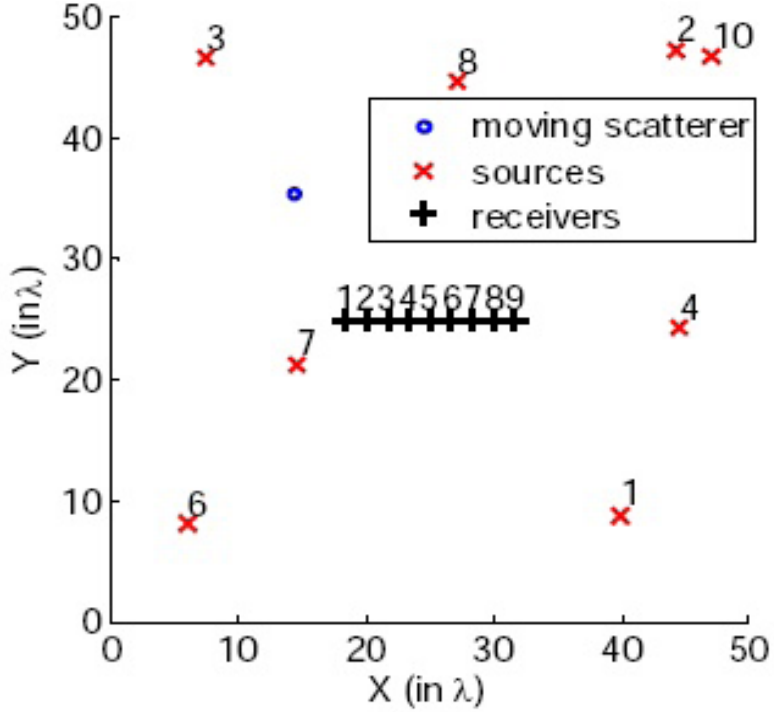
Locating weak changes in the multiple scattering regime

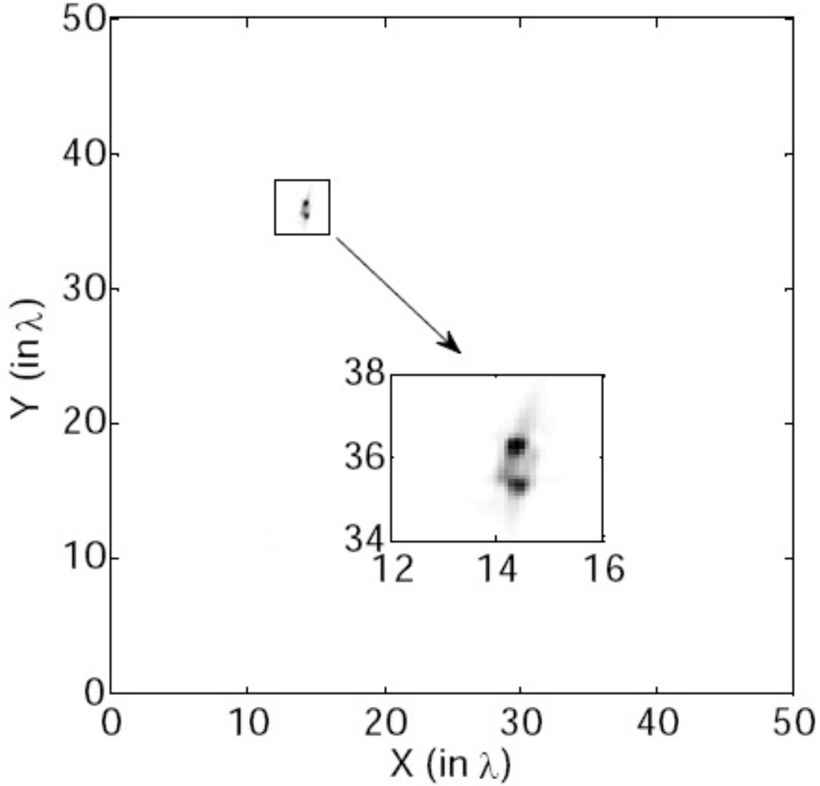
Institut des Sciences de la Terre

Thomas PLANES , Eric LAROSE, Vincent ROSSETTO, Ludovic MARGERIN.

Classical imaging (pulse-echo)

Homogeneous medium ⇔ Single scattering regime



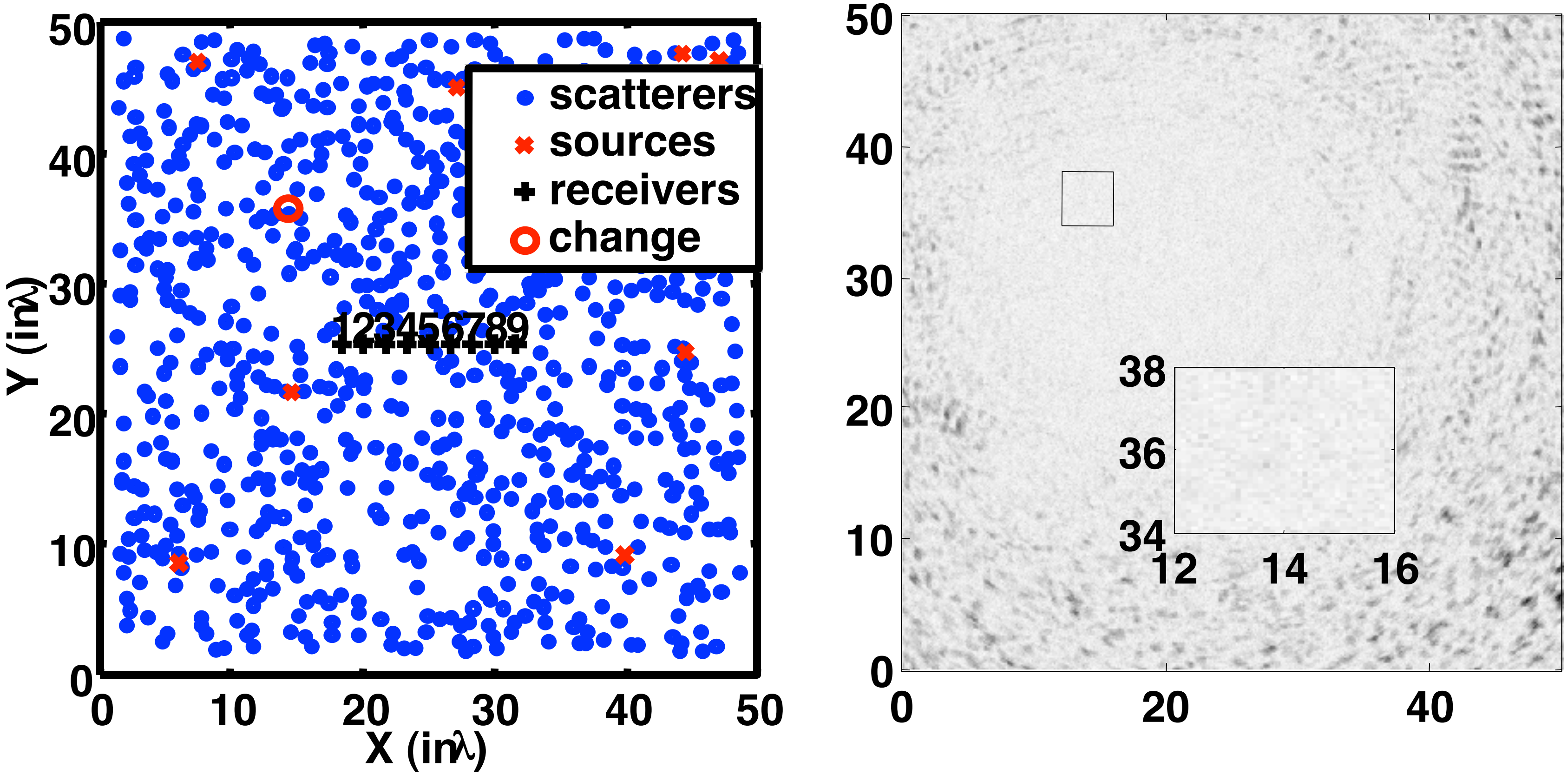


$$I(x,y) = \sum_{S,R} \left[\phi_0(S,R,\delta) - \phi_1(S,R,\delta)\right]^2 \quad \delta : \text{Time of flight } S \text{ - pixel}(x,y) \text{ - R}$$

Classical imaging (pulse-echo)

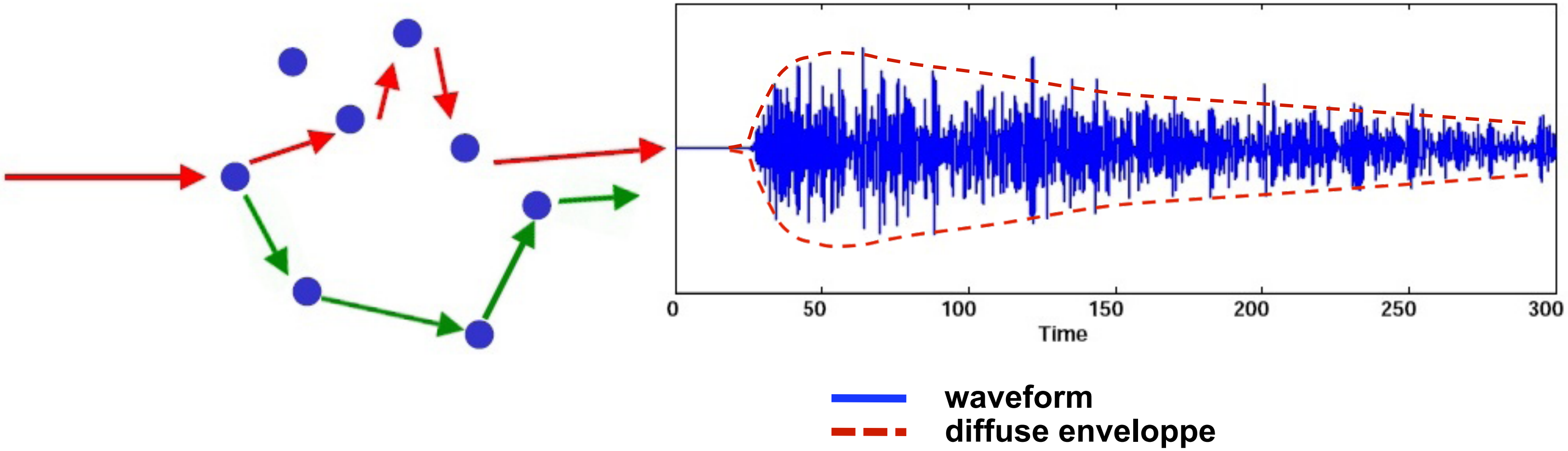
Highly heterogeneous medium ⇔ Multiple scattering regime

$$\lambda << l^* << l_{abs}, L_{medium}$$



$$I(x,y) = \sum_{S,R} \left[\phi_0(S,R,\delta) - \phi_1(S,R,\delta)\right]^2$$ δ : Time of flight S - pixel(x,y) - R

Locating with the coda

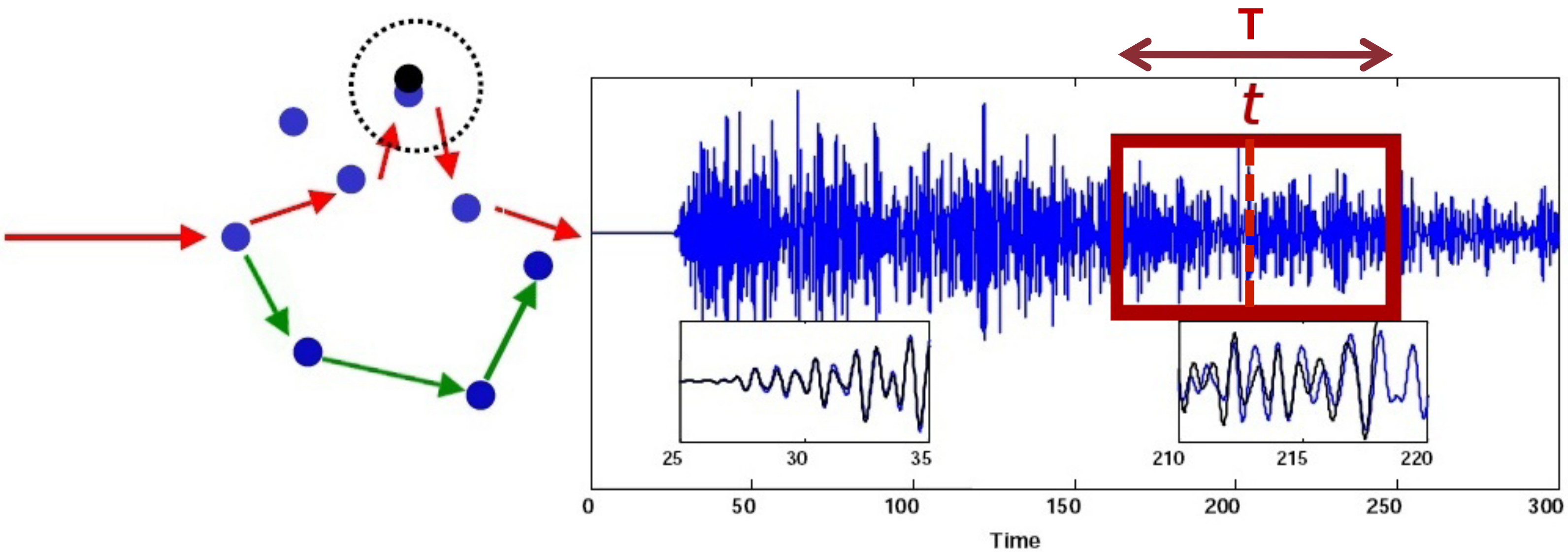


- Complex signal (one arrival time ⇔ several trajectories)
- Diffuse intensity

➡ **Statistical approach**

- Intensity correlation [Feng & Sornette 1991]
- Time-lapse travel time change [Pacheco & Snieder 2005]
- D(A)WS…[Pine et al. 1988, Cowan et al. 2002]

Signature of a change in the coda

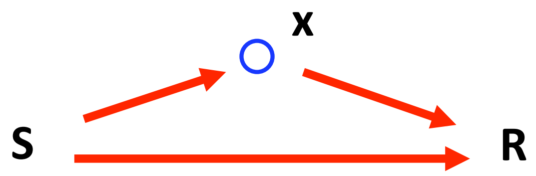


Very sensitive to weak changes

Decorrelation : $DC(t) = 1 - \frac{\langle \phi_0(t).\phi_1(t) \rangle_T}{\sqrt{\langle \phi_0(t)^2 \rangle_T \langle \phi_1(t)^2 \rangle_T}}$

Stretching factor : $\epsilon(t) = \epsilon$ that maximises $\langle \phi_0(t).\phi_1(t(1-\epsilon)) \rangle_T$

Decorrelation induced by an extra scatterer : Theoretical model



Role of an extra scatterer : Nieuwenhuizen & Van Rossum [1993]

Theoretical decorrelation

$$DC^{th}(\boldsymbol{S},\boldsymbol{R},\boldsymbol{r},t) = \frac{c\sigma}{2}\frac{\int_0^t I(\boldsymbol{S},\boldsymbol{r},u)I(\boldsymbol{r},\boldsymbol{R},t-u)du}{I(\boldsymbol{S},\boldsymbol{R},t)}$$

Rossetto et al. [JAP 2011]

I : Intensity propagator (Diffusion solution, Radiative Transfer)

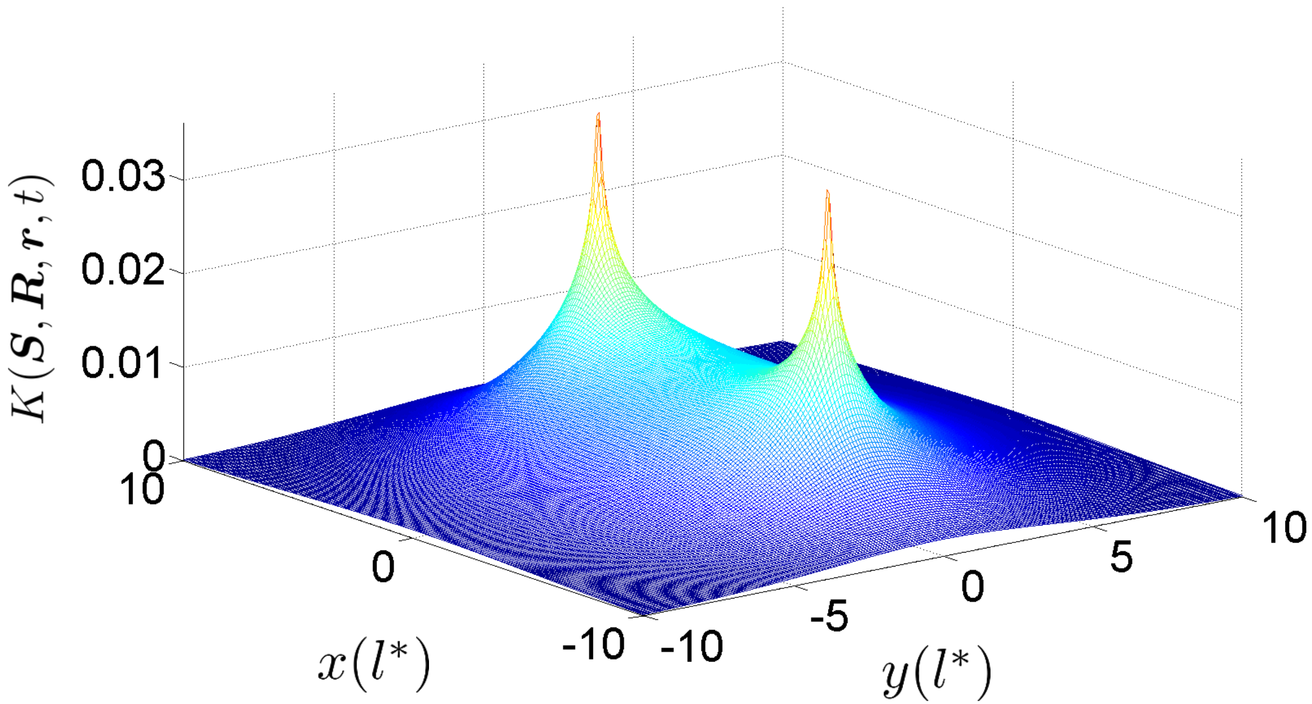
σ : Scattering cross section of the new defect

Sensitivity kernel

decorrelation

$$DC^{th}(\boldsymbol{S},\boldsymbol{R},\boldsymbol{r},t) = \frac{c\sigma}{2}K(\boldsymbol{S},\boldsymbol{R},\boldsymbol{r},t)$$

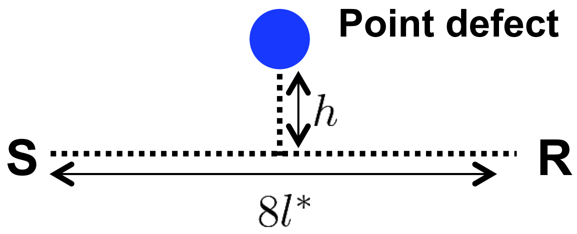
$$K(\boldsymbol{S},\boldsymbol{R},\boldsymbol{r},t) = \frac{\int_0^t I(\boldsymbol{S},\boldsymbol{r},u)I(\boldsymbol{r},\boldsymbol{R},t-u)du}{I(\boldsymbol{S},\boldsymbol{R},t)}$$

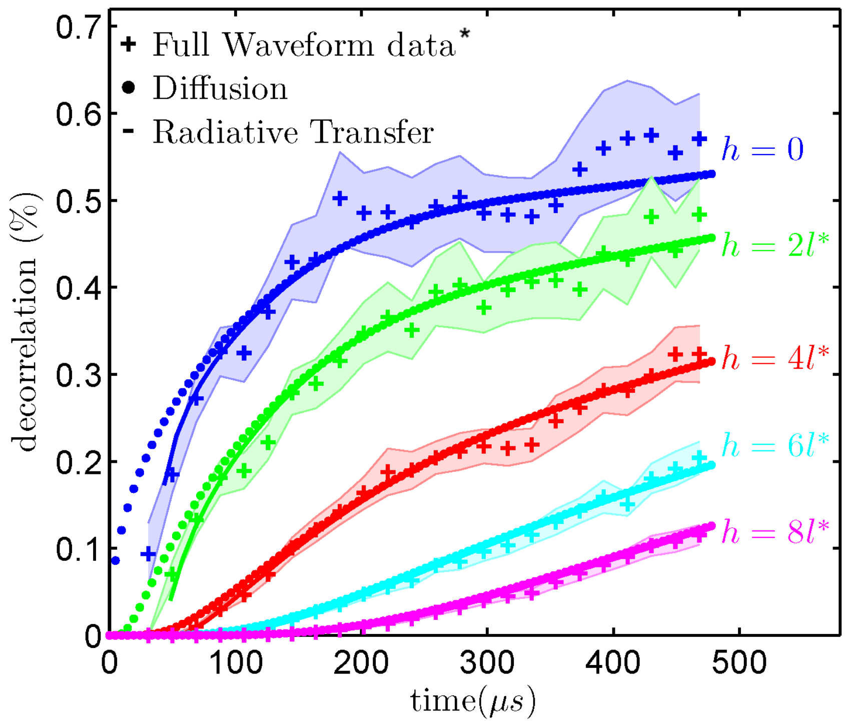


$$I(\boldsymbol{S},\boldsymbol{R},t) = \text{Diffusion solution}$$

Forward problem validation

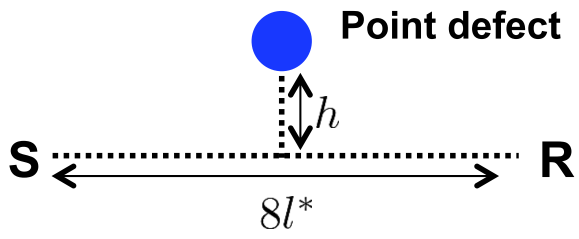
Far field

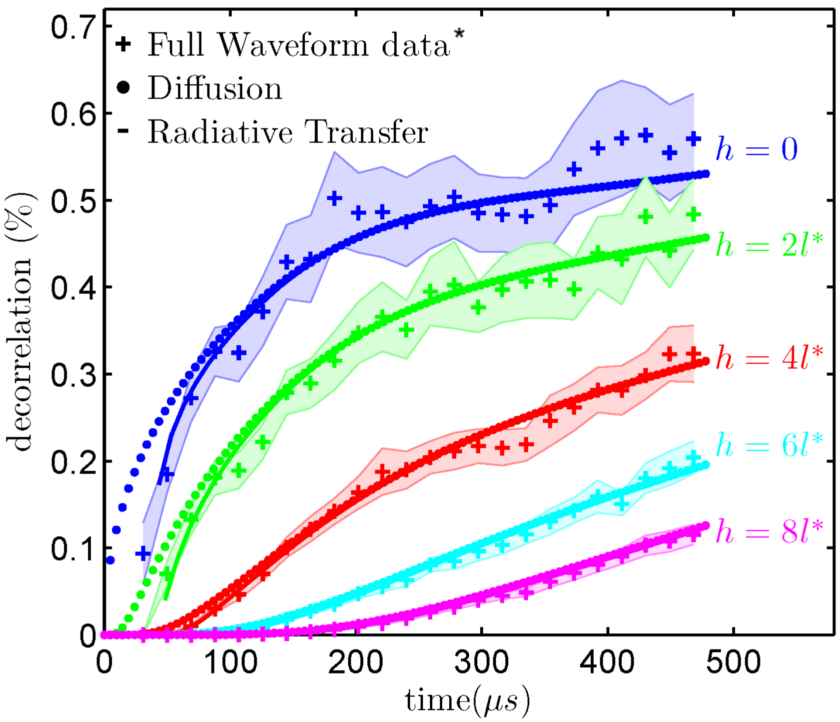




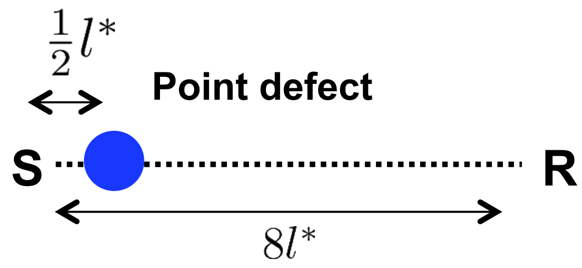
Forward problem validation

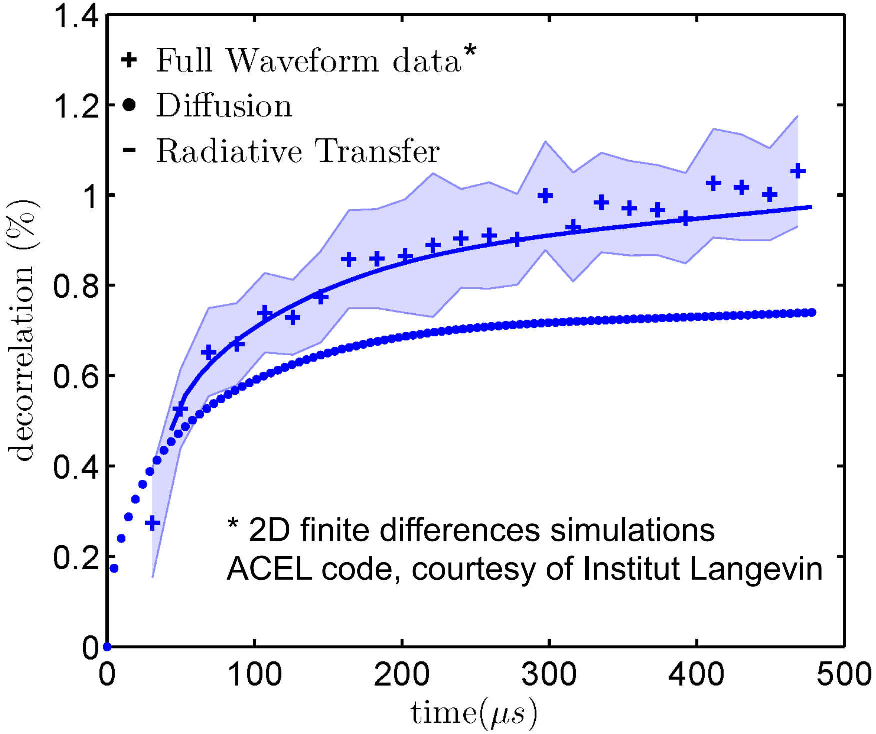
Far field





Near field





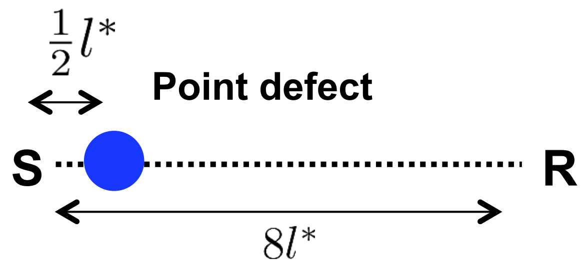
Forward problem validation

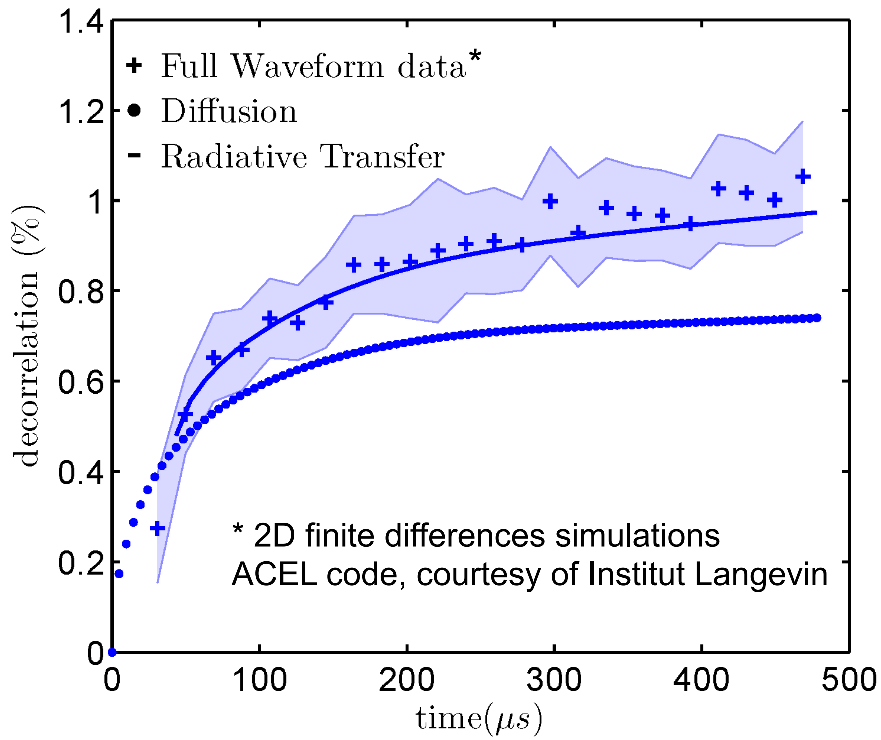
2D Radiative Transfer Solution
[Paasschens PRE 1997] :

$$I(\boldsymbol{r},t) = \underbrace{\frac{e^{-ct/l}}{2\pi r}\delta(ct-r)}_{\text{cohérent}}$$

$$\underbrace{+\frac{1}{2\pi l c t}\left(1-\frac{r^2}{c^2t^2}\right)^{-\frac{1}{2}} e^{[l^{-1}(\sqrt{c^2t^2-r^2}-ct]}\Theta(ct-r)}_{\text{incohérent}}$$

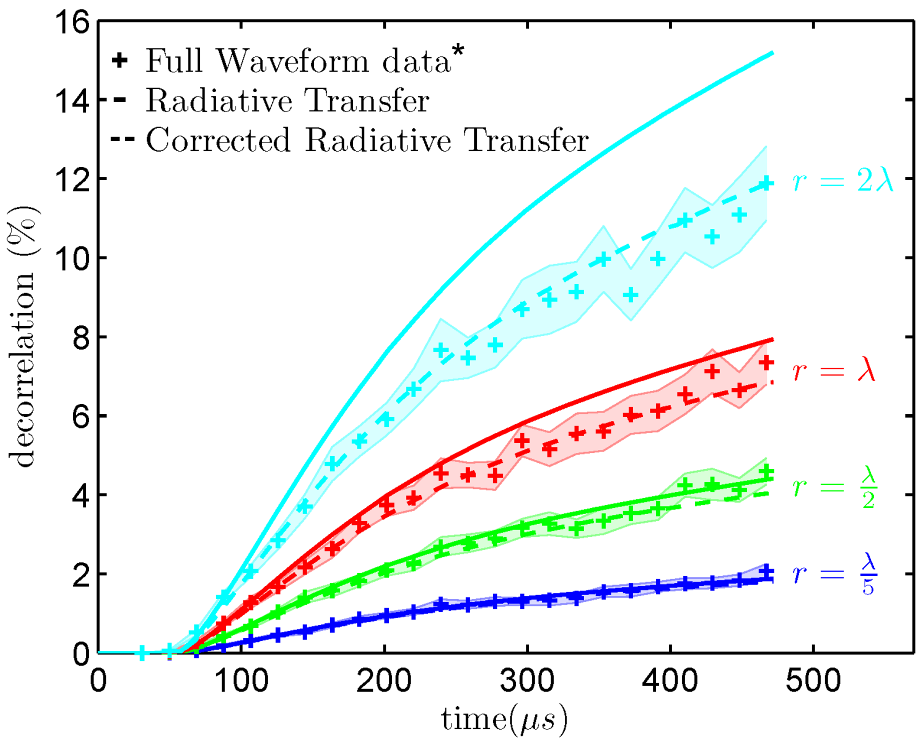
Near field

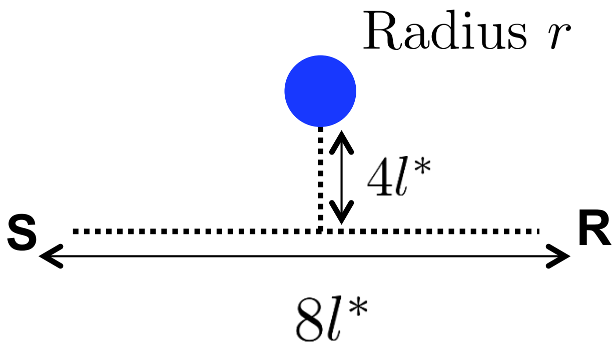




Forward problem validation

Size of the defect

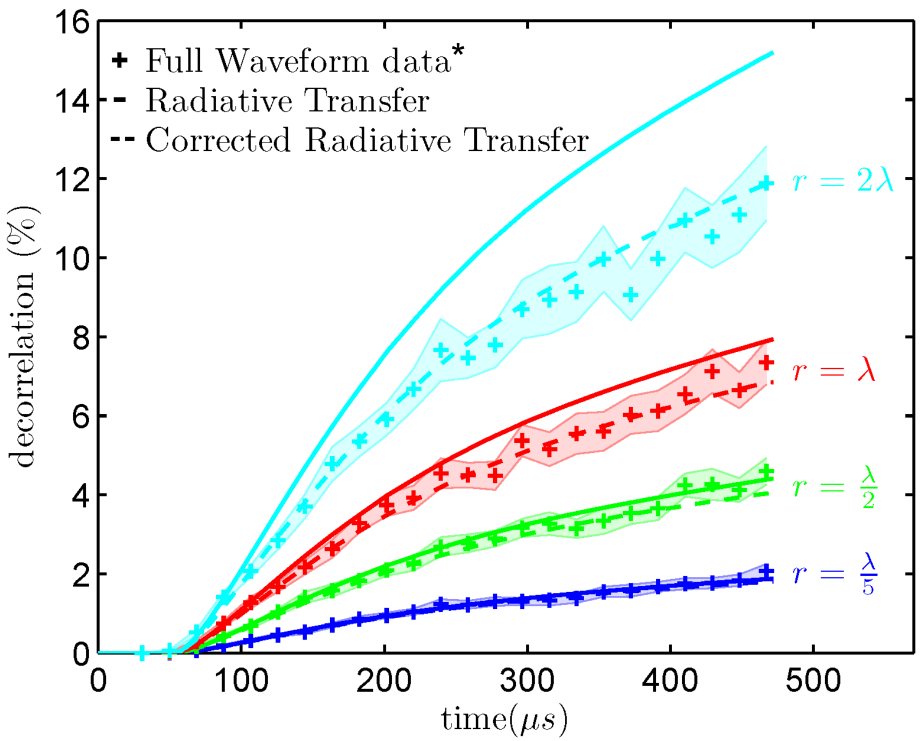


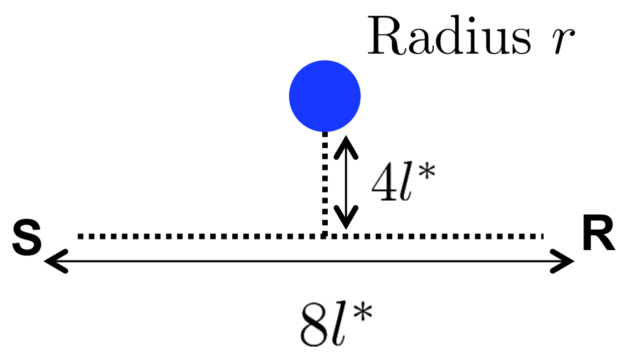


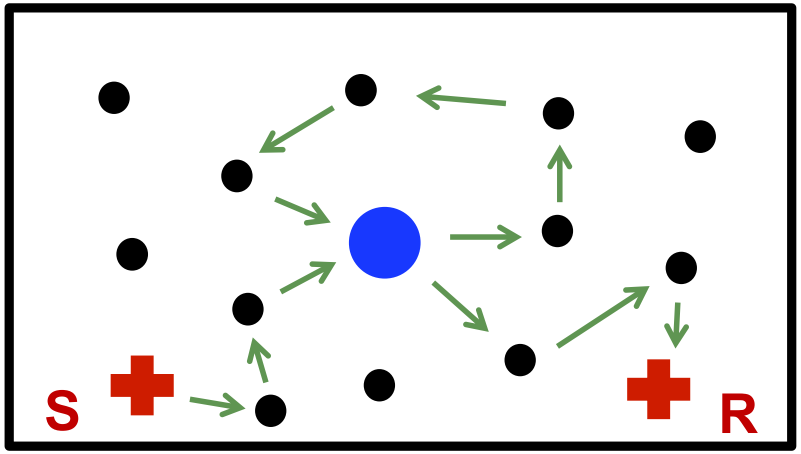
* 2D finite differences simulations
ACEL code, courtesy of Institut Langevin

Forward problem validation

Size of the defect







* 2D finite differences simulations
ACEL code, courtesy of Institut Langevin

Loops contribution

Inversion process

First approach : locating one local change

Experiment:

$\phi_0^{ij}(S_i, R_j, t) \quad \phi_1^{ij}(S_i, R_j, t)$

$\Rightarrow DC_{ij}^{exp}(S_i, R_j, t)$

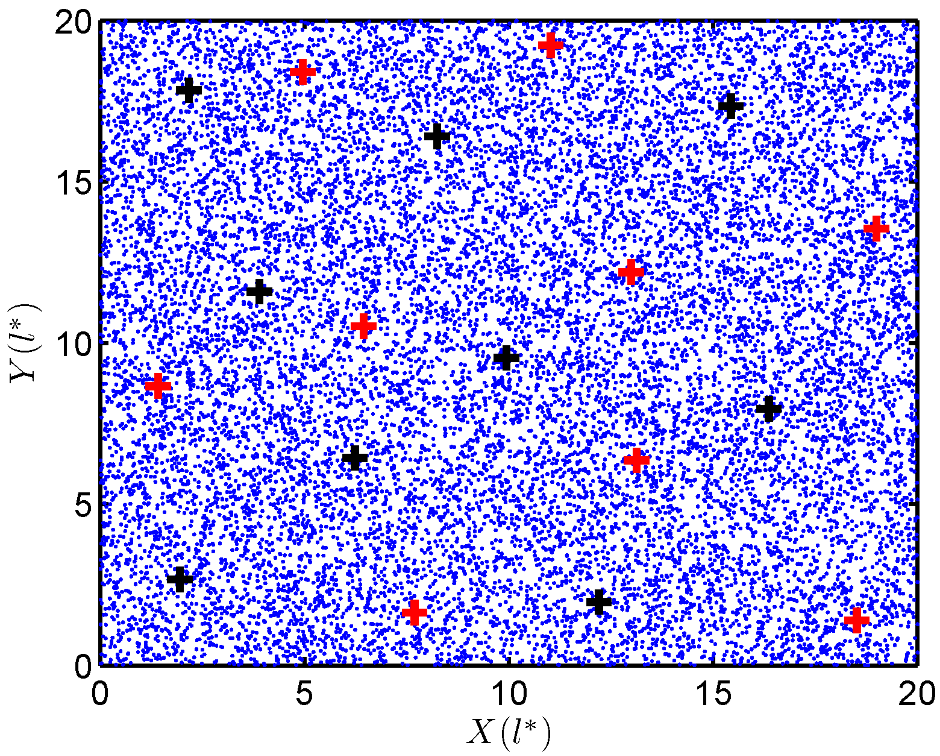
Experimental decorrelations

Numerical model :

For each pixel r :

$\Rightarrow DC_{ij}^{th}(S_i, R_j, \boldsymbol{r}, t)$

Theoretical decorrelation



$(\boldsymbol{r}, \sigma)$ that minimizes the misfit ?

Inversion process

First approach : locating one local change

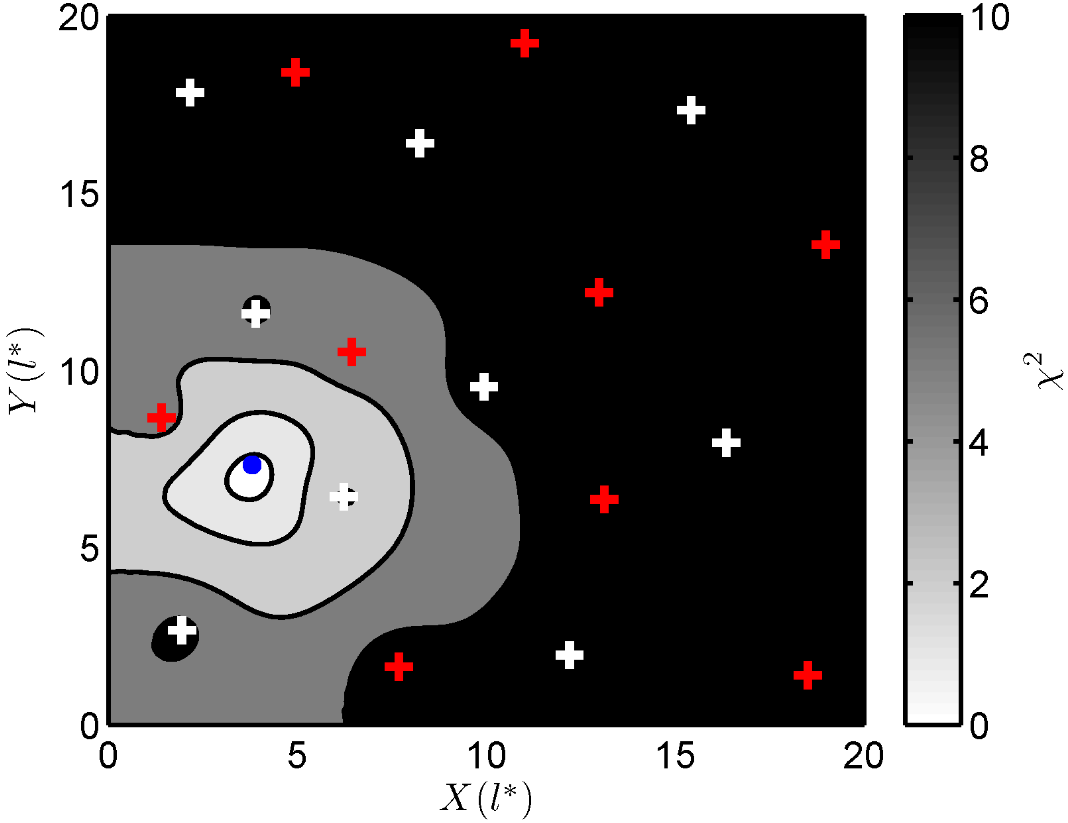
- 2D Acoustic Finite-Difference Simulation
- Reflective Boundaries

Sources

Receivers

New defect :

Point Defect



Misfit function map : $\chi^2(\boldsymbol{r}) = \frac{1}{N\epsilon^2}\sum_{ij}(DC_{ij}^{exp} - DC_{ij}^{th})^2$

Inversion process

First approach : locating one local change

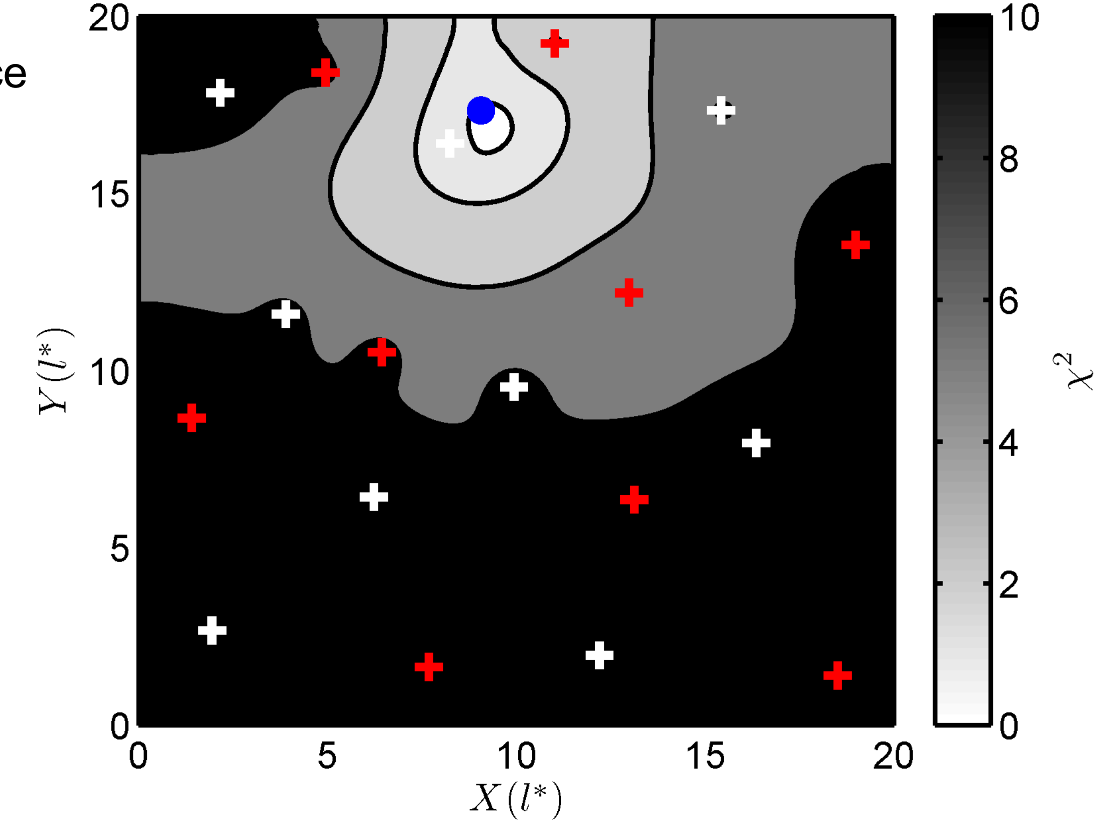
- 2D Acoustic Finite-Difference Simulation
- Reflective Boundaries

Sources

Receivers

New defect :

$$\text{Radius} = \frac{\lambda}{4}$$

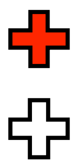


Misfit function map : $\chi^2(\boldsymbol{r}) = \frac{1}{N\epsilon^2}\sum_{ij}(DC_{ij}^{exp} - DC_{ij}^{th})^2$

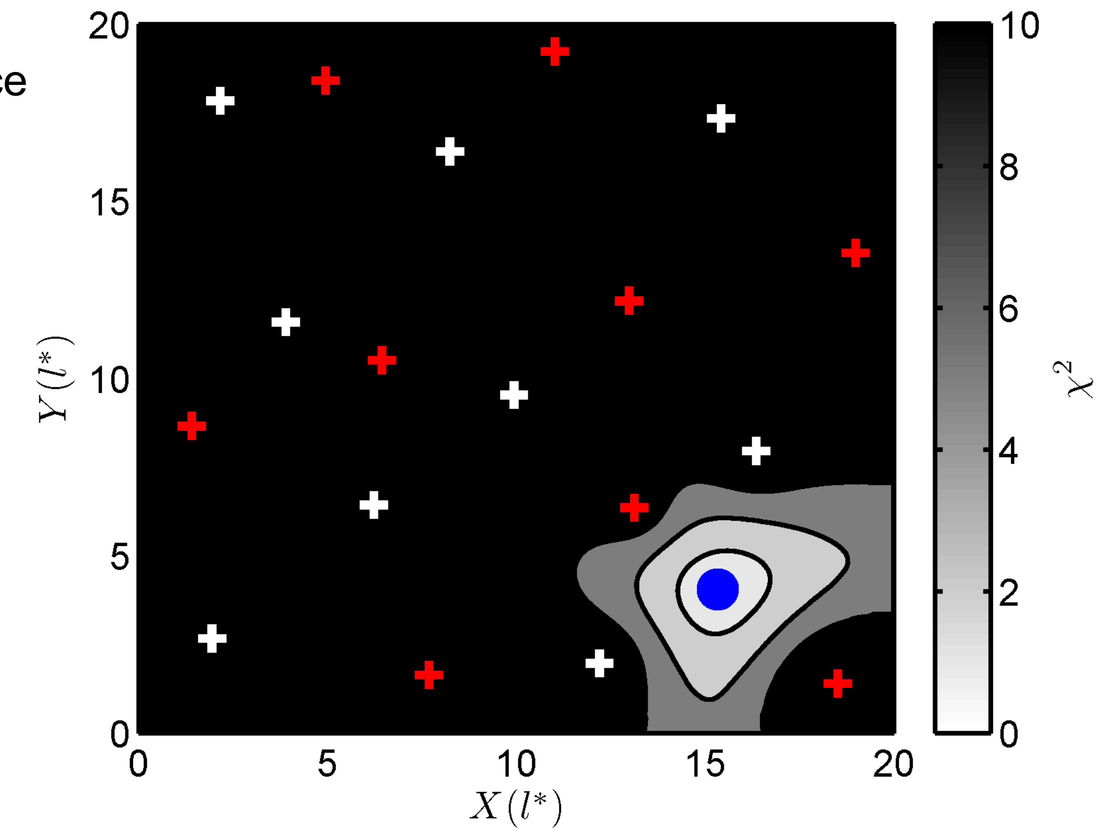
Inversion process

First approach : locating one local change

- 2D Acoustic Finite-Difference Simulation
- Reflective Boundaries



$\text{Radius} = \frac{\lambda}{2}$



Misfit function map : $\chi^2(\boldsymbol{r}) = \frac{1}{N\epsilon^2}\sum_{ij}(DC_{ij}^{exp} - DC_{ij}^{th})^2$

Inversion process

First approach : locating one local change

- 2D Acoustic Finite-Difference Simulation
- Reflective Boundaries

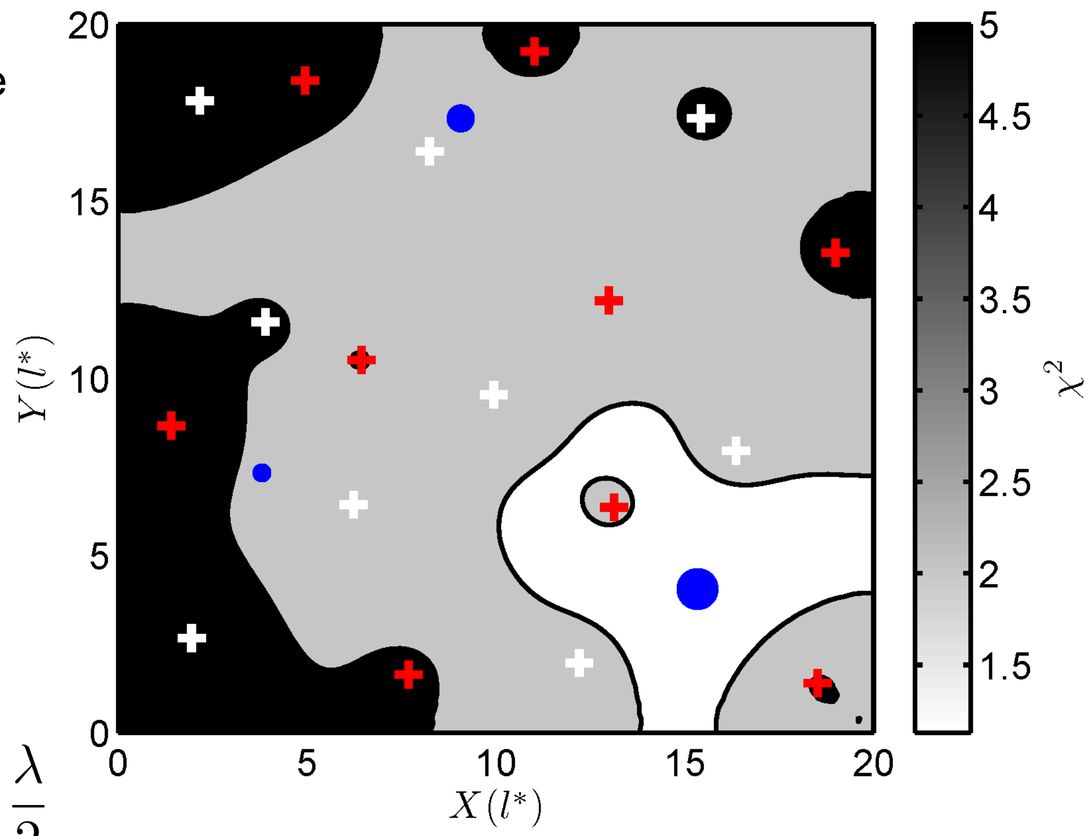
Sources

Receivers

New defect :

Point Defect,

$$\text{Radius} = \frac{\lambda}{4}, \ \text{Radius} = \frac{\lambda}{2}$$



Misfit function map : $\chi^2(\boldsymbol{r}) = \frac{1}{N\epsilon^2}\sum_{ij}(DC_{ij}^{exp} - DC_{ij}^{th})^2$

Inversion process

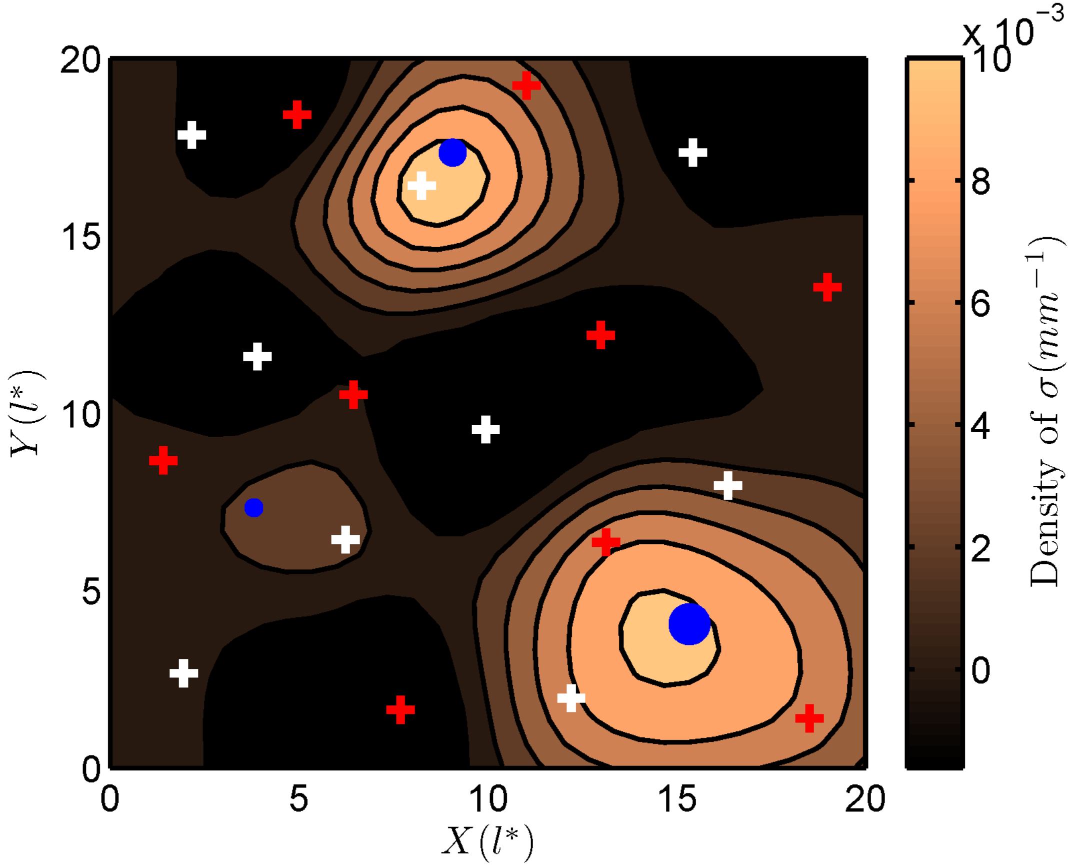
Locating several changes

Linear forward problem :

$$\boldsymbol{DC} = \frac{c}{2}\boldsymbol{K}\boldsymbol{\sigma}$$

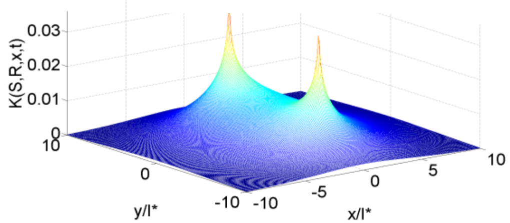
Least square inversion [Tarantola 2005] :

$$\Rightarrow \quad \tilde{\boldsymbol{\sigma}}$$



Applications :

- Same sensitivity kernel, different measures (extra scatterer, velocity change)
- Non destructive testing in civil engineering
- Monitoring in geophysics (active faults, volcanoes)



Outlook :

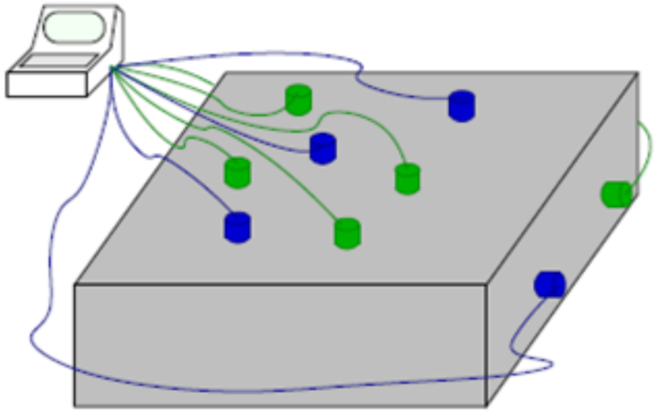
- Imaging of extended or multiple defects
- Caracterizing the change (fluid ?, absorbing ?, geometry ?)

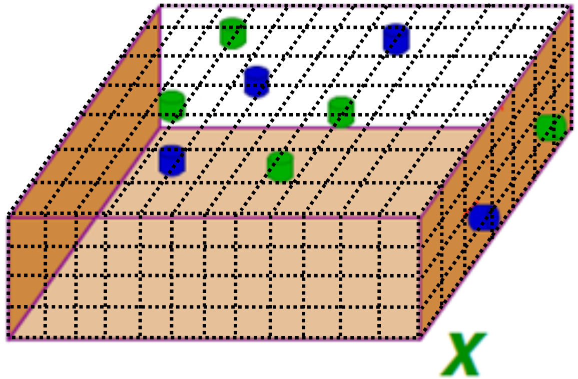
Publications :

- Larose et al., Appl. Phys. Lett. 96, 204101 (2010)
- Rossetto et. al., J. Appl. Phys. 109, 034903 (2011)
- Patent No. FR09-50612

Inversion process

First approach : locating one local change





Experiment :

$\varphi_0^{ij}(S_i, R_j, t)$ $\varphi_1^{ij}(S_i, R_j, t)$

$\Rightarrow Q_{ij}^{\exp}(S_i, R_j, t)$

Experimental decorrelations

Numerical model :

For each voxel x :

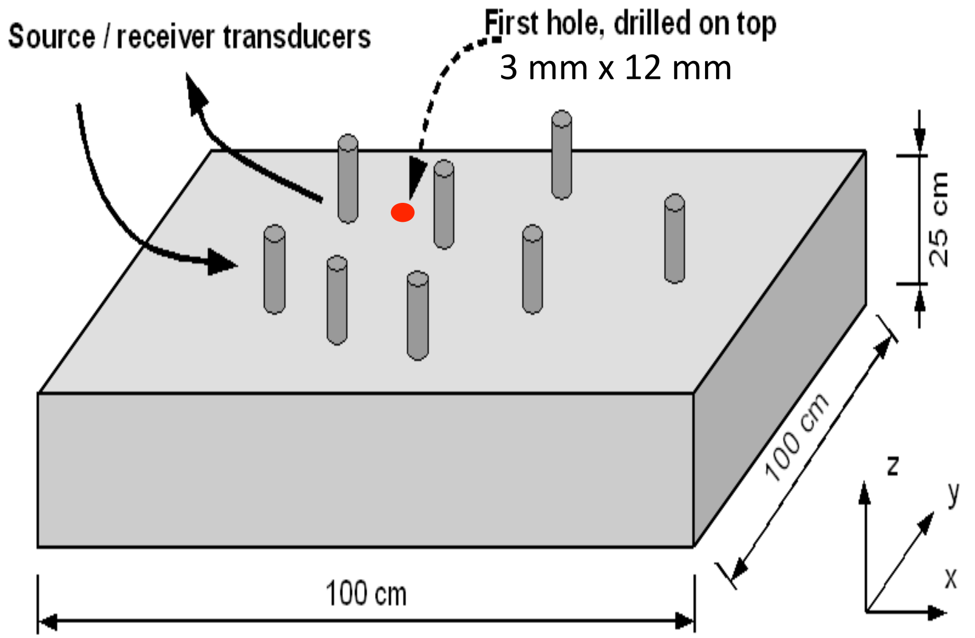
$\Rightarrow Q_{ij}^{th}(S_i, R_j, x, t)$

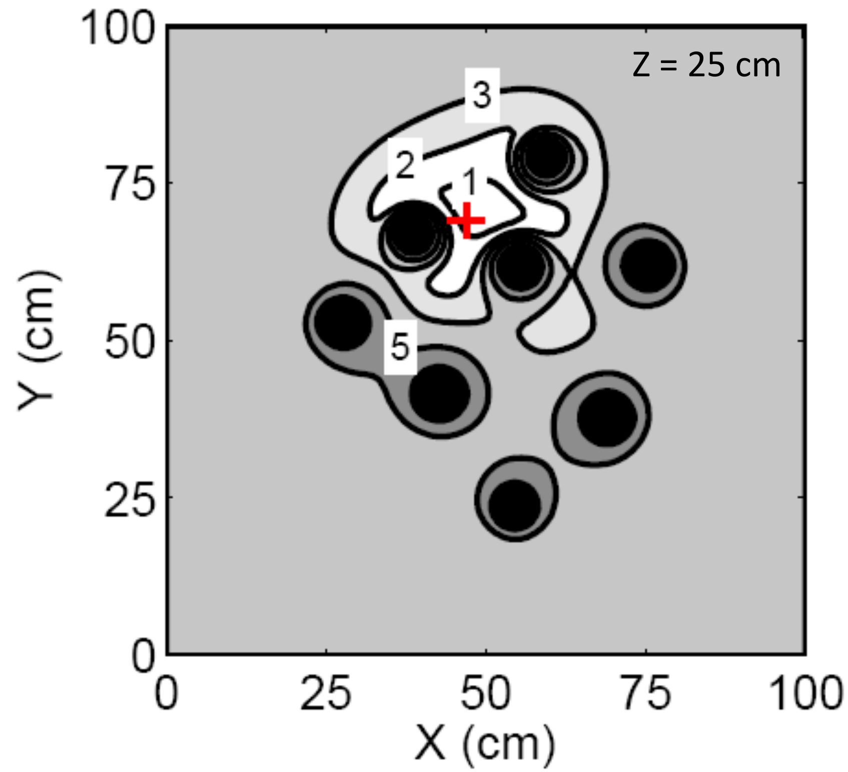
Theoretical decorrelation

(x, σ) that minimizes the misfit ?

Experimental results on concrete

Larose et al. [Appl. Phys. Lett. 2010]





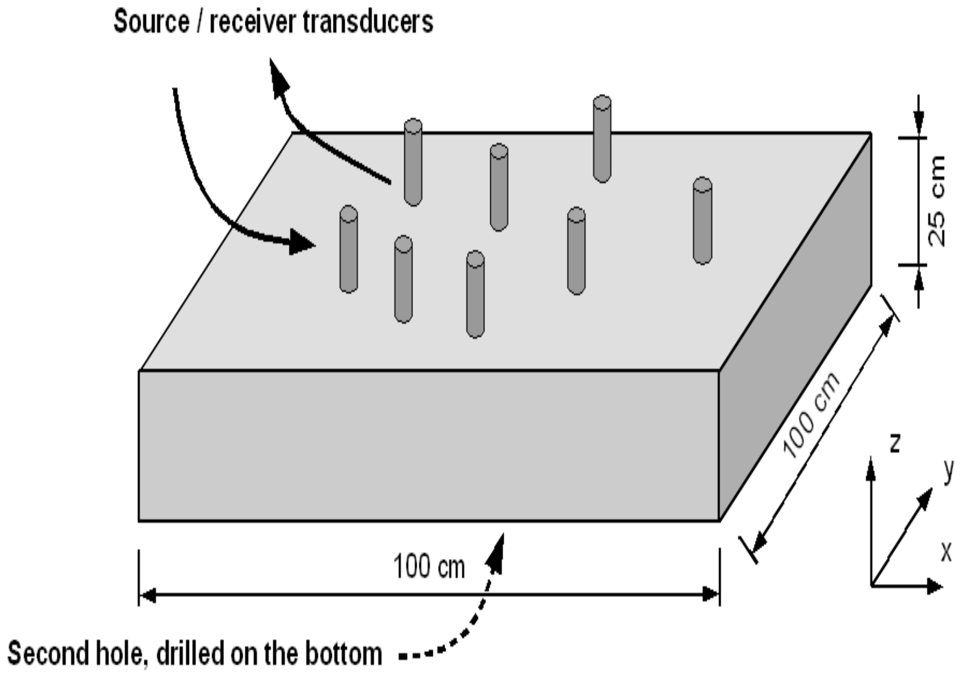
$$\chi^2(x) = \frac{1}{N}\sum_{i,j}\left(Q_{ij}^{\exp}(t) - Q_{ij}^{th}(x,t)\right)^2 / \varepsilon^2$$

N : number of transducer pairs

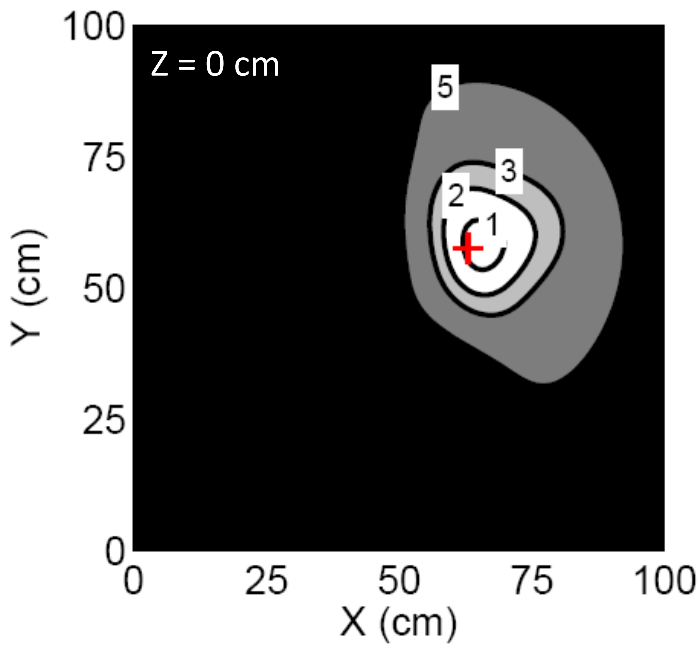
ε : measurement error

Experimental results on concrete

Larose et al. [APL 2010]



8 mm x 20 mm

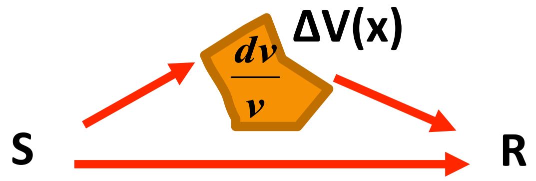


$$\chi^2(x) = \frac{1}{N} \sum_{i,j} \left(Q_{ij}^{\exp}(t) - Q_{ij}^{th}(x,t) \right)^2 / \varepsilon^2$$

N : number of transducer pairs

ε : measurement error

Theoretical model predicting the stretching factor induced by a local velocity change



Time-lapse travel time change : Pacheco and Snieder [JASA 2005]

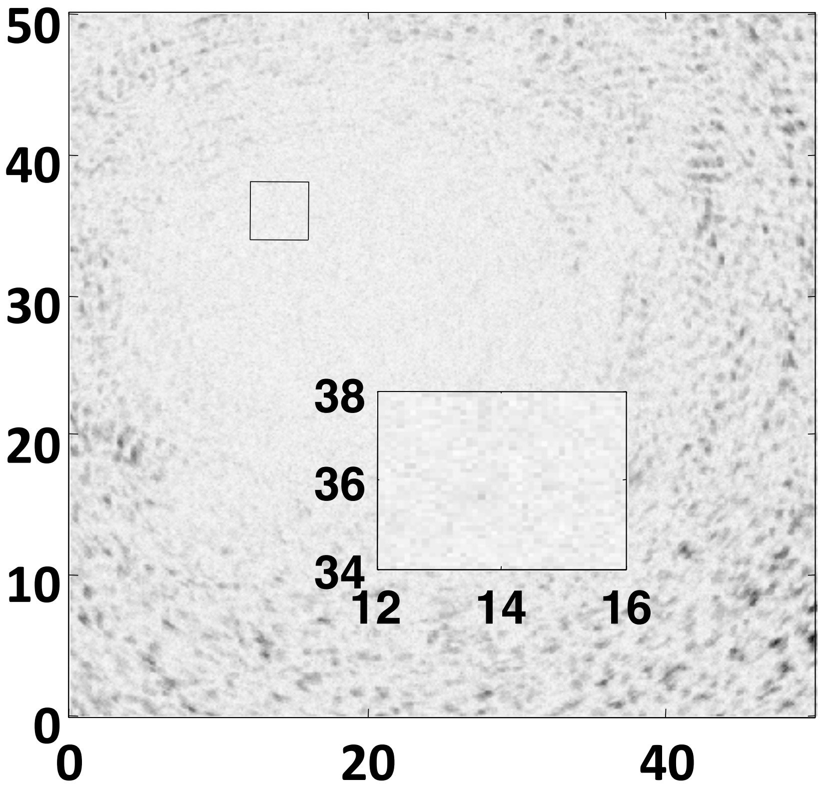
Theoretical stretching factor

$$\varepsilon^{\mathrm{th}}(\mathrm{S},\mathrm{R},\mathrm{x},\mathrm{t}) = \frac{dv}{v}\frac{\Delta \mathrm{V}}{t}\frac{\int_0^t g(S,x,u)g(x,R,t-u)du}{g(S,R,t)}$$

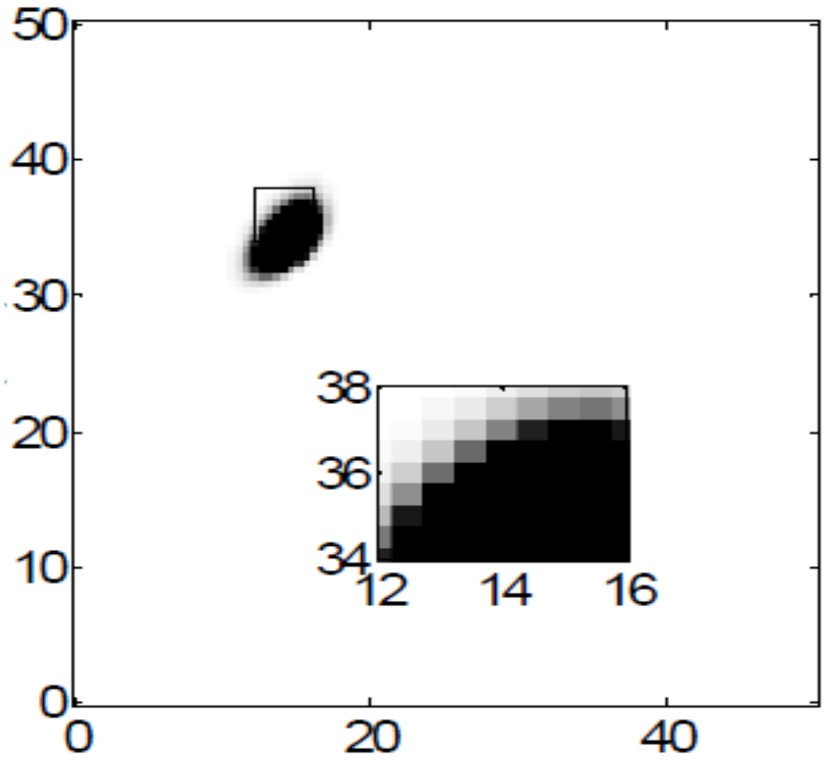
- g(S,R,t)= intensity propagator (diffusion solution, radiative transfer)
- $\frac{dv}{v}$: local relative velocity change
- ΔV : elementary volume centered on x

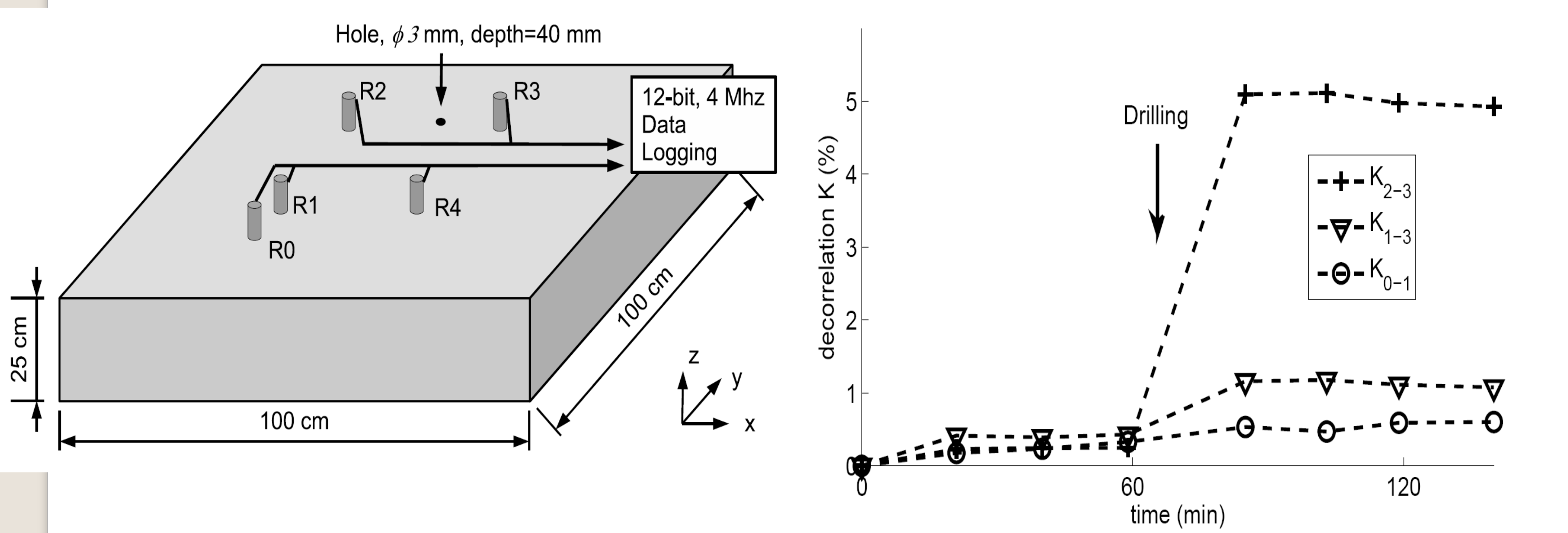
Results from numerical example

Standard imaging

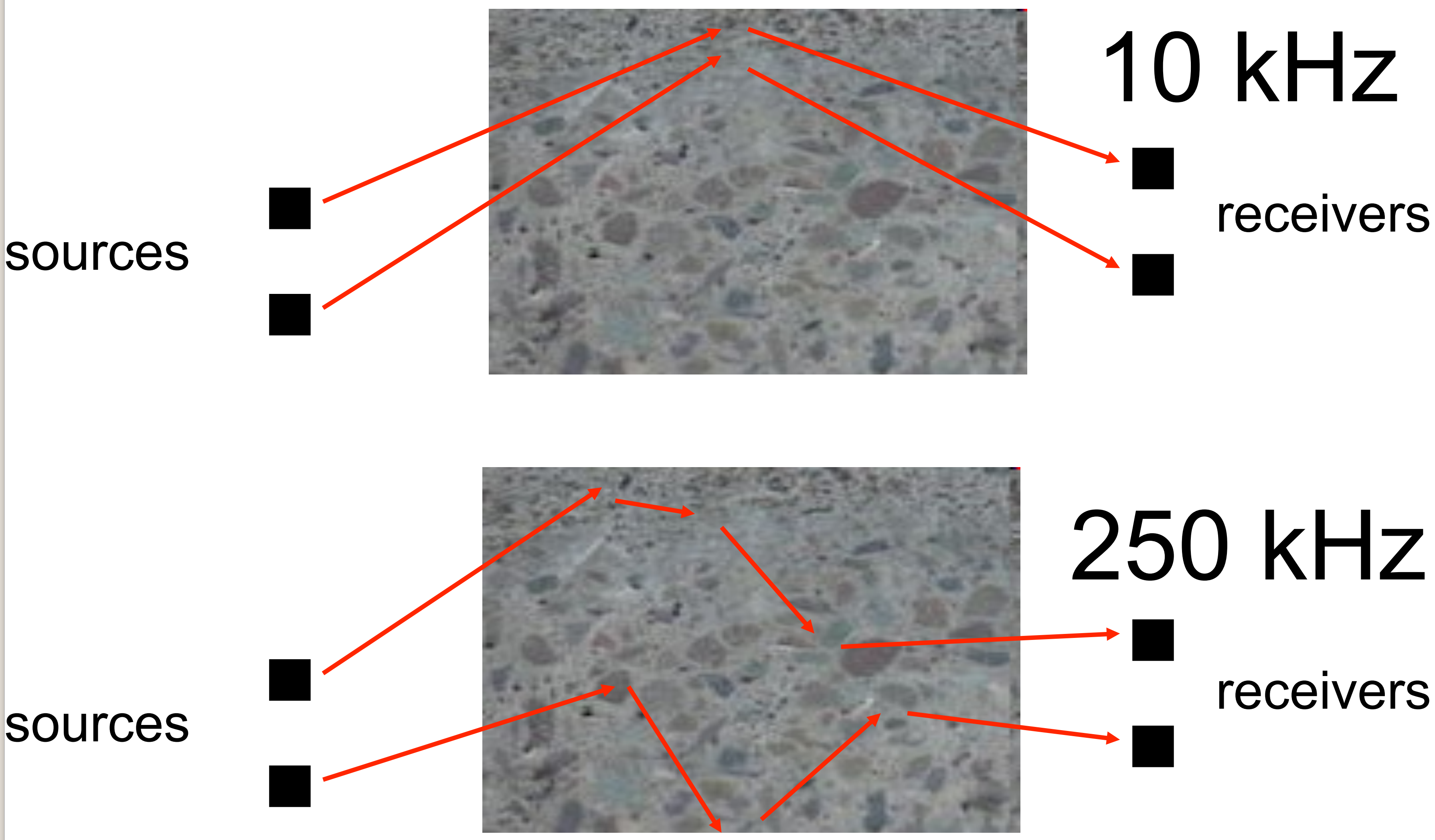


LOCADIFF

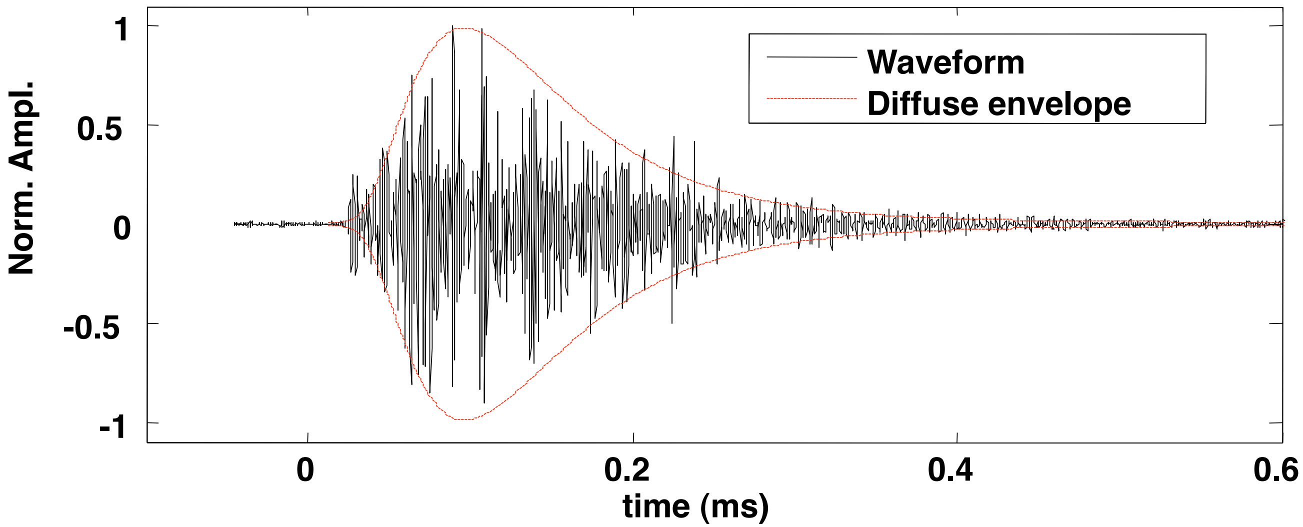




$$\chi^2(\mathbf{x}) = \sum_{i,j} \left(K^d_{ij}(t) - K^n_{ij}(\mathbf{x},t)\right)^2 / \epsilon^2$$



c=2500m.s^{-1}, λ=1 cm, ℓ^*=3 cm, ℓ_{abs}=50 cm

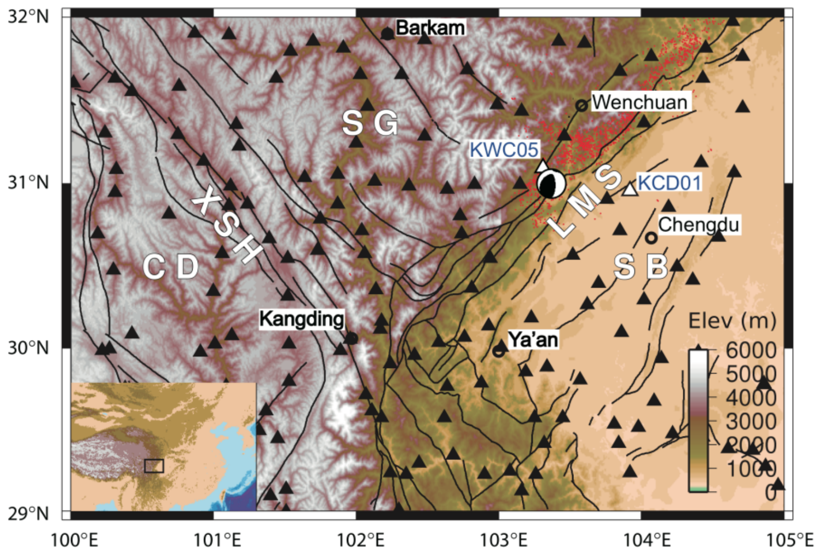


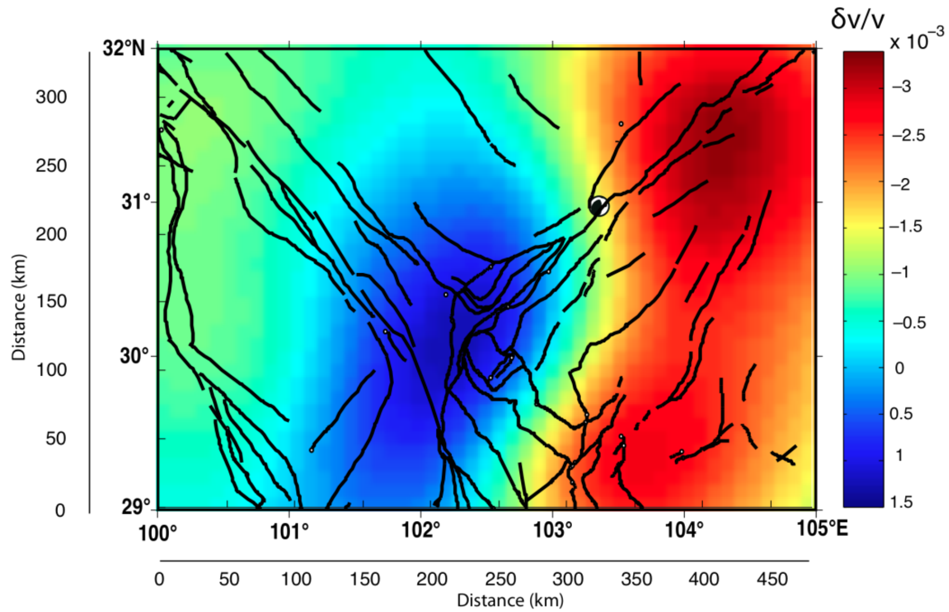
c=2500m.s^{-1}, λ=1 cm, ℓ^*=3 cm, ℓabs=50 cm

Passive seismic data inversion

Berenice Froment (Phd), Michel campillo

Wenchuan earthquake (May 12, 2008)
Longmen Shan fault zone, Sichuan province, China





Data:

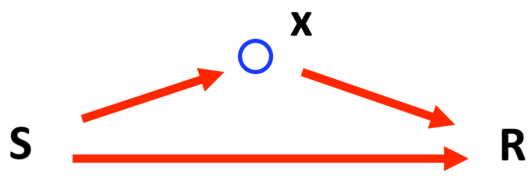
. 156 broadband stations

. 2 years of noise (2007-2008)

. run by the Institute of Geology of the China Earthquake Administration

Relative velocity change map

Theoretical model predicting the decorrelation induced by an extra scatterer



Rôle of an extra scatterer :
Nieuwenhuizen & Van Rossum [1993]

Theoretical decorrelation

$$Q^{\mathrm{th}}(\mathrm{x},\mathrm{t}) = \frac{c\sigma}{2}\frac{\int_0^t g(S,x,u)g(x,R,t-u)du}{g(S,R,t)}$$

- g(S,R,t)= Intensity propagator
- σ : scattering cross section

Rossetto et al. [JAP 2011]

Sensitivity kernel

$$Q^{\mathrm{th}}(\mathrm{x},\mathrm{t}) = \frac{c\sigma}{2}K(x,t)$$