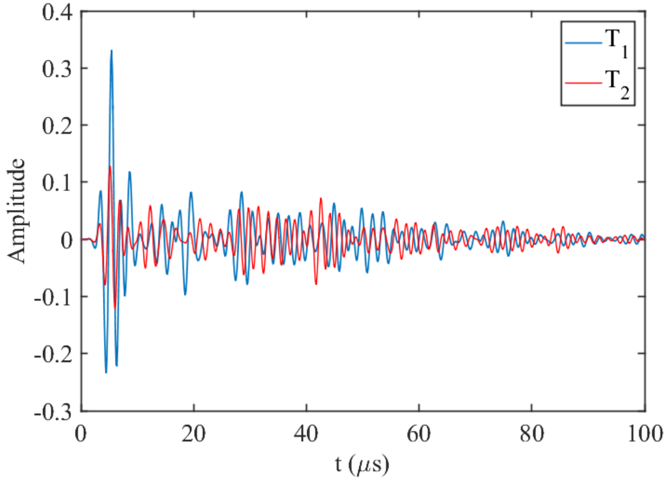
Vibea

DWS: *Diffusing wave spectroscopy*



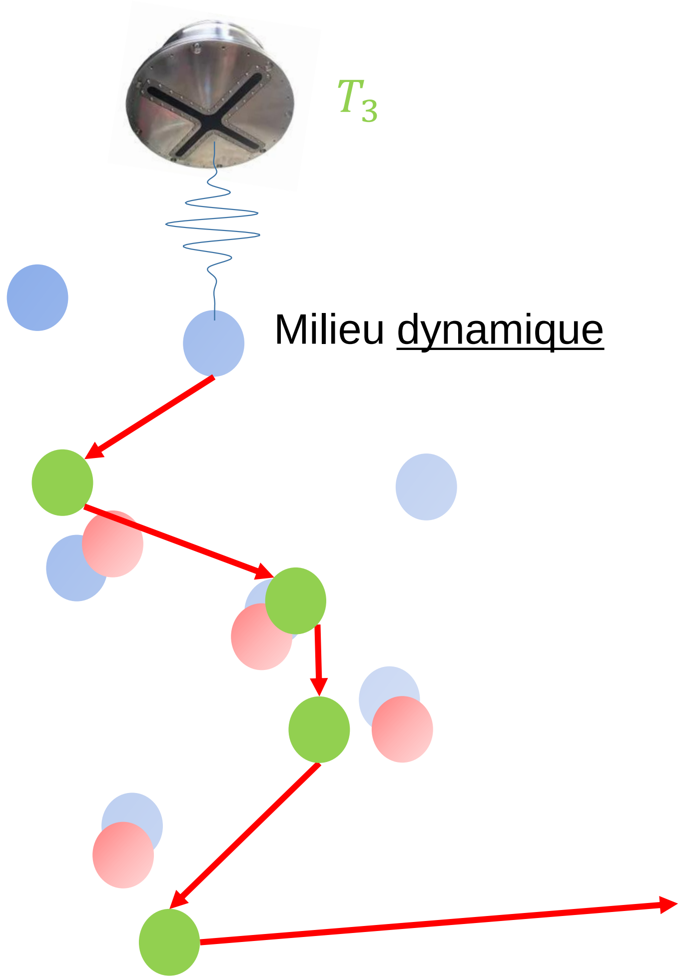
Milieu dynamique



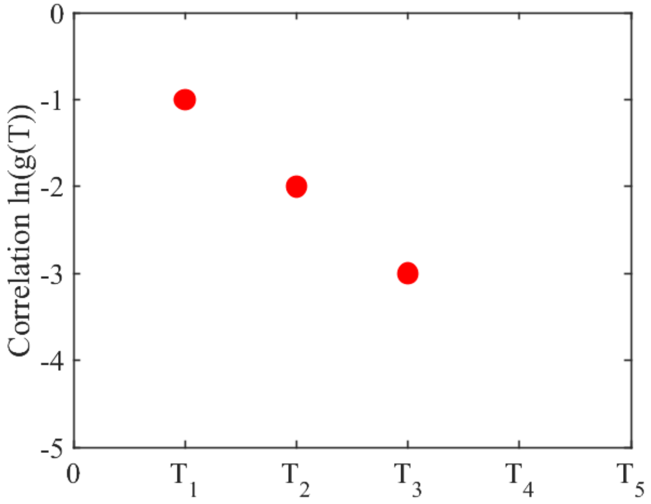


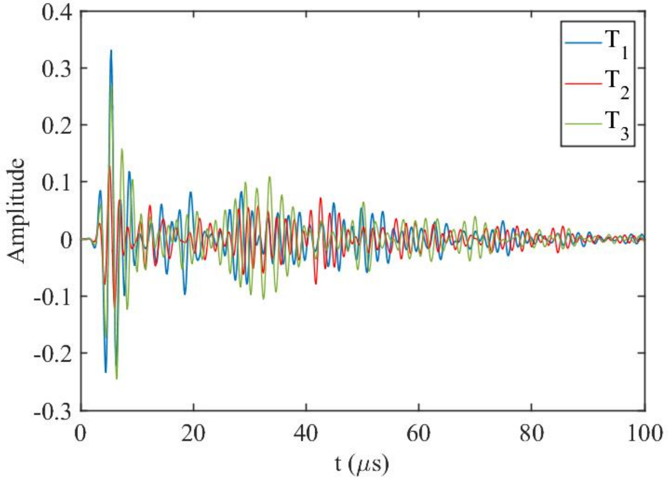
Vibea

DWS: *Diffusing wave spectroscopy*



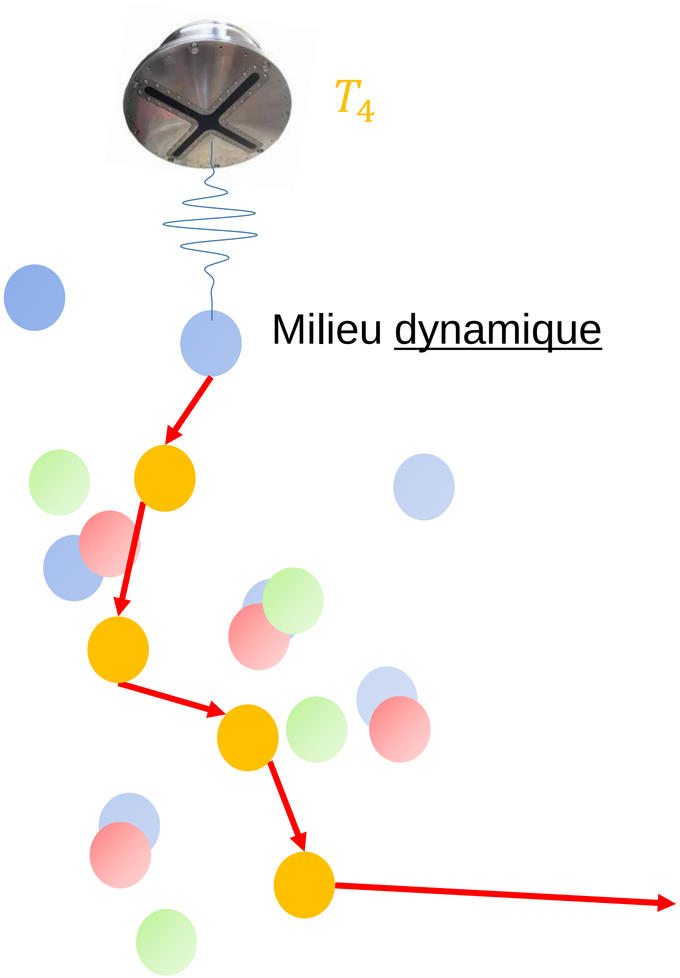
Milieu dynamique



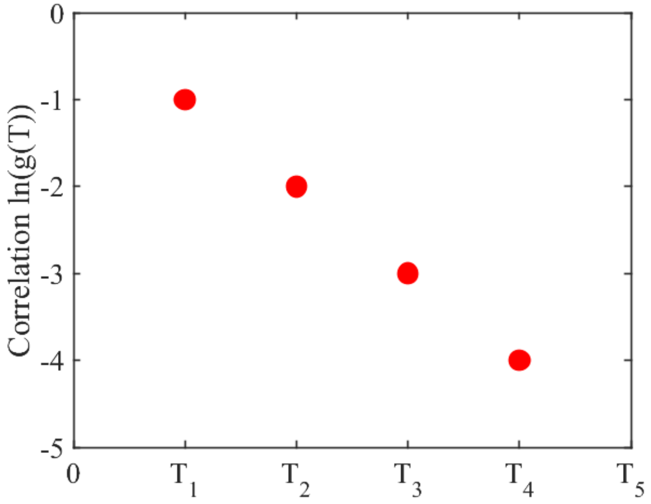


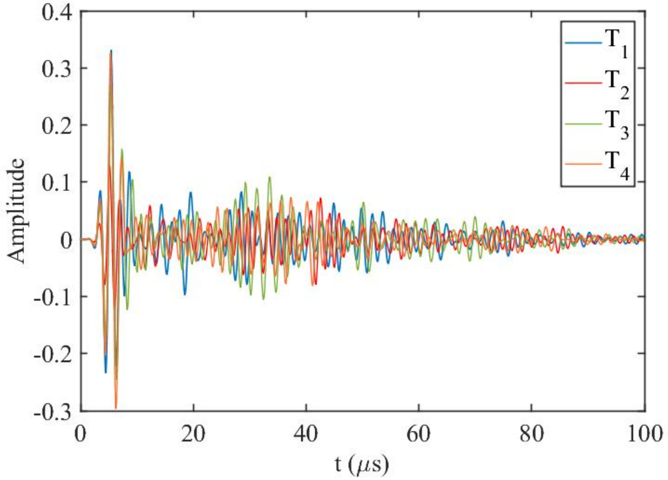
Vibea

DWS: *Diffusing wave spectroscopy*



Milieu <u>dynamique</u>





Vibea

DWS: *Diffusing wave spectroscopy*

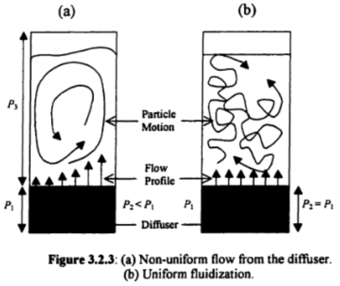
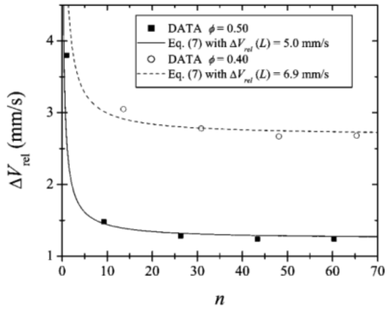
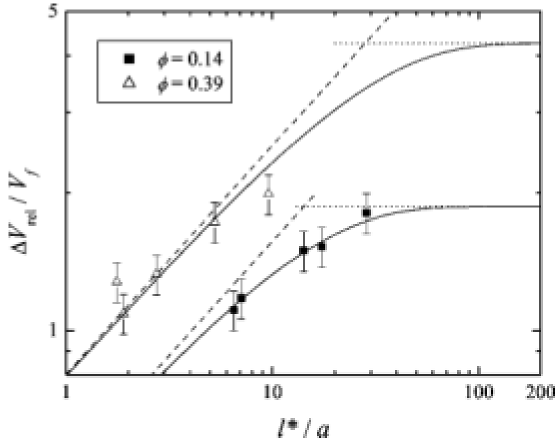


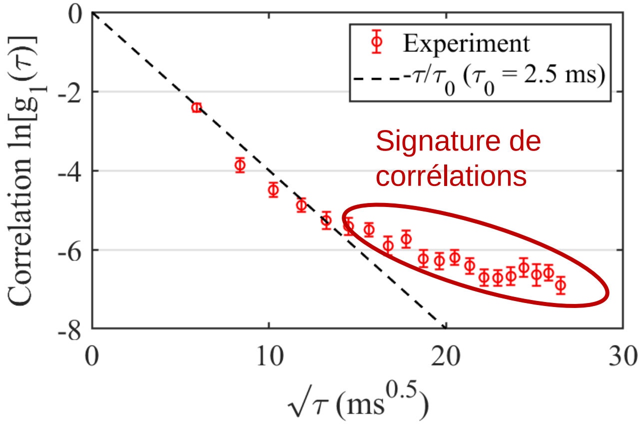
Figure 3.2.3: (a) Non-uniform flow from the diffuser. (b) Uniform fluidization.



Lorsque la dynamique est connue :



M. Cowan *et al.*, *Phys. Rev. E* **65**, 066605 (2002)



Signature de corrélations

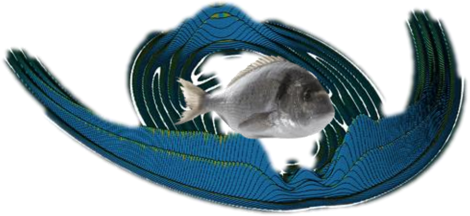
Spectroscopie acoustique
(Daurades)

Étude de la dynamique
du banc

Estimation de la
Densité du banc ?

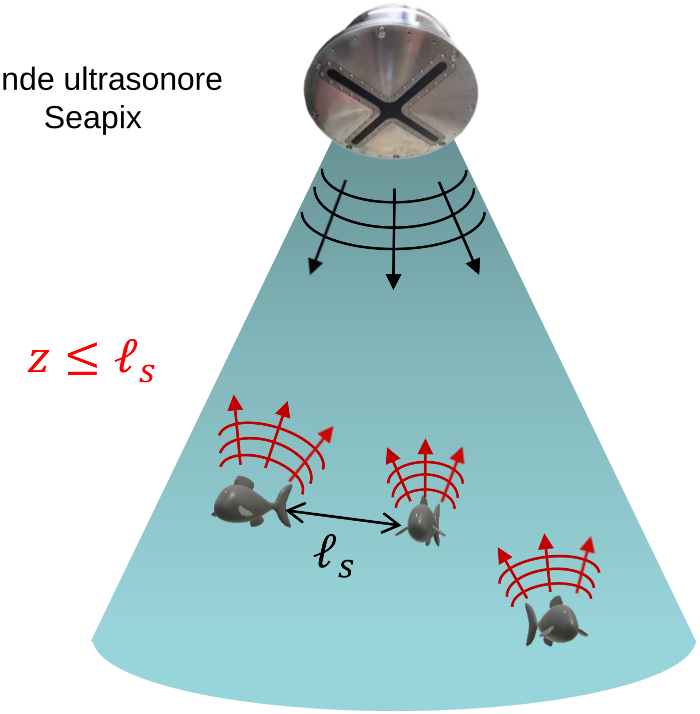
Shoal biomass estimation : low density

<ins>Poissons osseux</ins> = forts diffuseurs pour les ultrasons

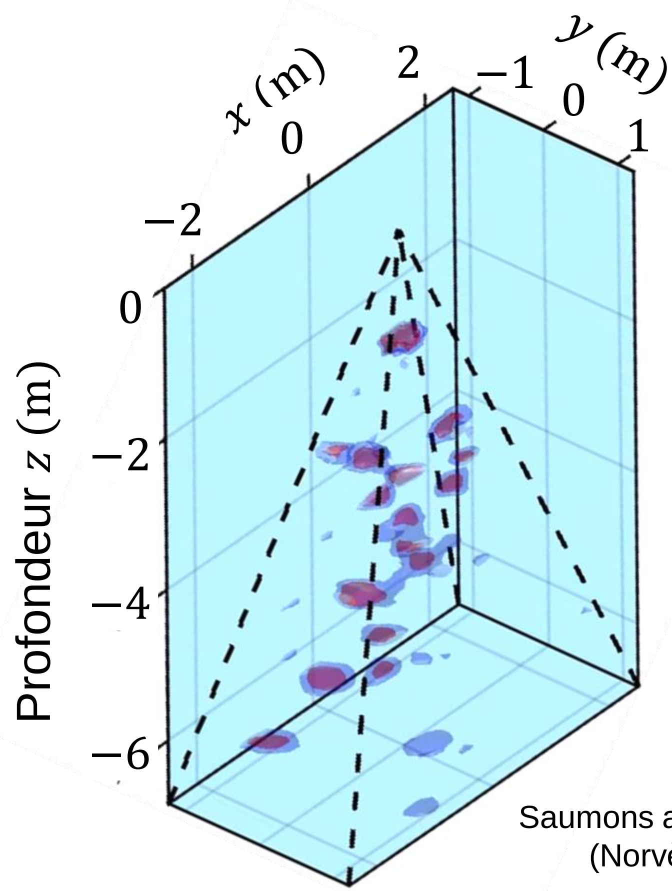


<ins>Pour une faible densité de poissons:</ins>

Sonde ultrasonore
Seapix



Régime de diffusion simple
⇒ Comptage traditionnel



Saumons atlantique
(Norvège)