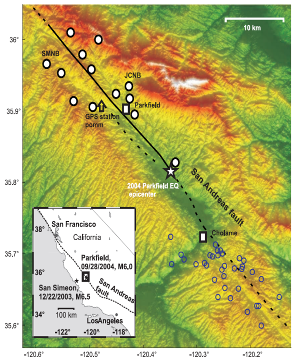
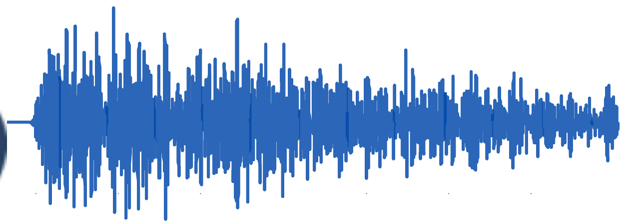
Monitoring and Locating with diffuse waves: from seismic waves to ultrasound (and vice-versa)



Eric LAROSE

ISTerre,

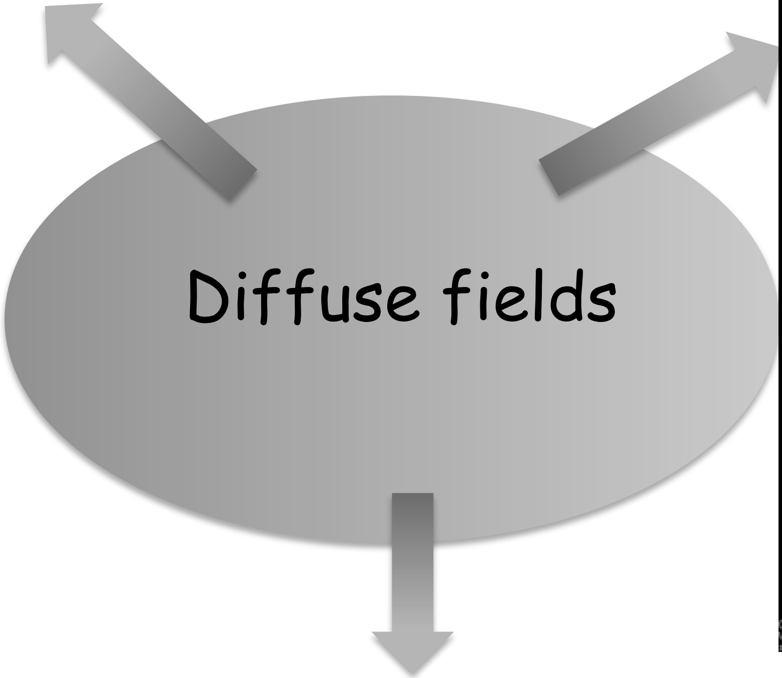
CNRS & Université J. Fourier

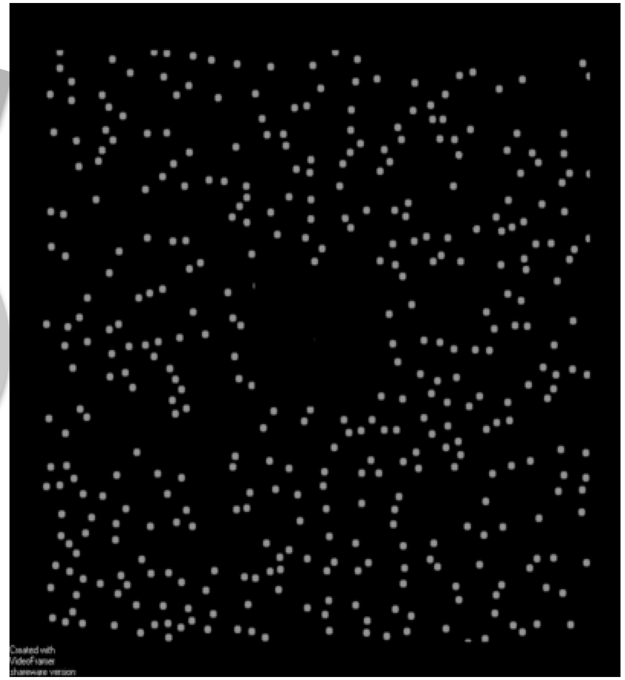


Institut des Sciences de la Terre

Ambient noise

Multiple scattering





What can we do with this???

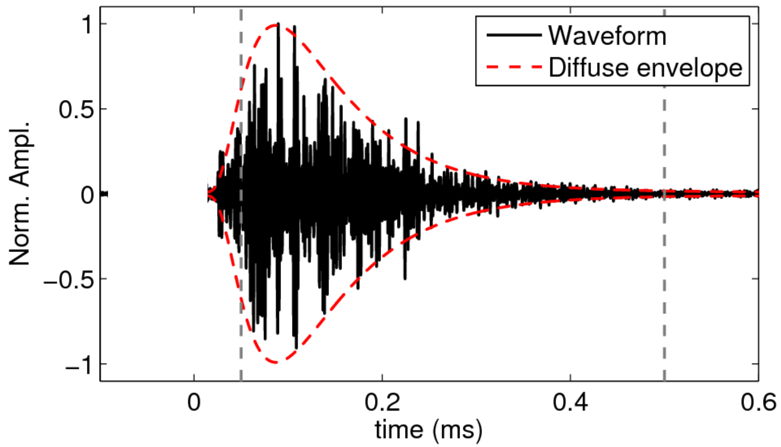
- PART 1.

Detecting velocity dV/V change (Global)

- PART 2.

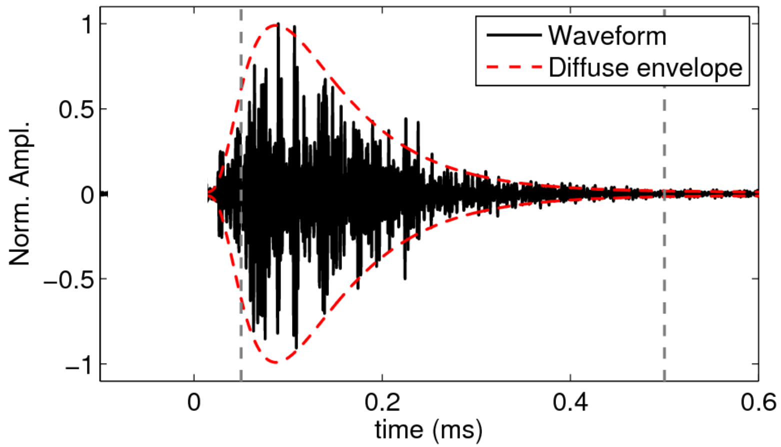
Locating changes (Local)

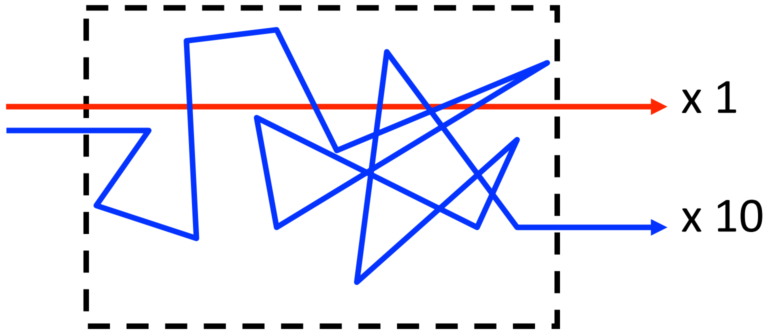
Multiple scattering regime (diffusion):



- Attenuation of direct waves
- Standard imaging procedures fail
- Increase late arrivals = onset of a "coda"

Multiple scattering regime (diffusion):

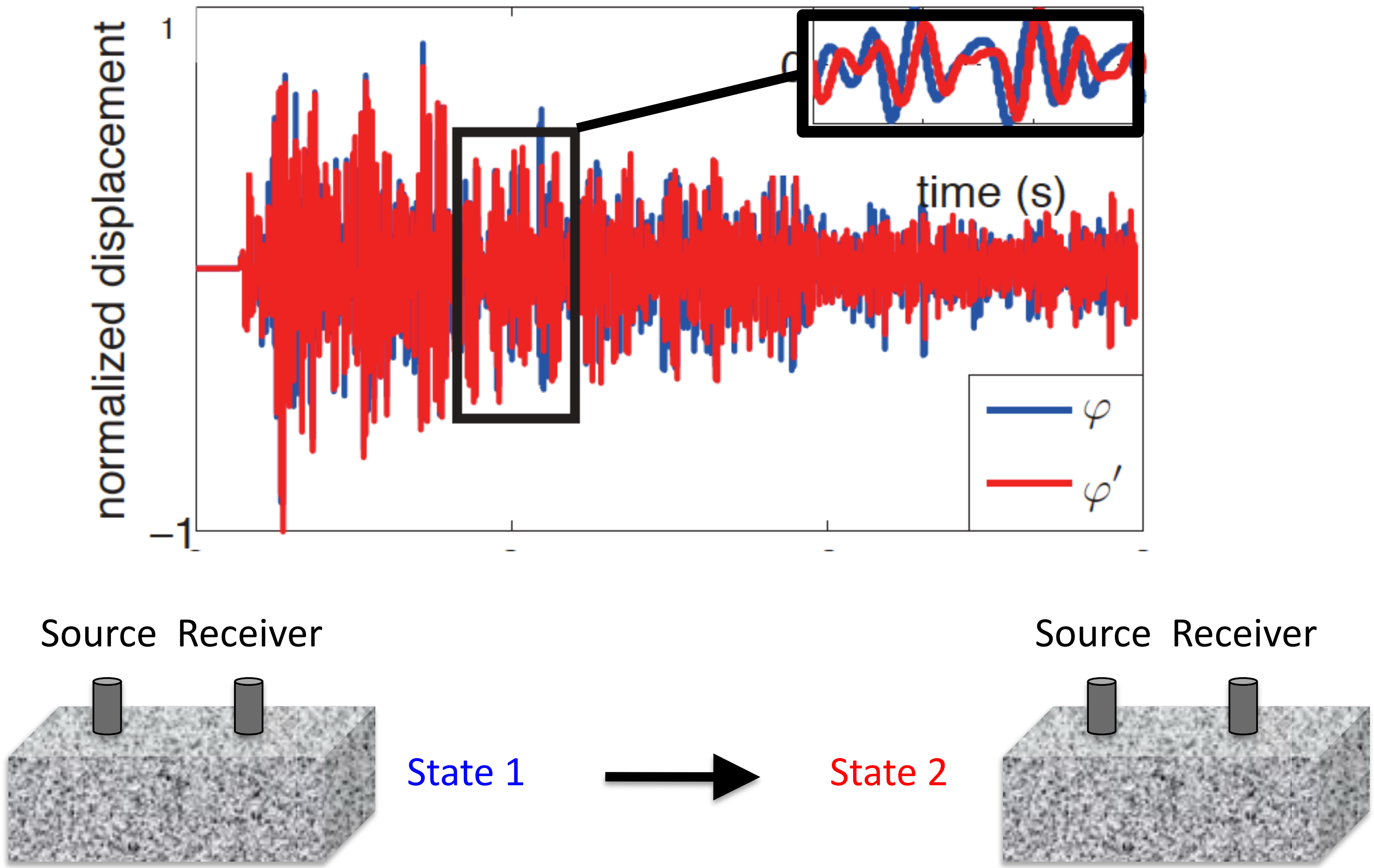




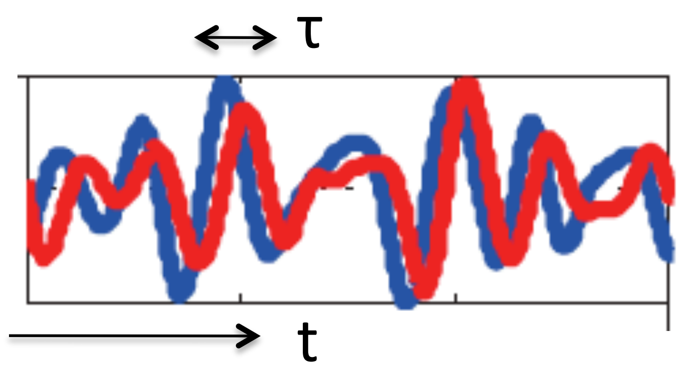
- Attenuation of direct waves
- Standard imaging procedures fail
- Increase late arrivals = onset of a “coda”

- … the coda is VERY sensitive to weak changes

Sensitivity of coda waves

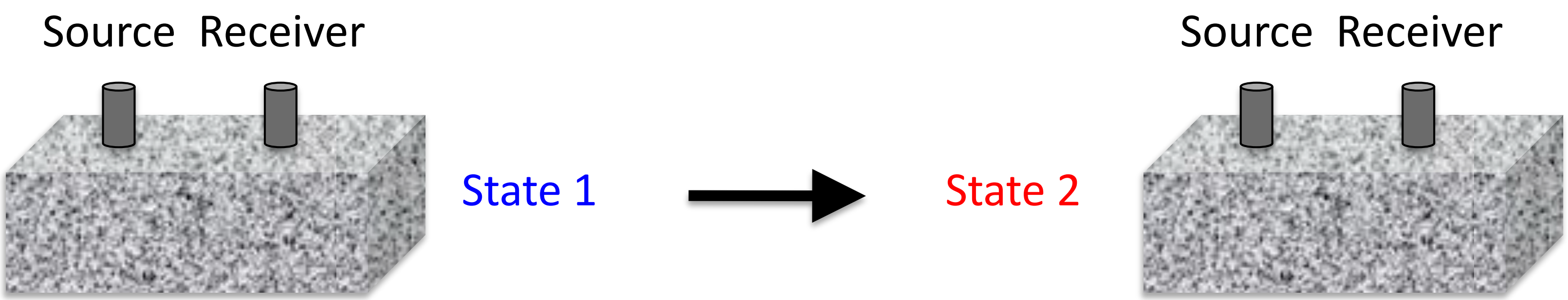


Weak change : 2 effects

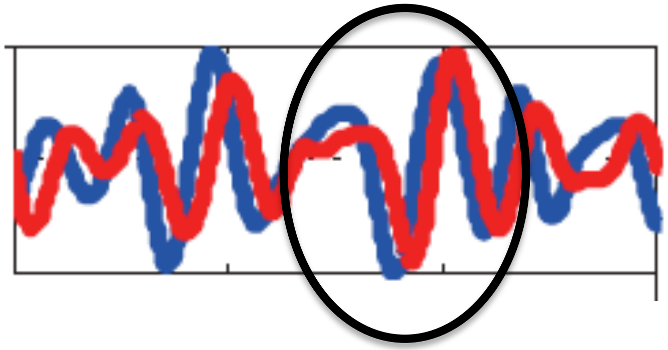


1) Relative velocity change $dV/V=-\tau/t$
   - -> global macroscopic change
   - -> elastic modulus

=> CWI



Weak change : 2 effects

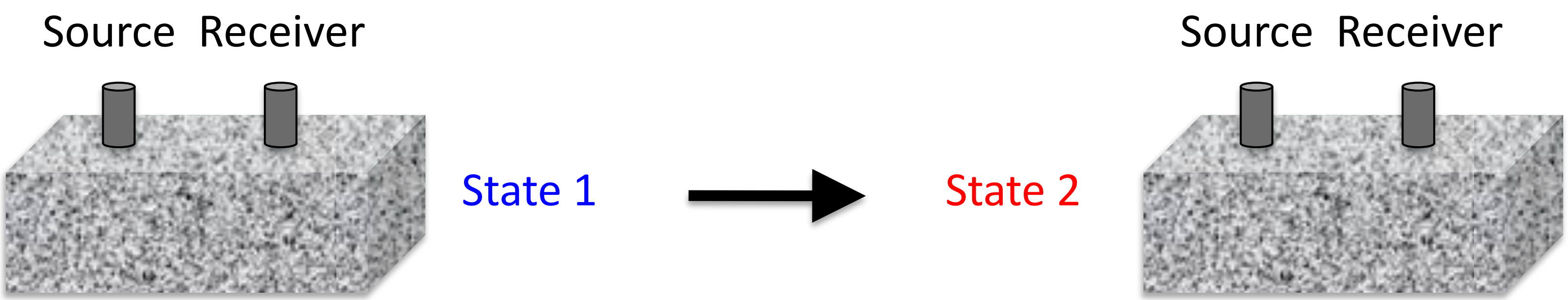


1) Relative velocity change dV/V=-τ/t
   -> global macroscopic change
   -> elastic modulus

   ⇒CWI

2) Decorrelation of the waveforms

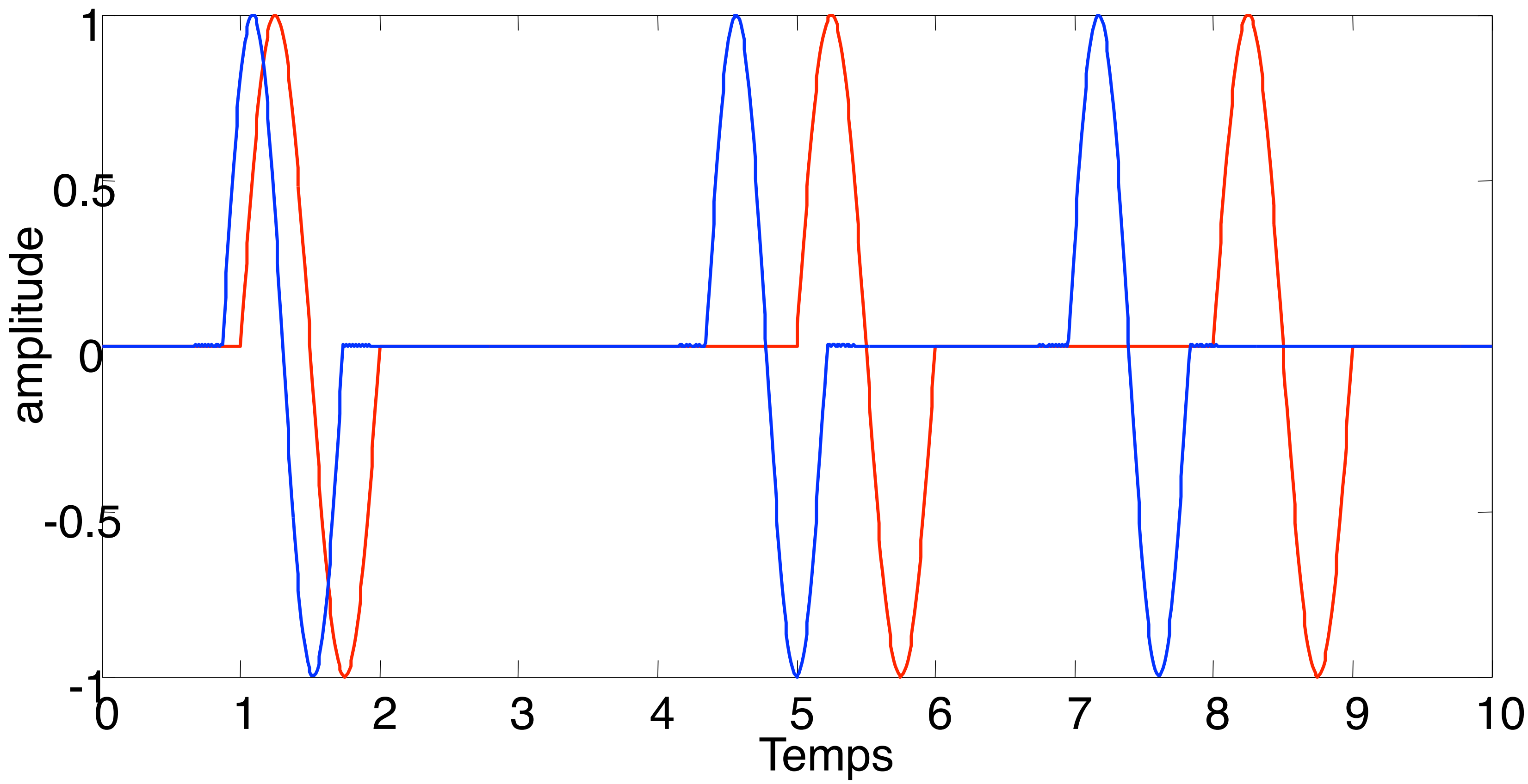
   ⇒DWS
   ⇒LOCADIFF



Numerical Test

Date #1 → $h_1(t)$ Date #2 → $h_2(t)$

SLOW FAST



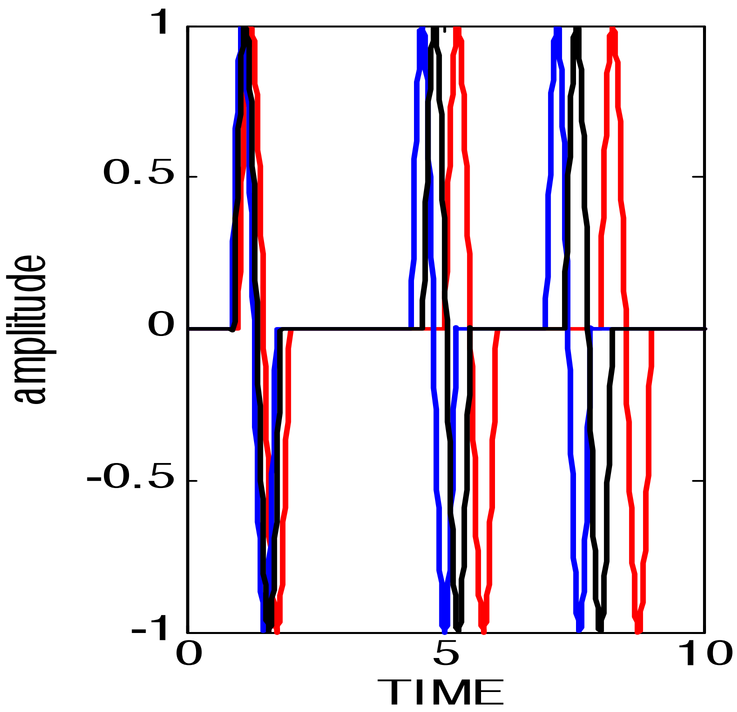
Numerical Test

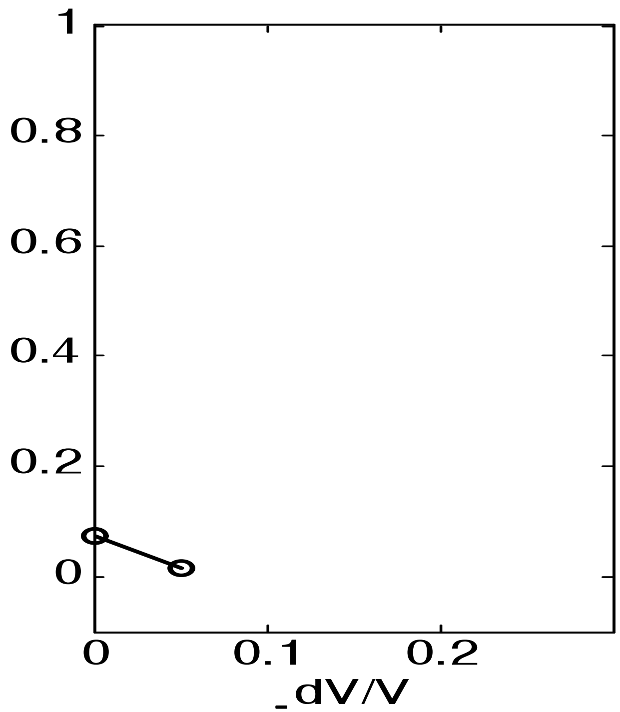
Signal date 2

Signal date 2 stretched (test)

Signal date 1

$$h_2(t) \rightarrow h_2(t[1+dV/V]) \rightarrow h_1(t)$$





Numerical Test

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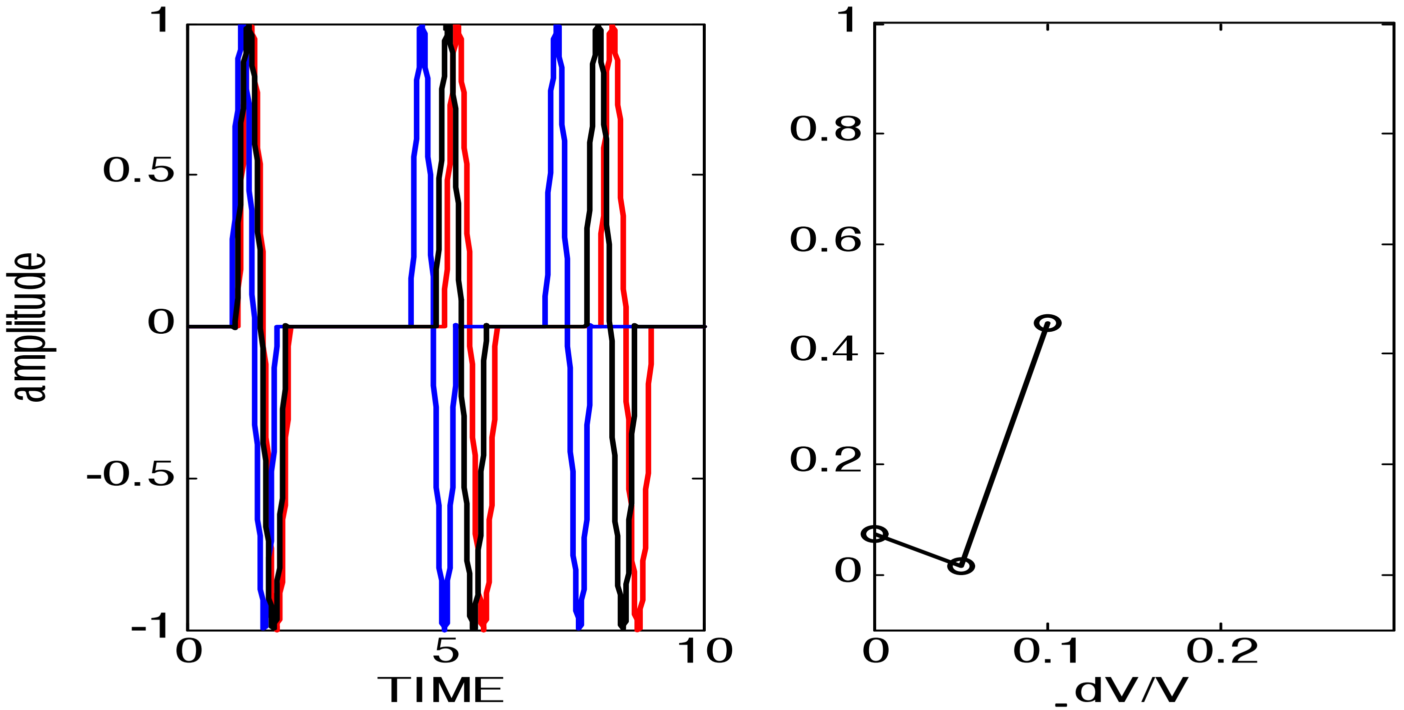
$$h_2(t) \rightarrow h_2(t[1+dV/V])$$

$$h_2(t[1+dV/V]) \rightarrow h_1(t)$$



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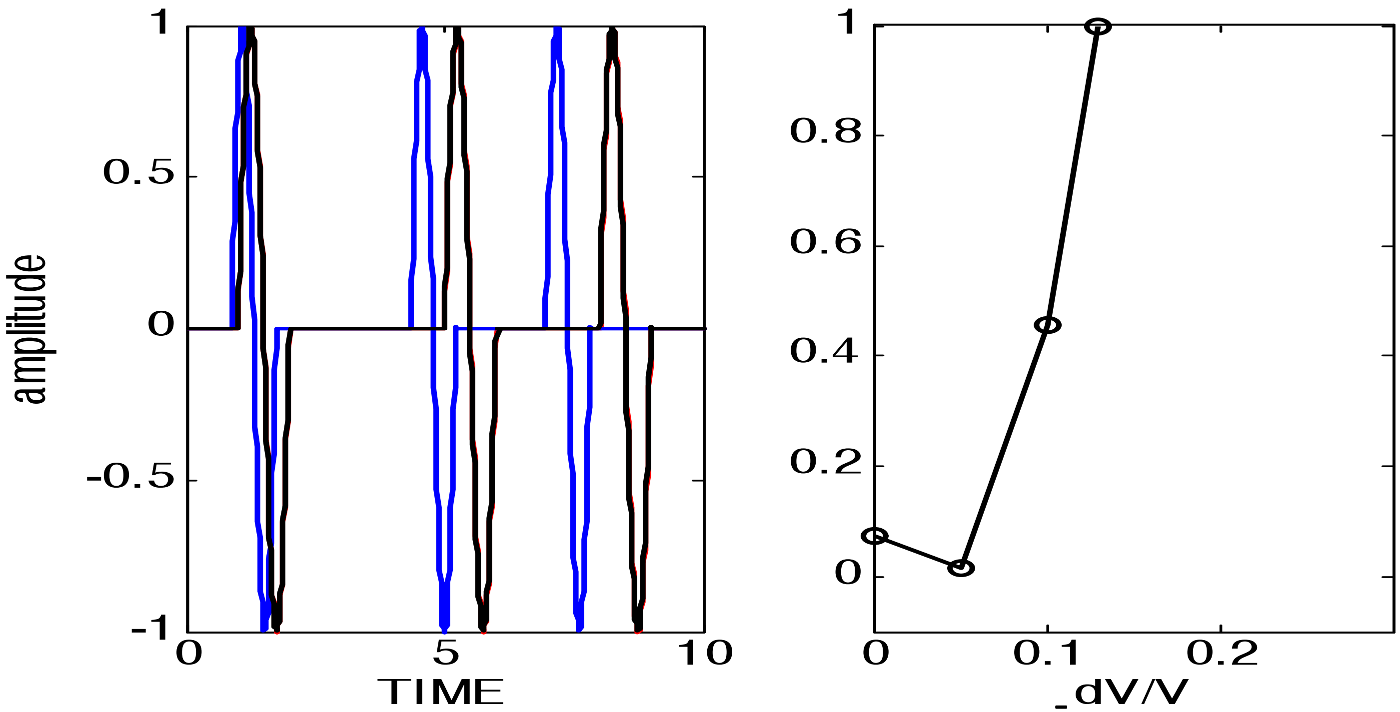

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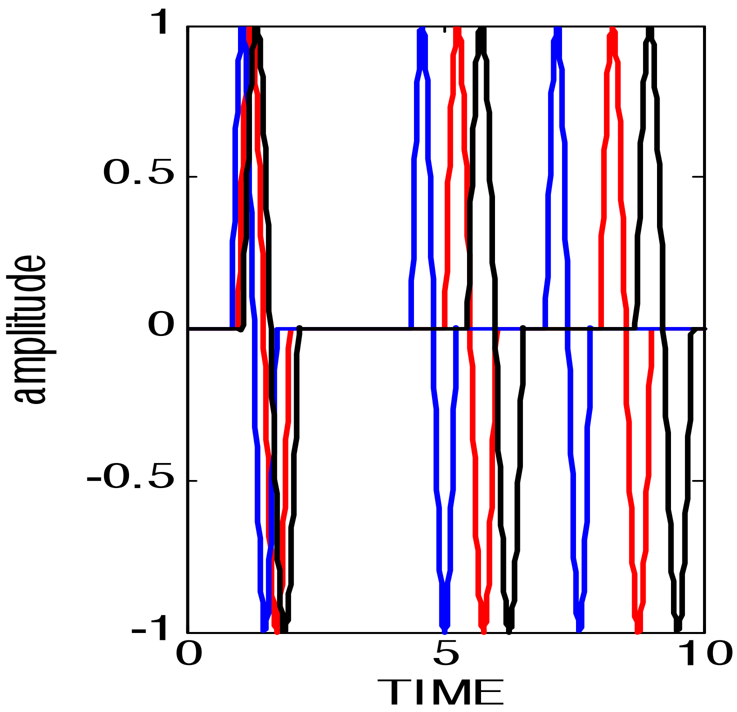

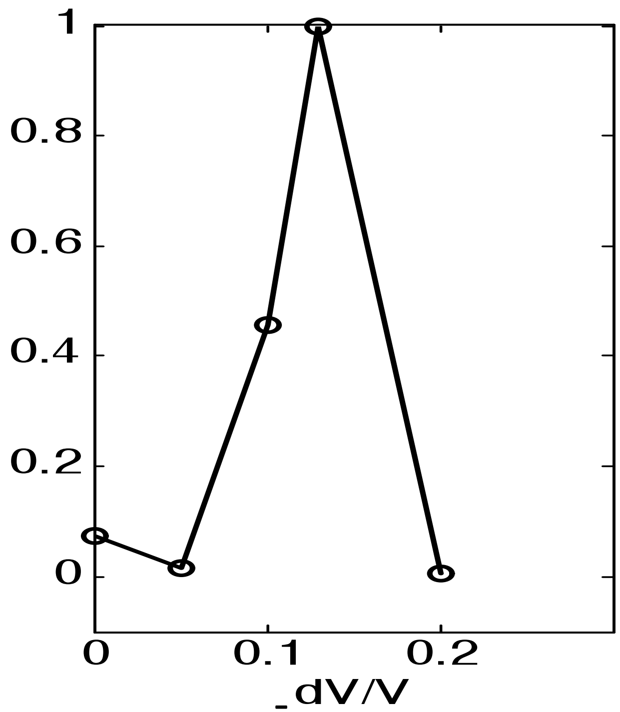

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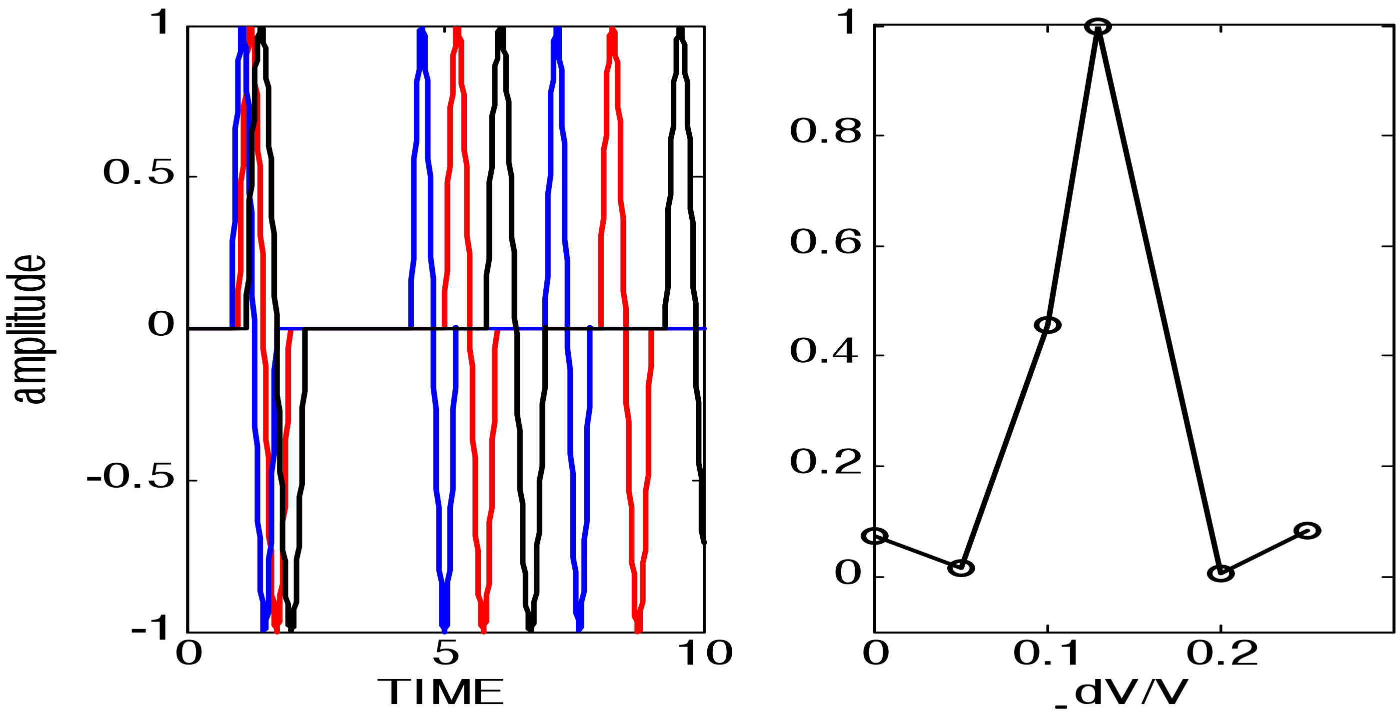

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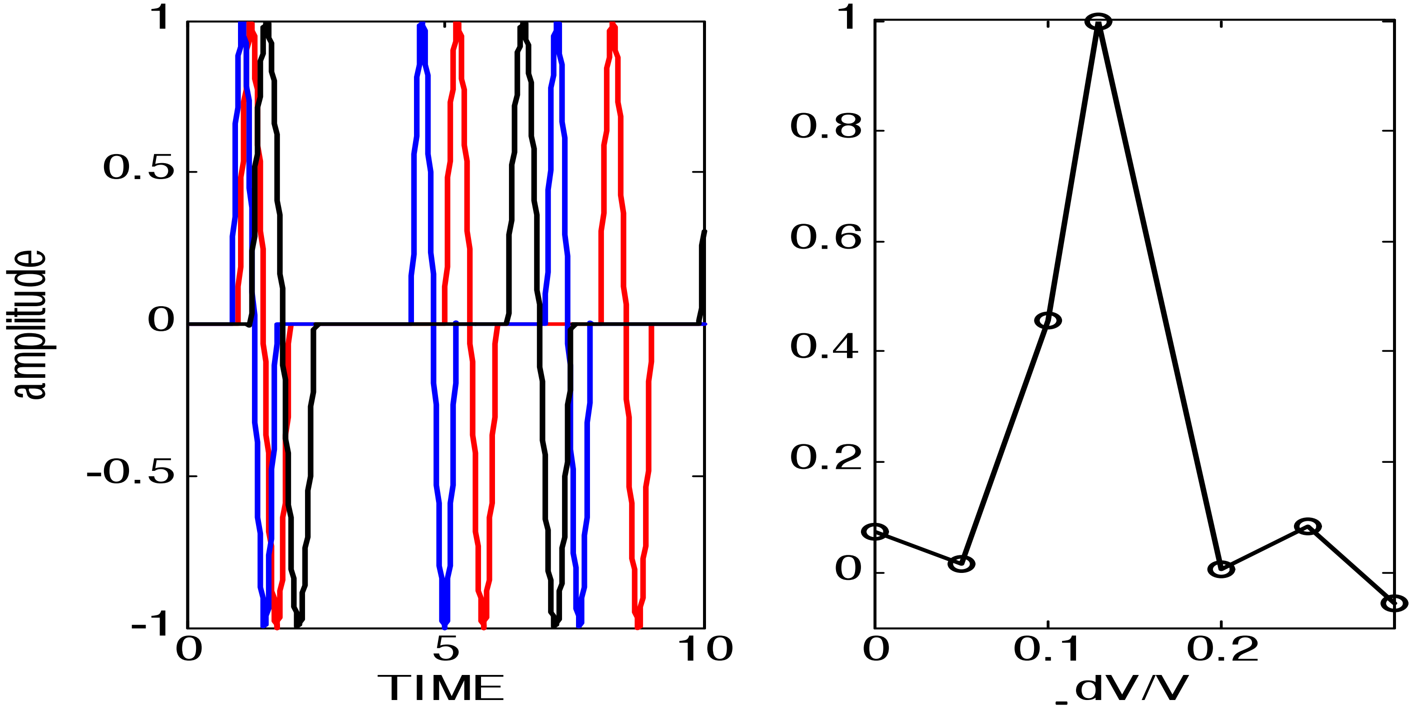
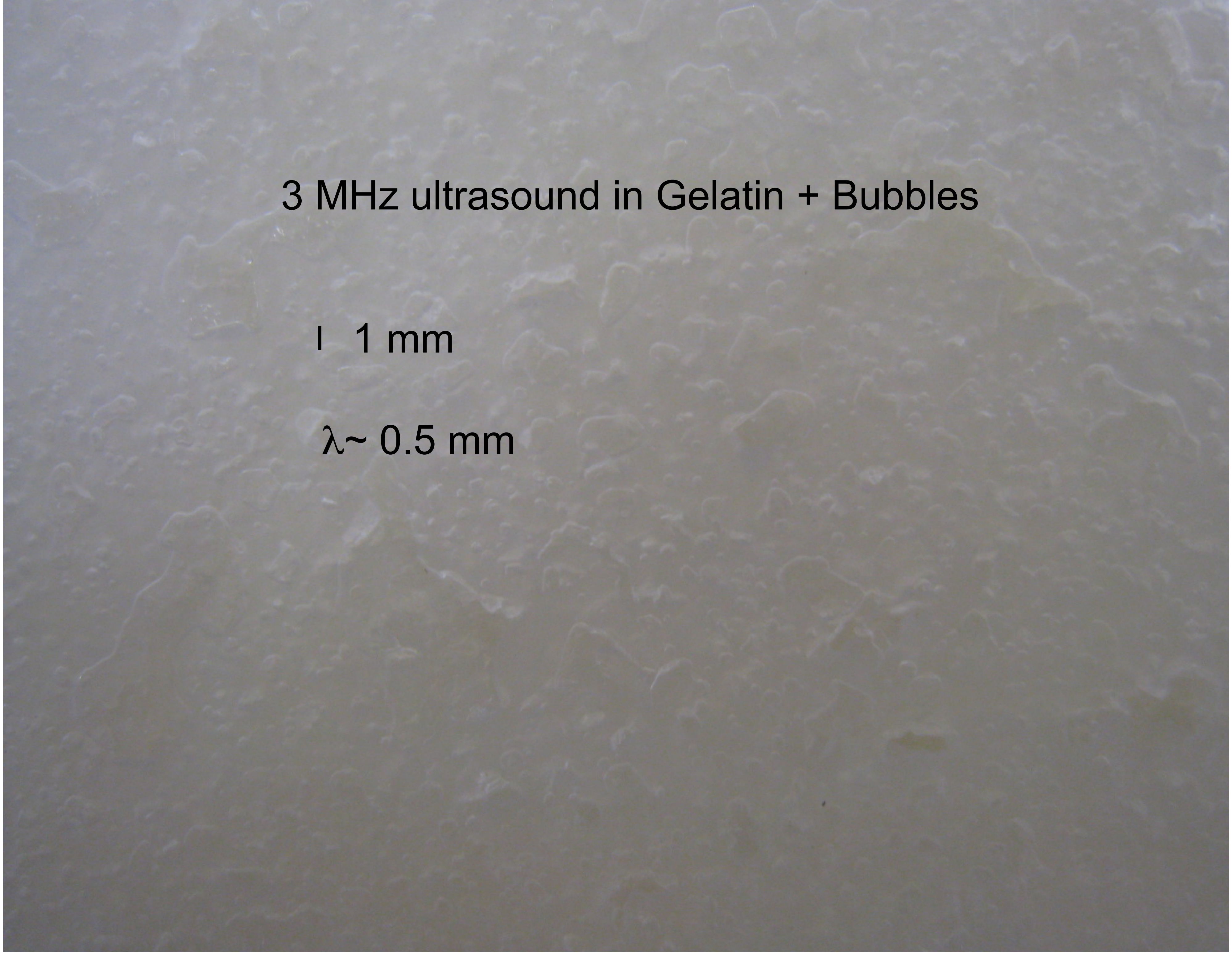
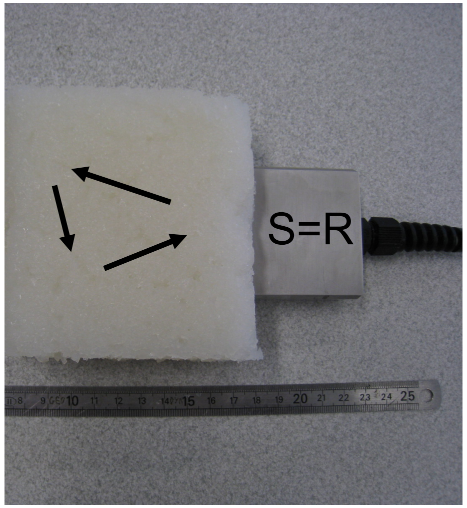
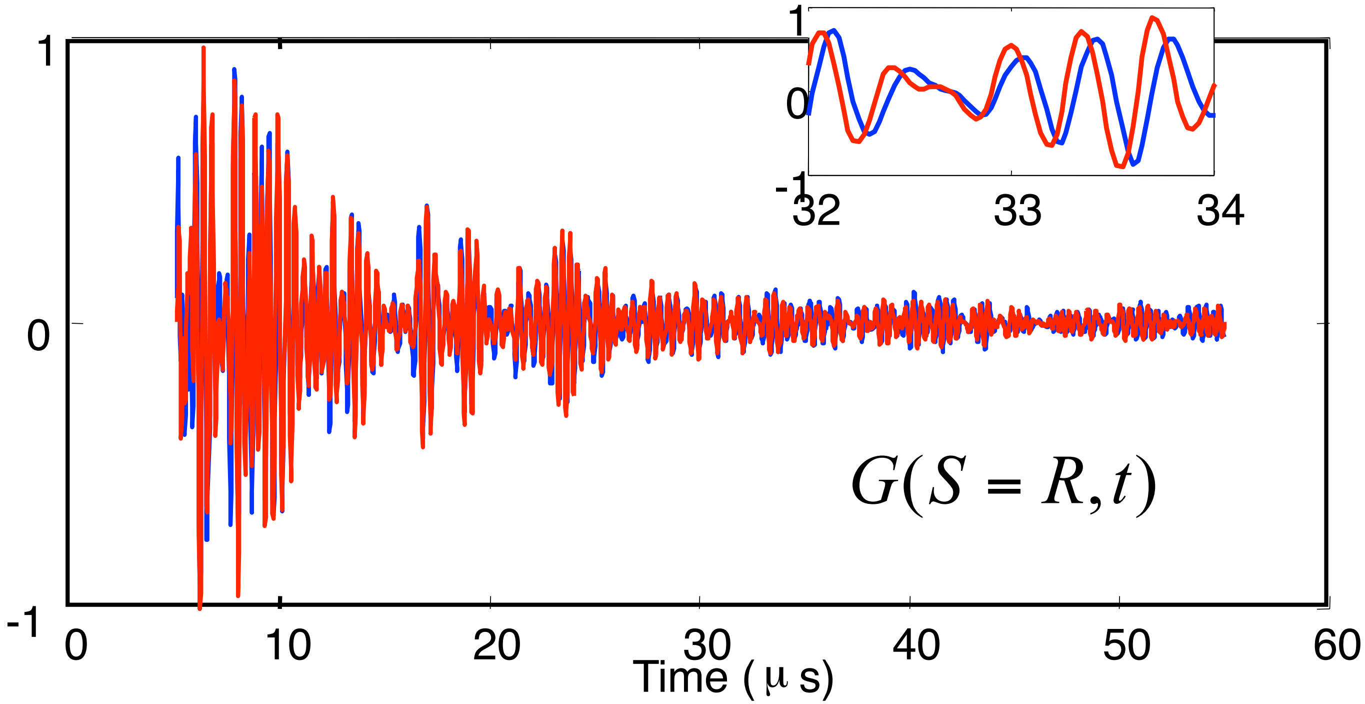



3 MHz ultrasound in Gelatin + Bubbles
1 mm
λ~ 0.5 mm

Active : backscattered waves

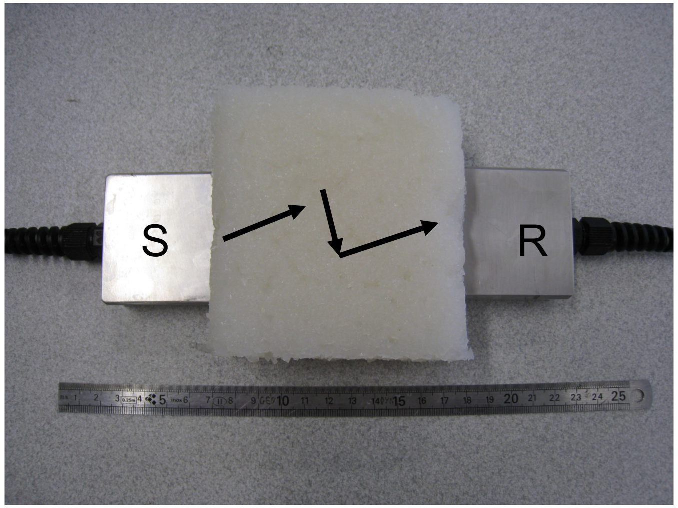




$$\frac{\Delta t}{t} = \varepsilon = 1.5\ ‰ \qquad \frac{\partial c}{\partial T} = 4.6 m/s/K \qquad \Delta T = 0.6°$$

Passive : entregistrement de bruinoise recordings

$$n^{d1}(t)$$



$$r^{d1}(t) = n^{d1}(t) \otimes G(S,R,t)$$

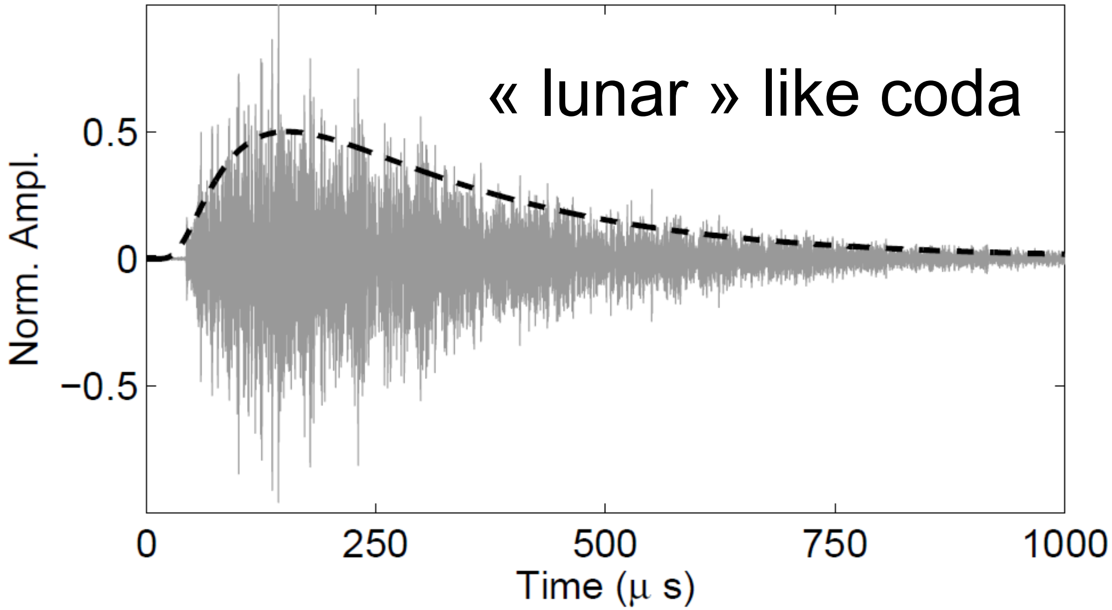
$$n^{d2}(t)$$

$$r^{d2}(t) = n^{d2}(t) \otimes G(S,R,t)$$

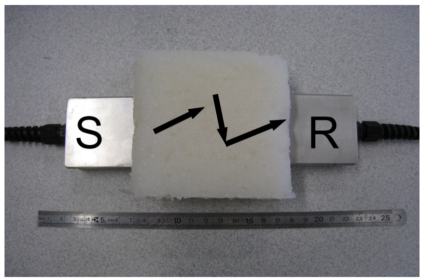
Transmission of « noise » *n(t)*

$$C^{d}(\tau) = \int r^{d}(t) r^{d}(t+\tau) dt$$

Passive : transmitted signal

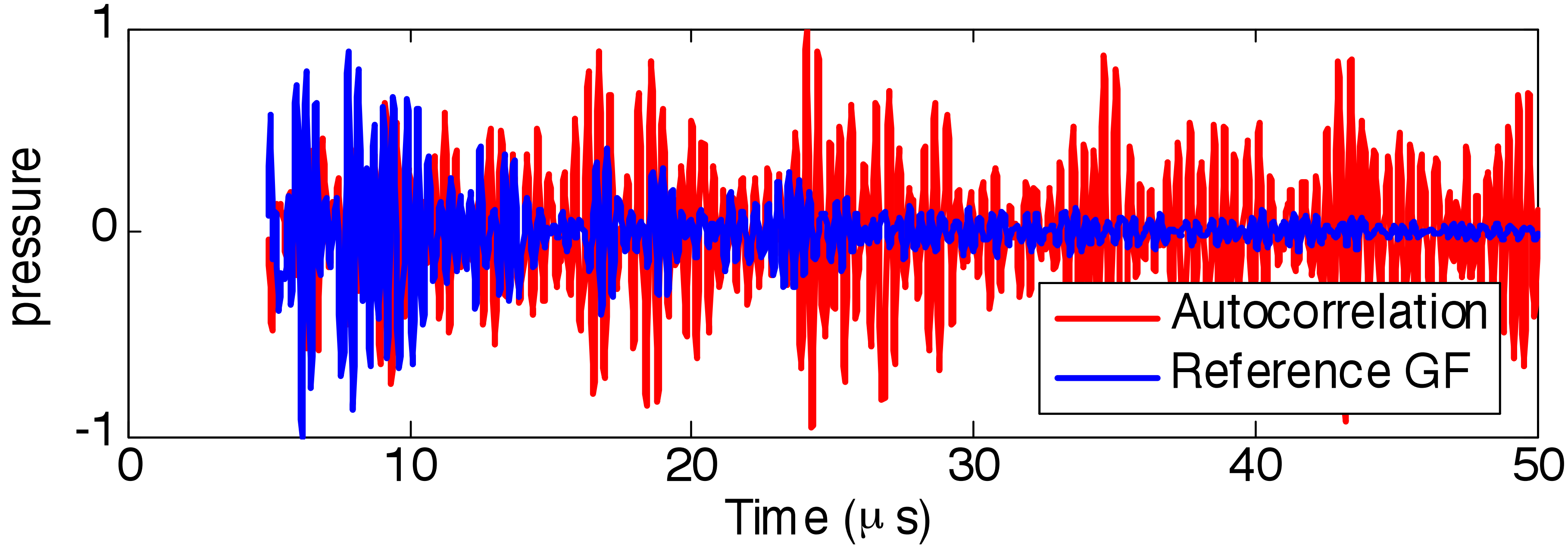


$$G(S,R,t)$$



Hadziioannou *et al*, J. Acoust. Soc. Am. 125 (2009)

Active Vs Passive

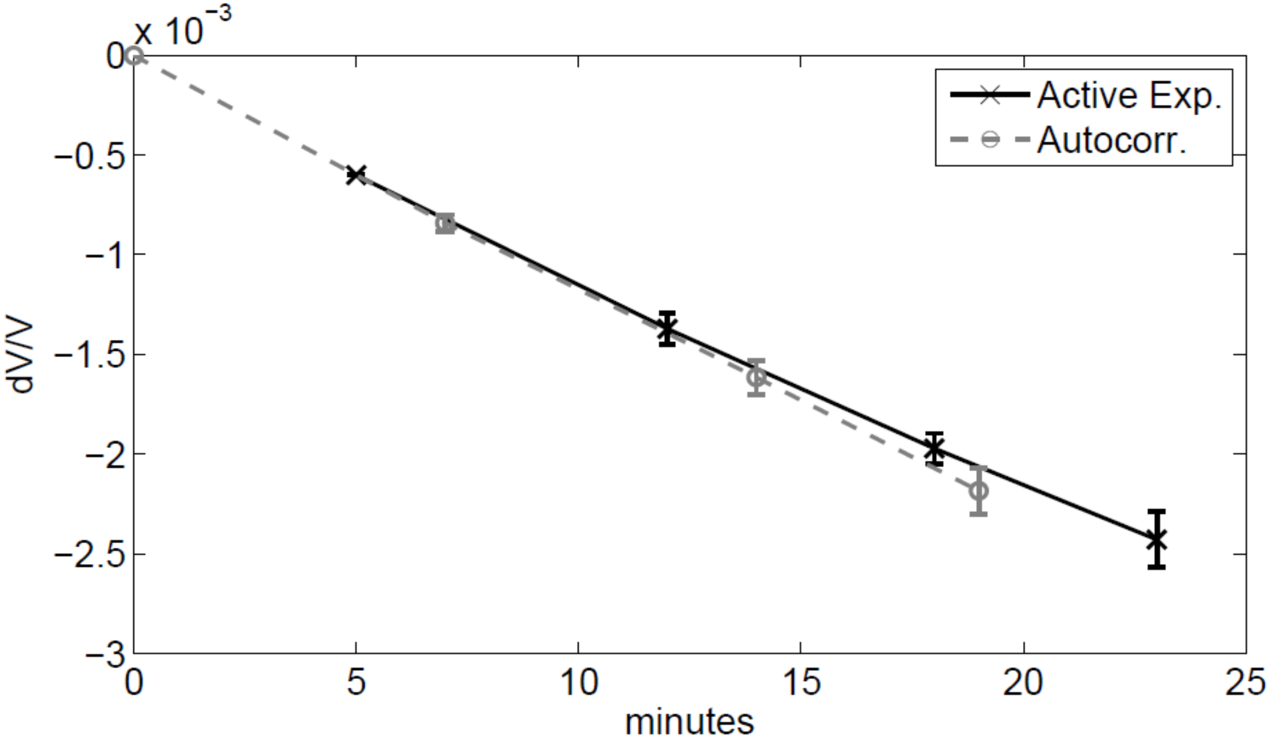


☹ auto-correlation from one noise source ≠ Green function

Corrr Coeff ~0.02%

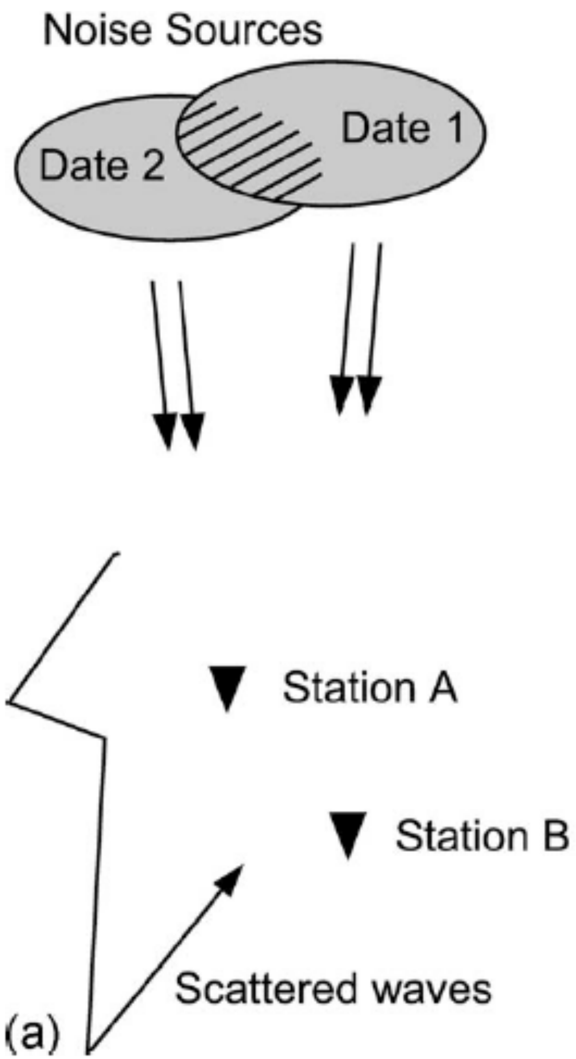
Hadziioannou *et al*, J. Acoust. Soc. Am. 125 (2009)

Monitoring (active AND passive)



☺ Auto-correlation from one noise source = monitoring

Hadziioannou *et al*, J. Acoust. Soc. Am. 125 (2009)

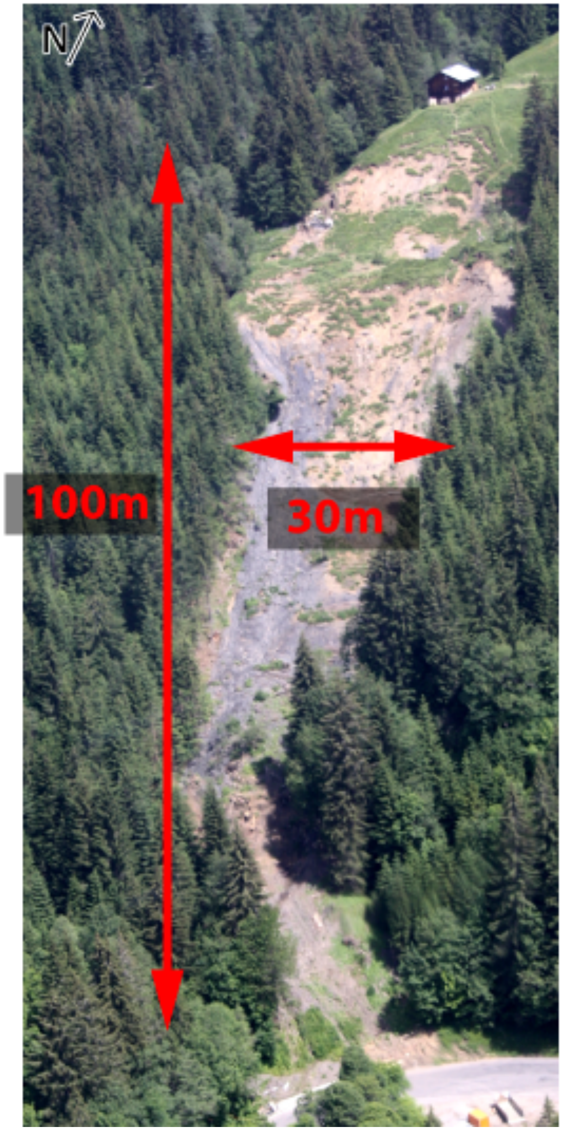


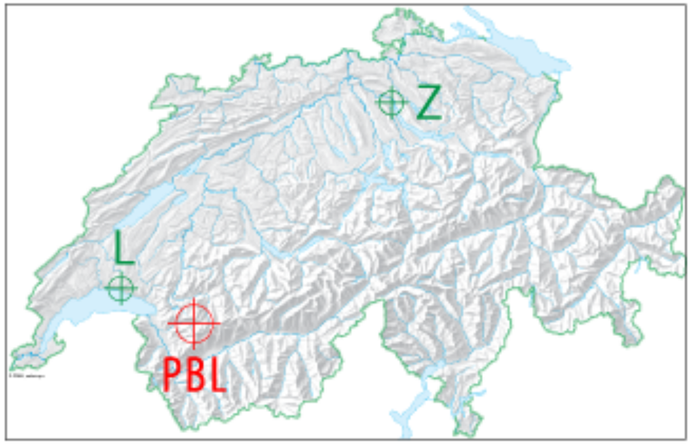
☺

SOME stable noise source
=> monitoring

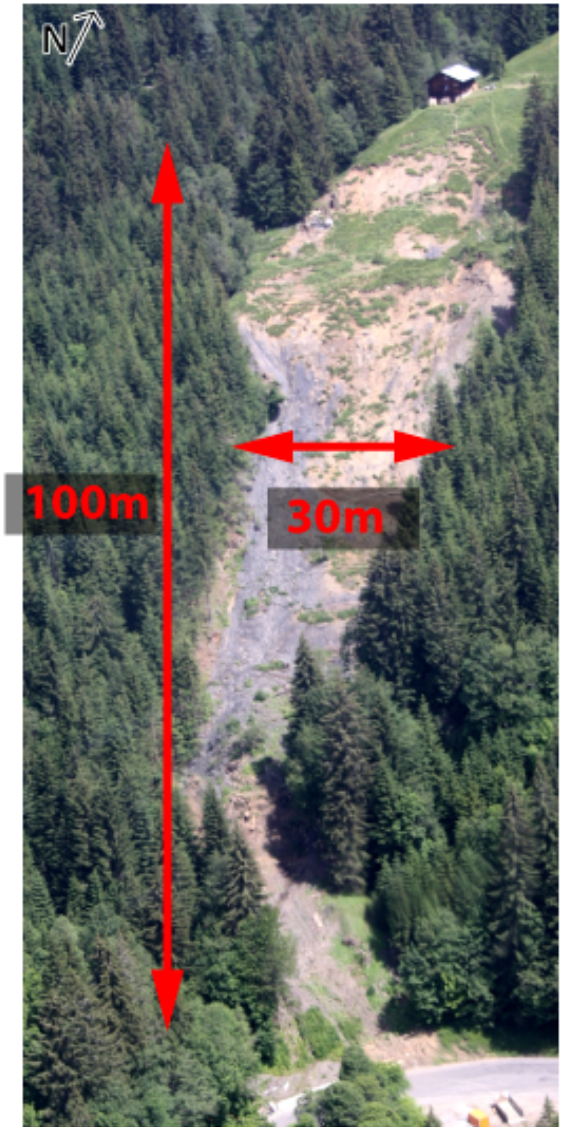
Hadziioannou *et al*, J. Acoust. Soc. Am. 125 (2009)

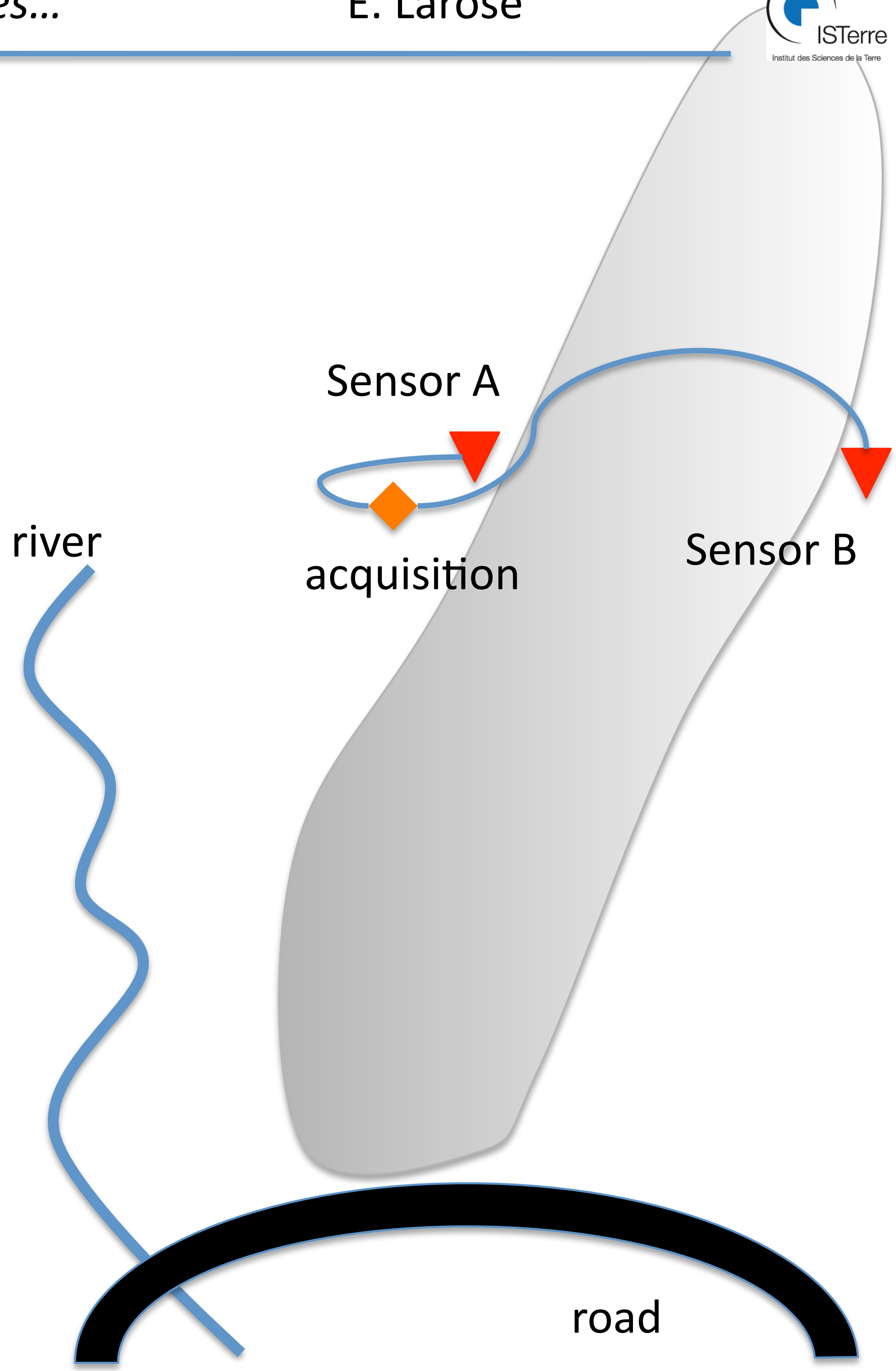
Installation in january 2010



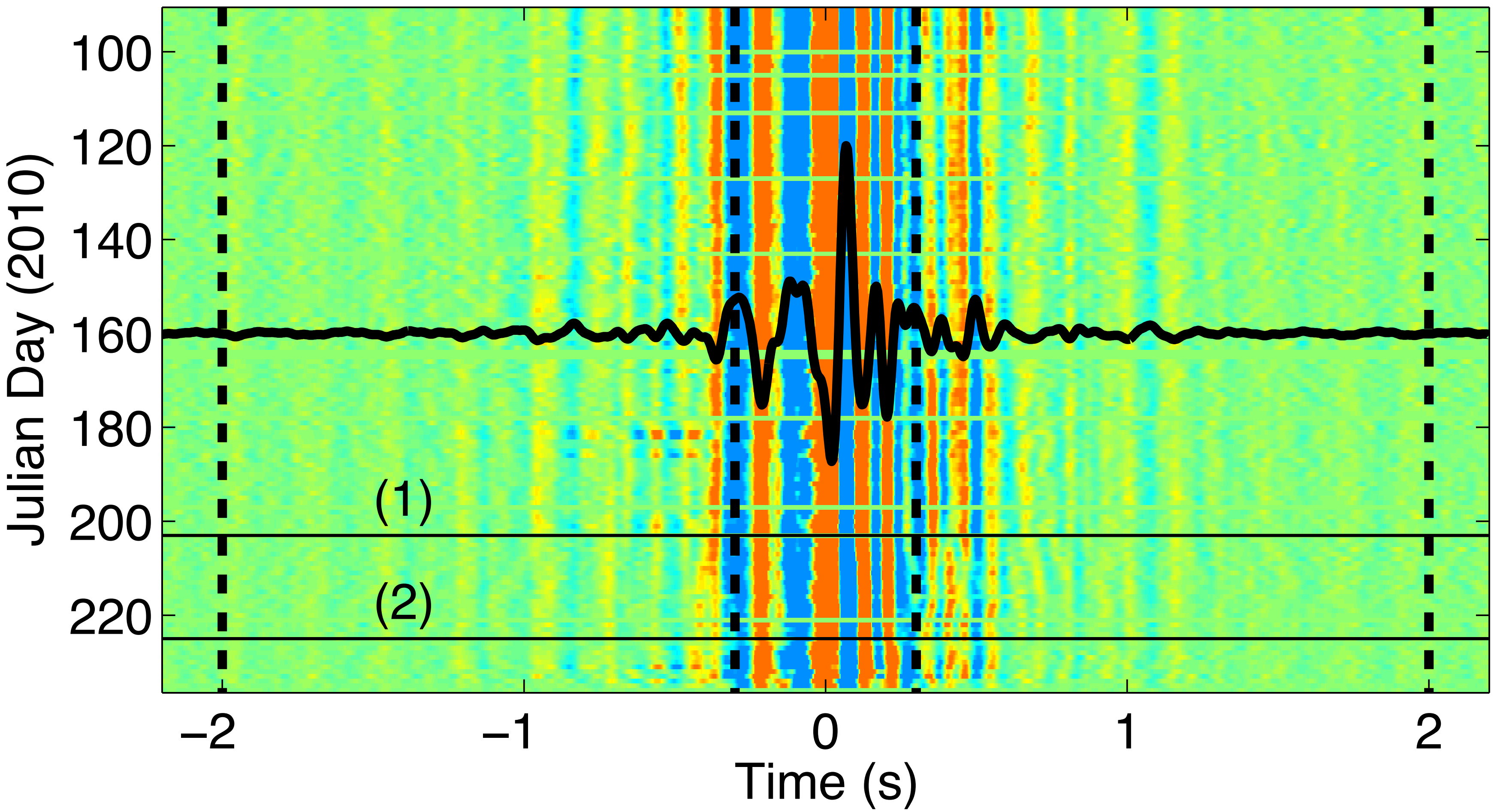


Installation in january 2010





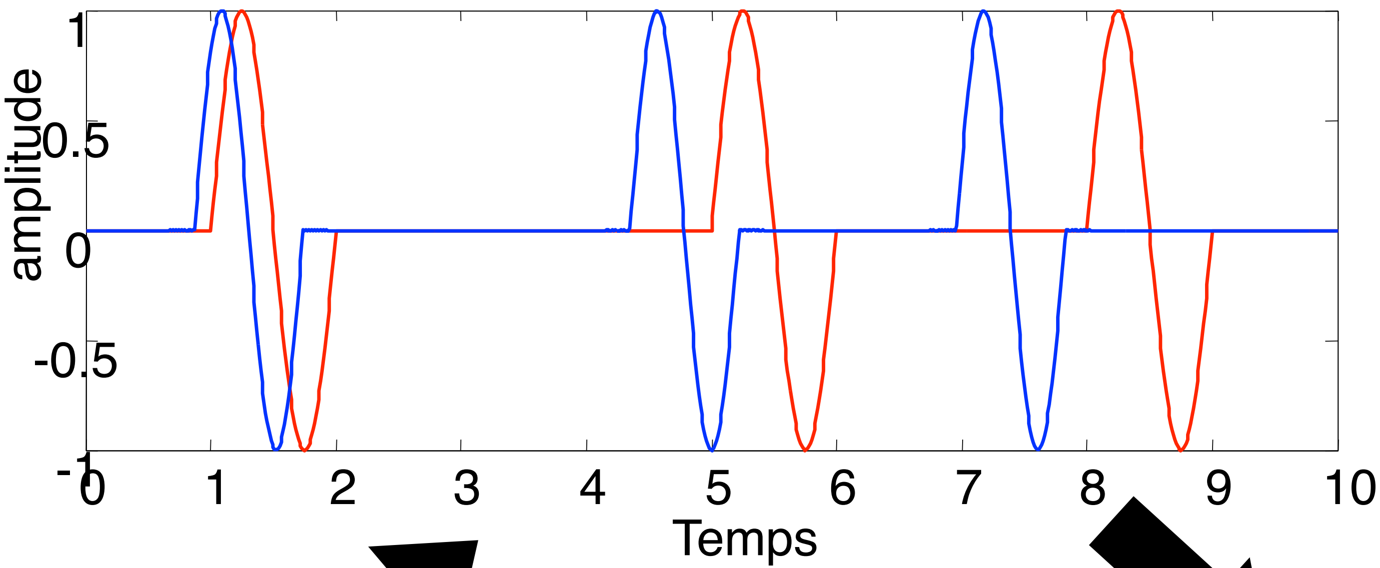
Daily cross-correlation

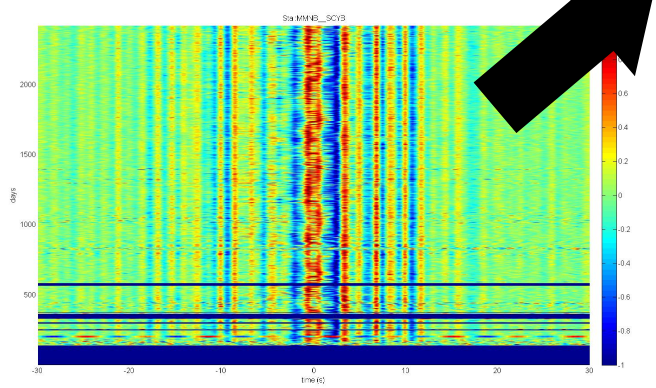


Campillo & Paul, Science (2003)

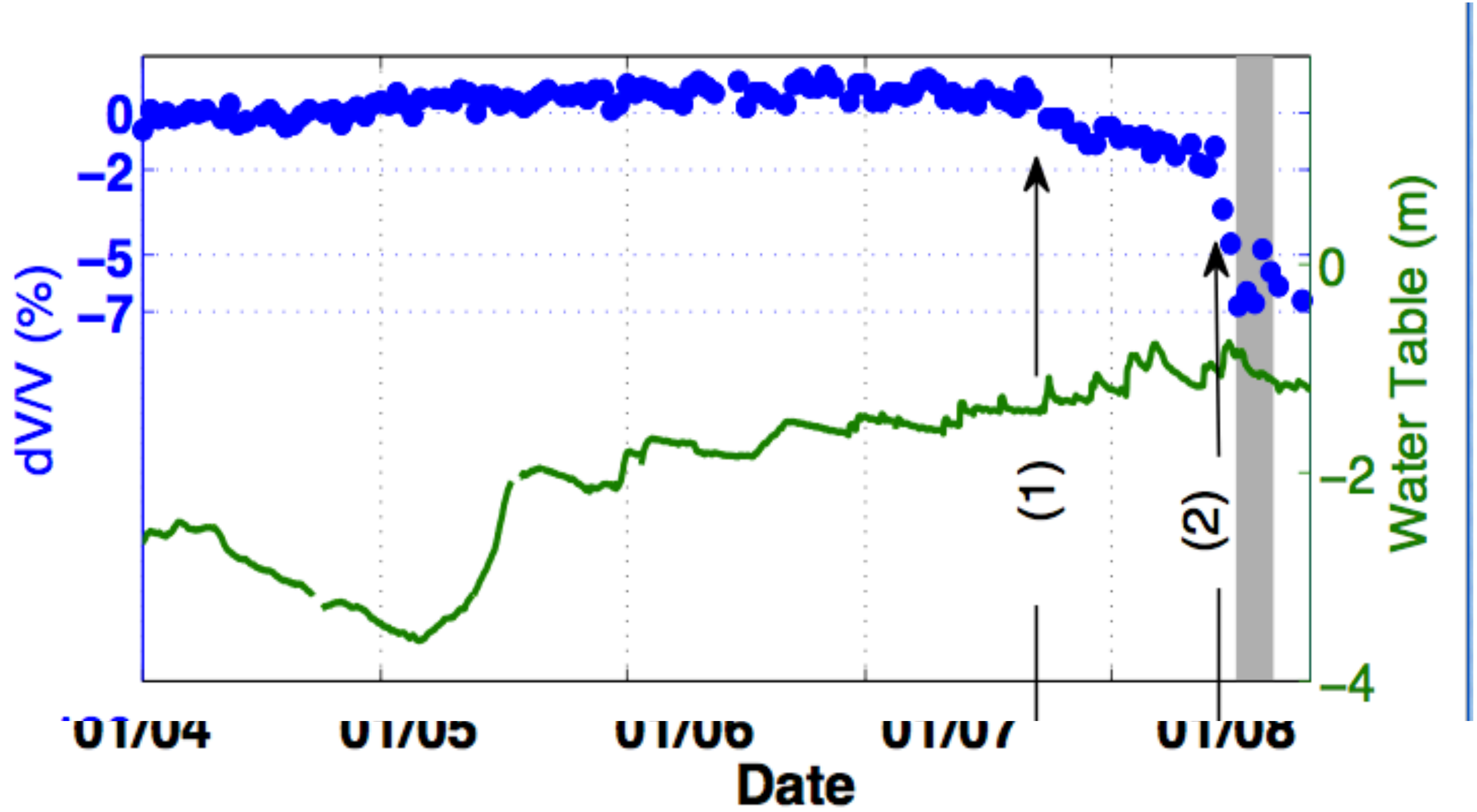
REFERENCE

CURRENT DATE





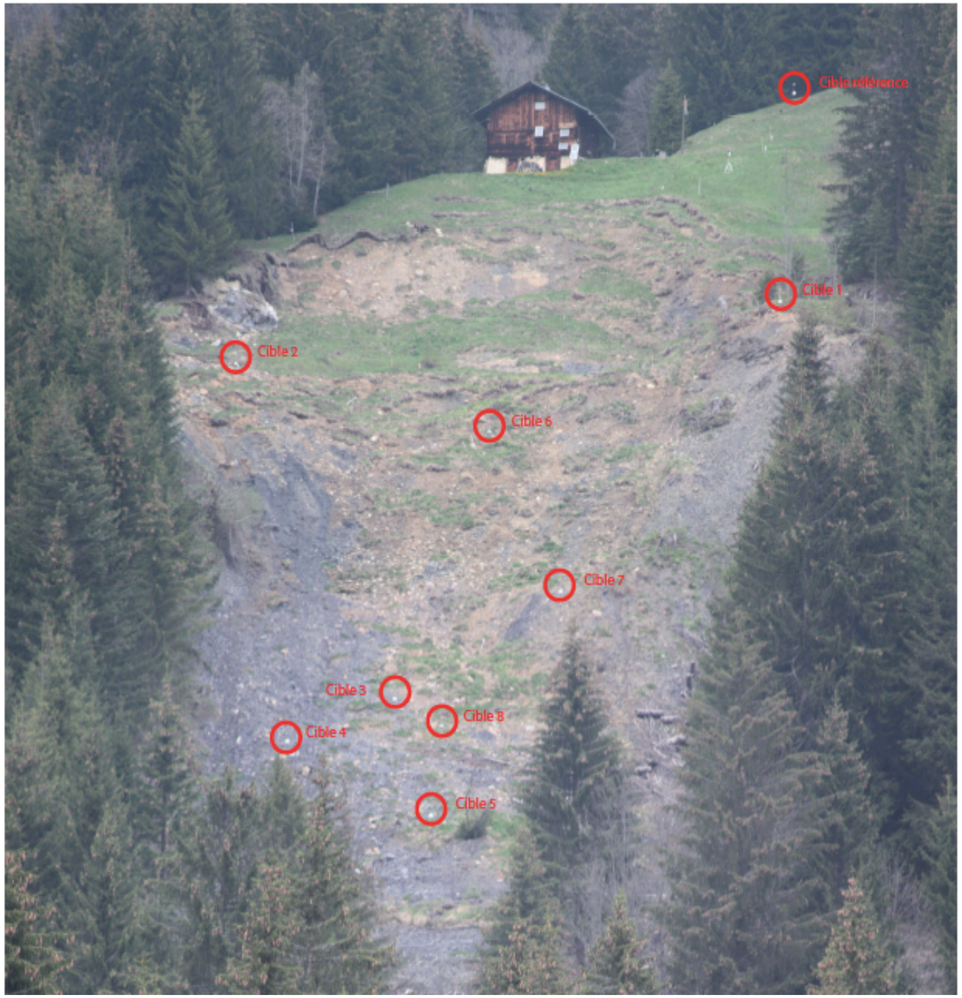
$dt/t=-dV/V$

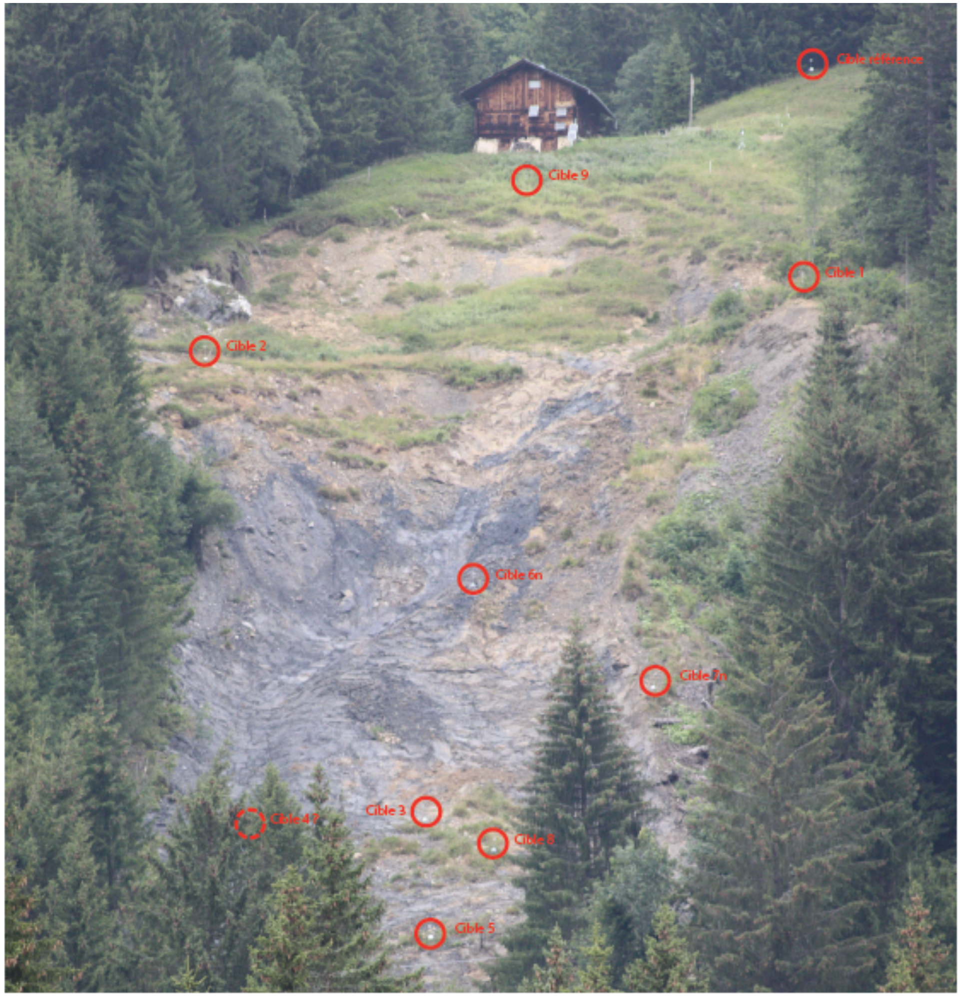


Mainsant et al, JGR (2011)

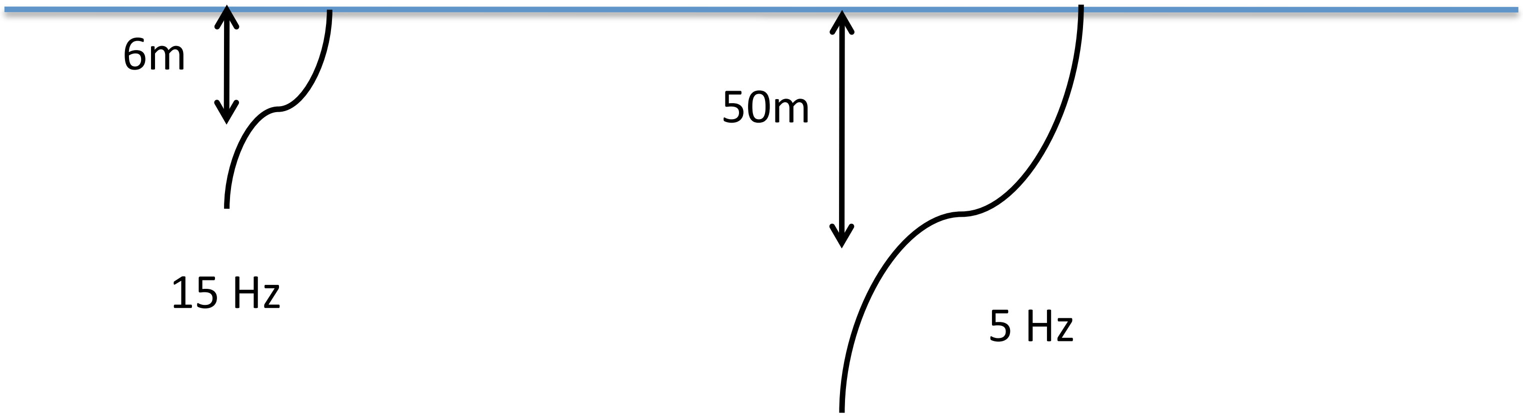
20 mai 2010

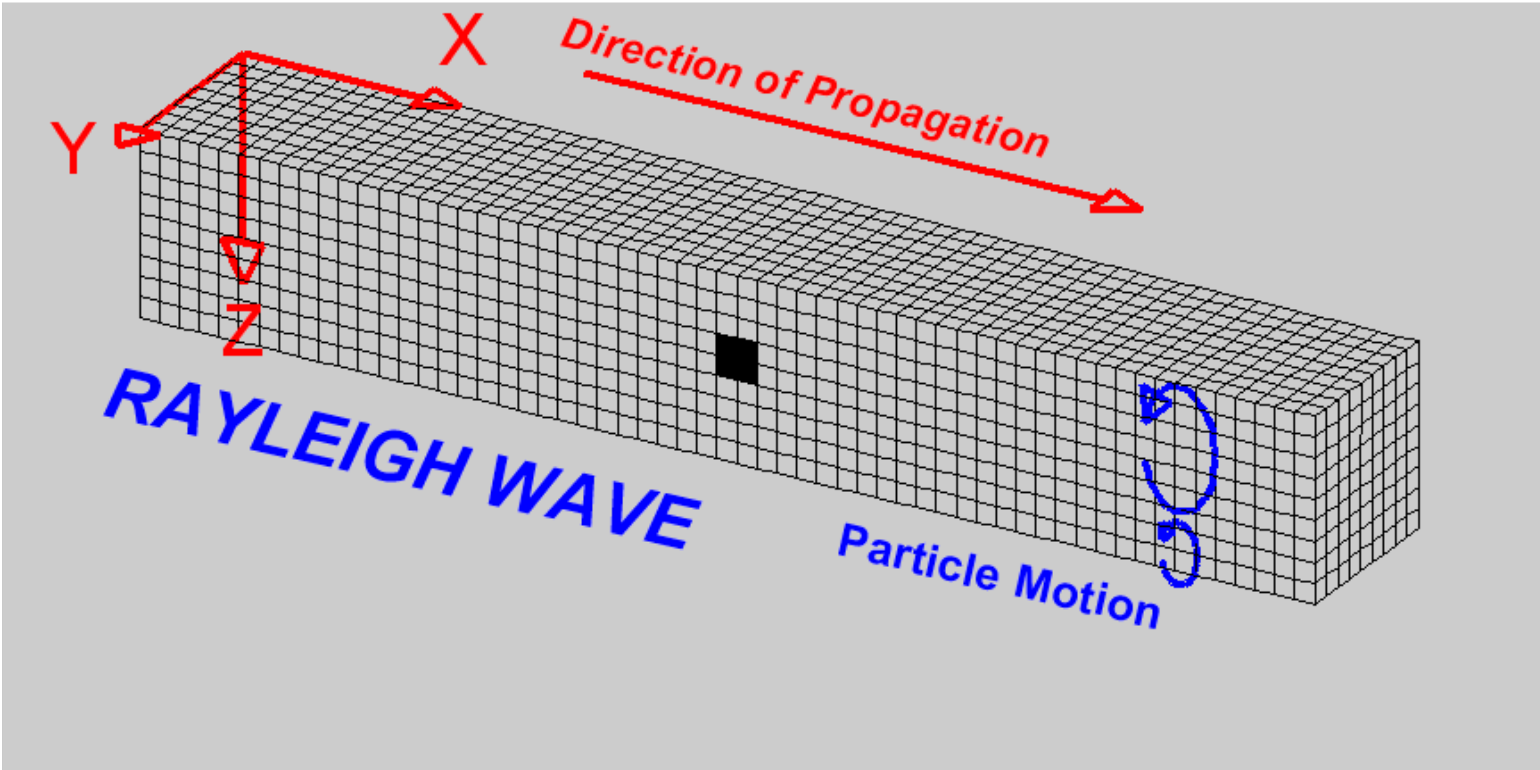
23 aout 2010

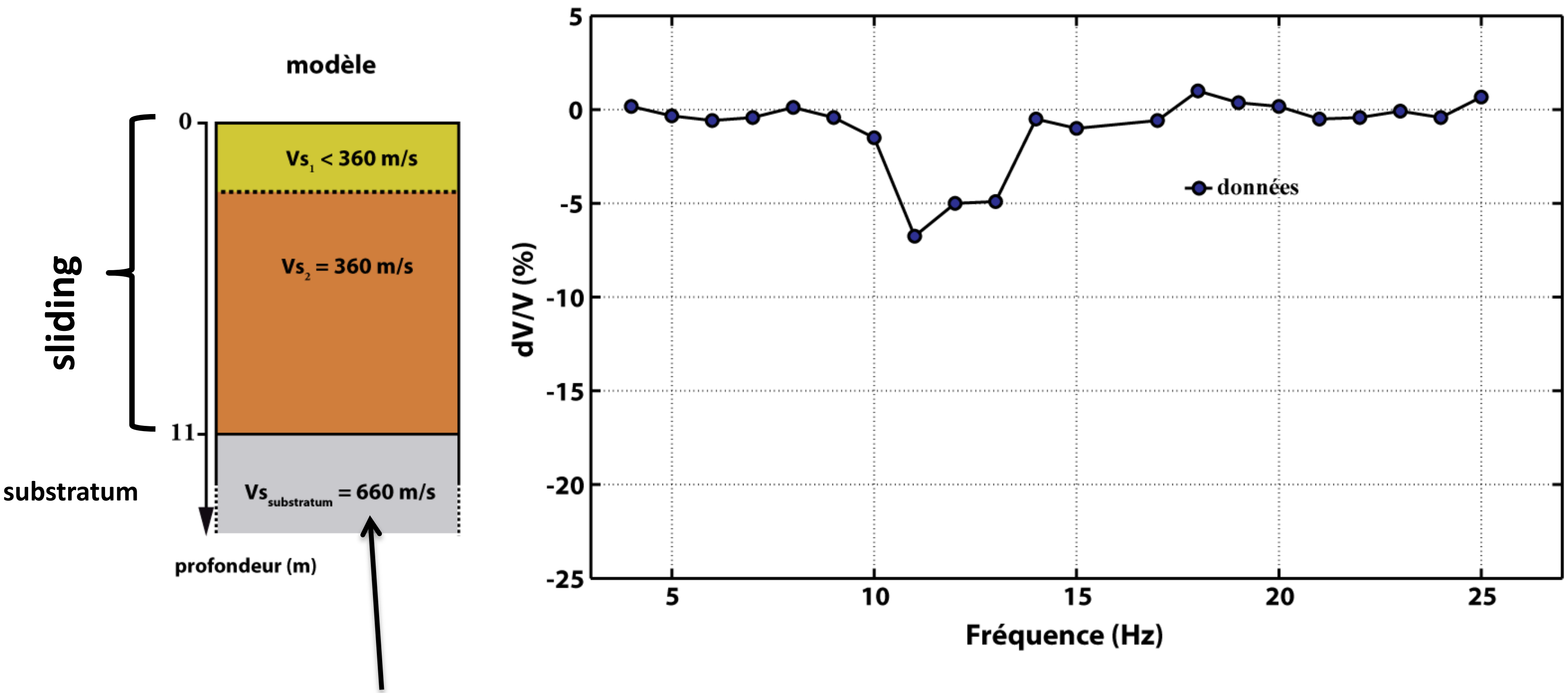




22 august 2010

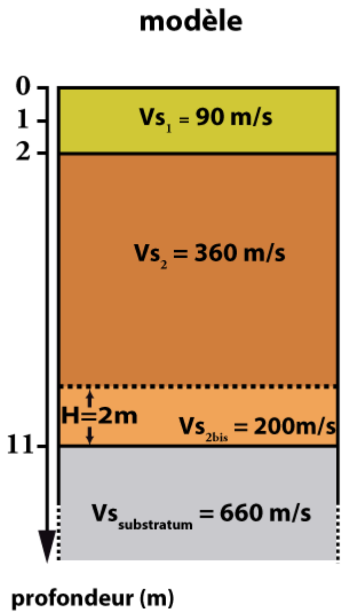

6m
15 Hz
50m
5 Hz

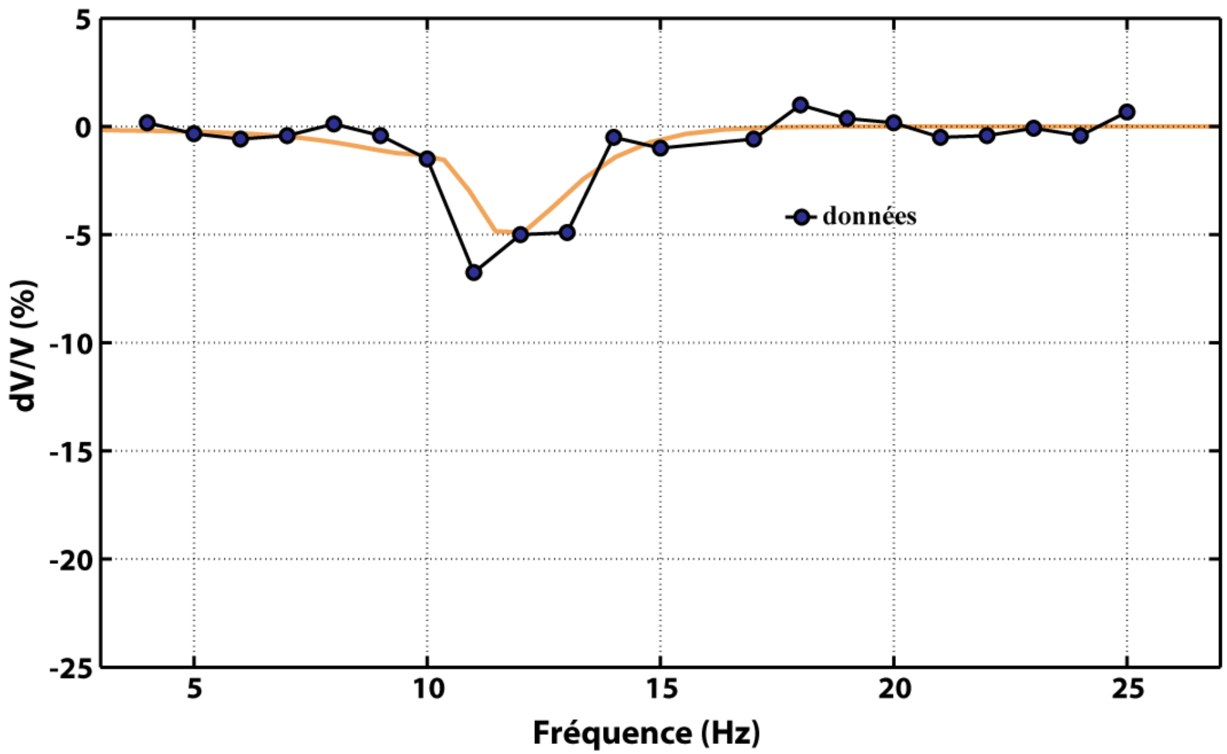

X
Y
Z
Direction of Propagation
RAYLEIGH WAVE
Particle Motion



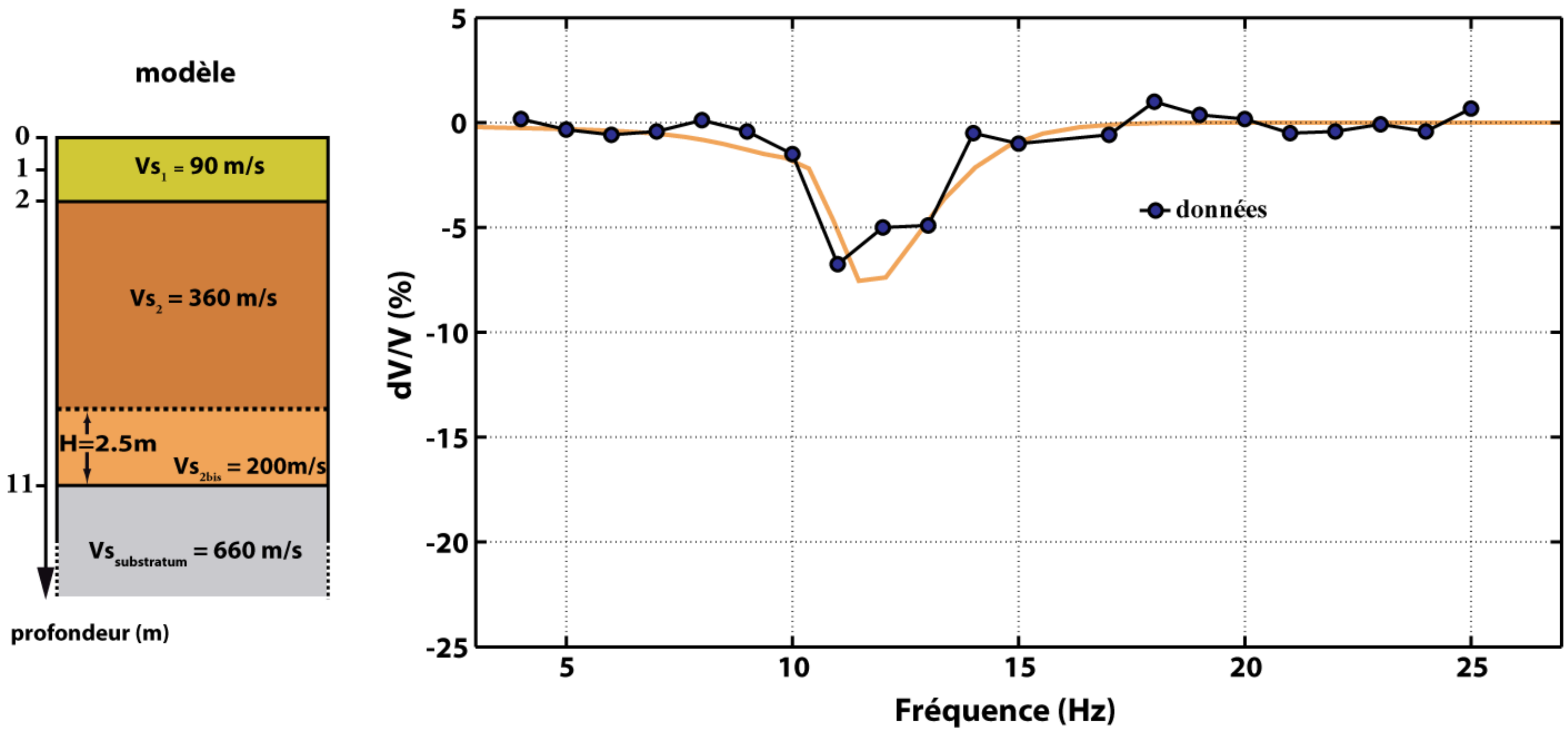
- **Starting model based on active seismics**

Numerical model :

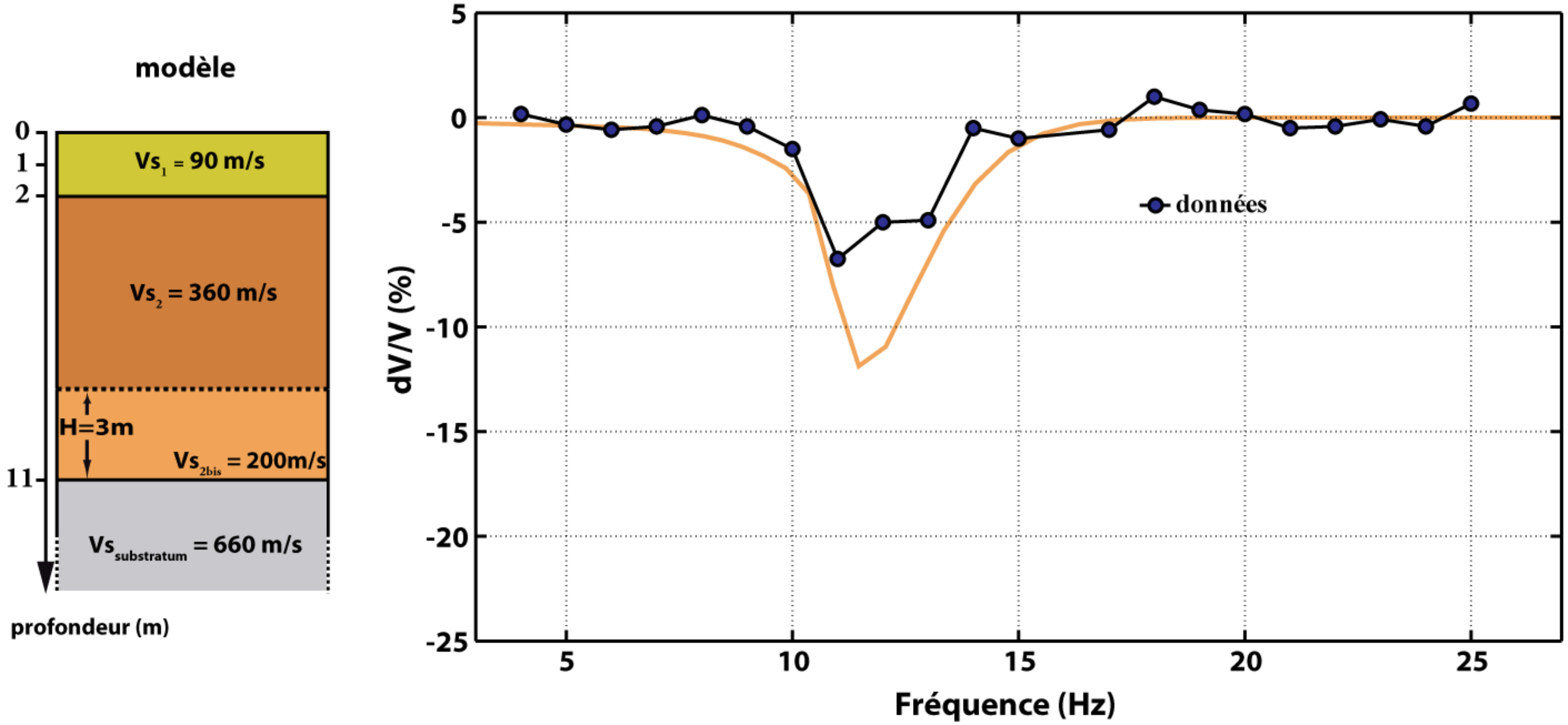




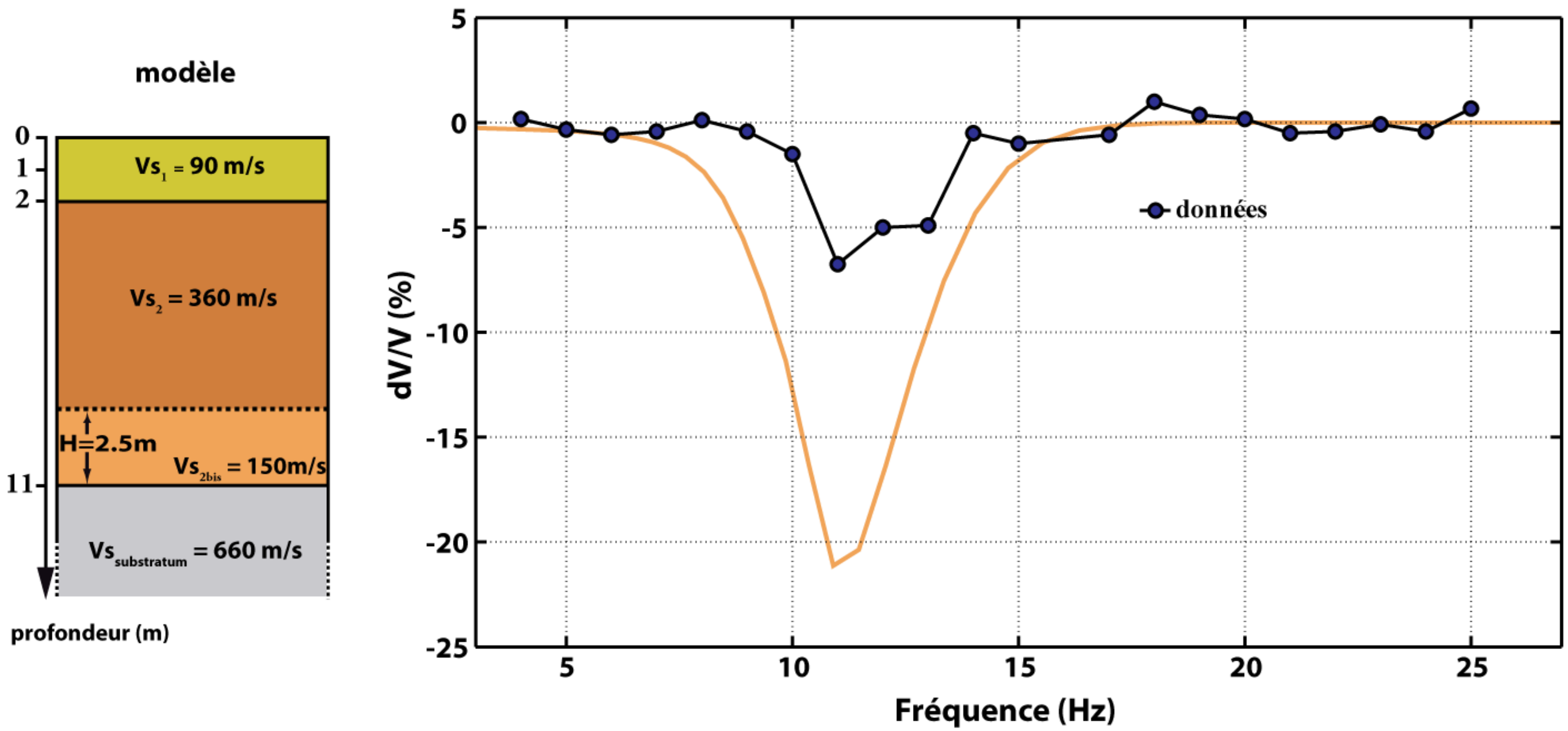
Numerical model :



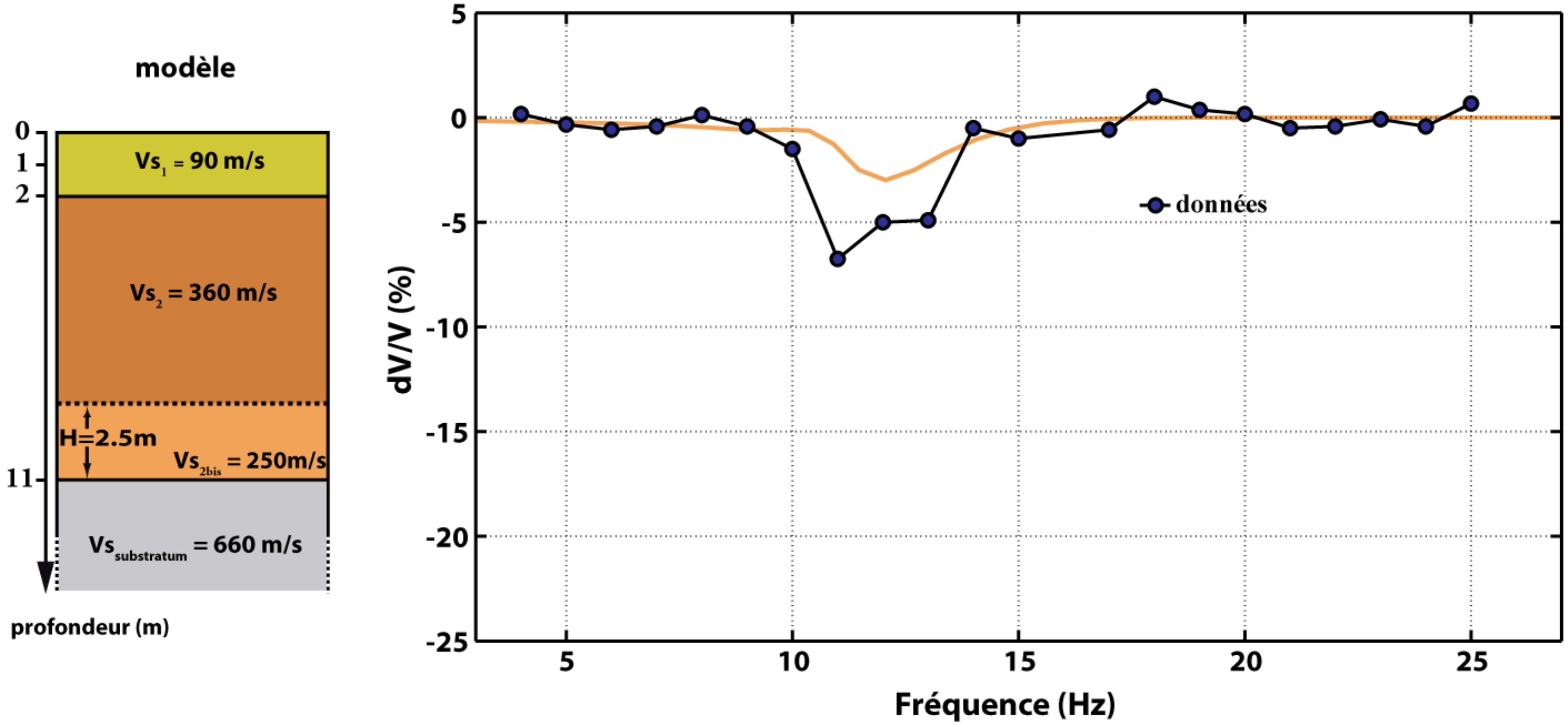
Numerical model :



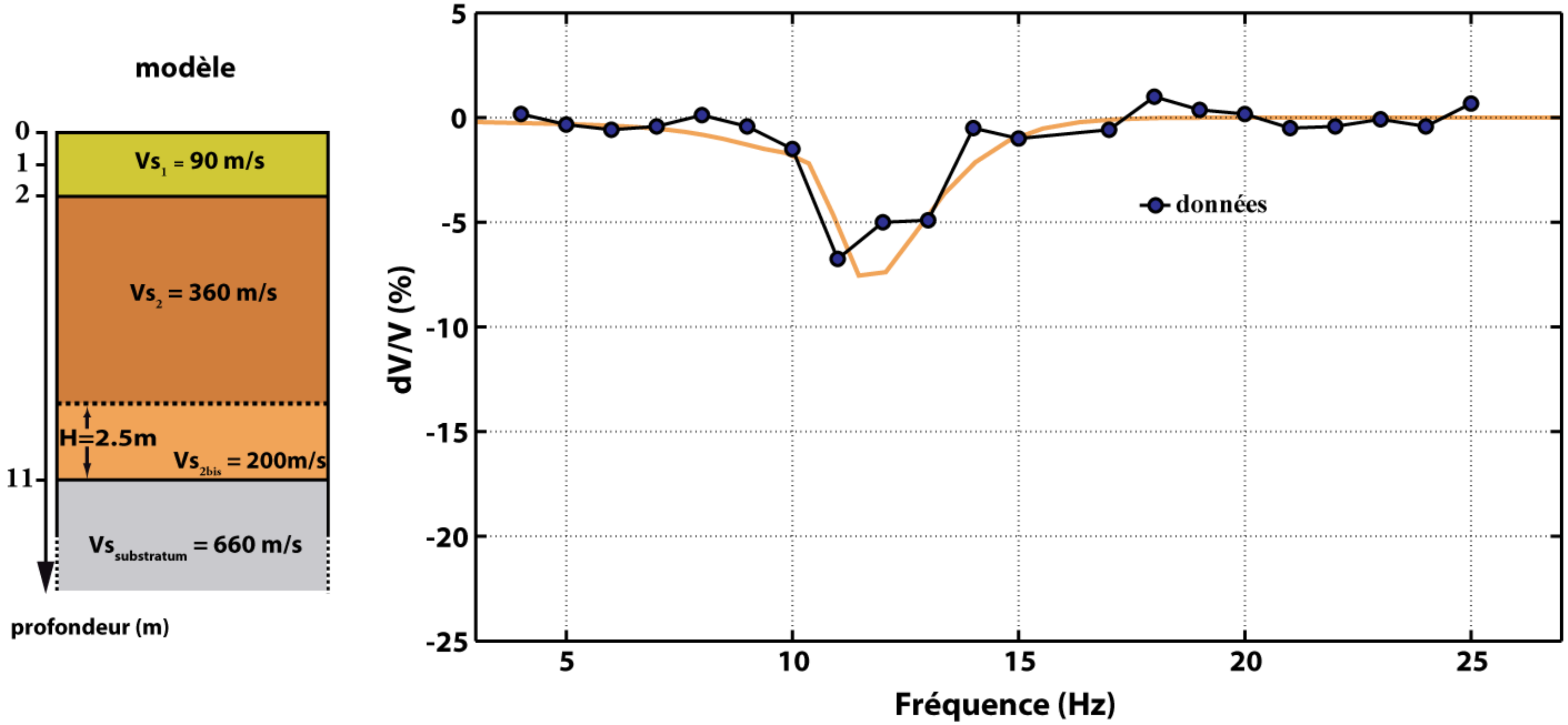
Numerical model :



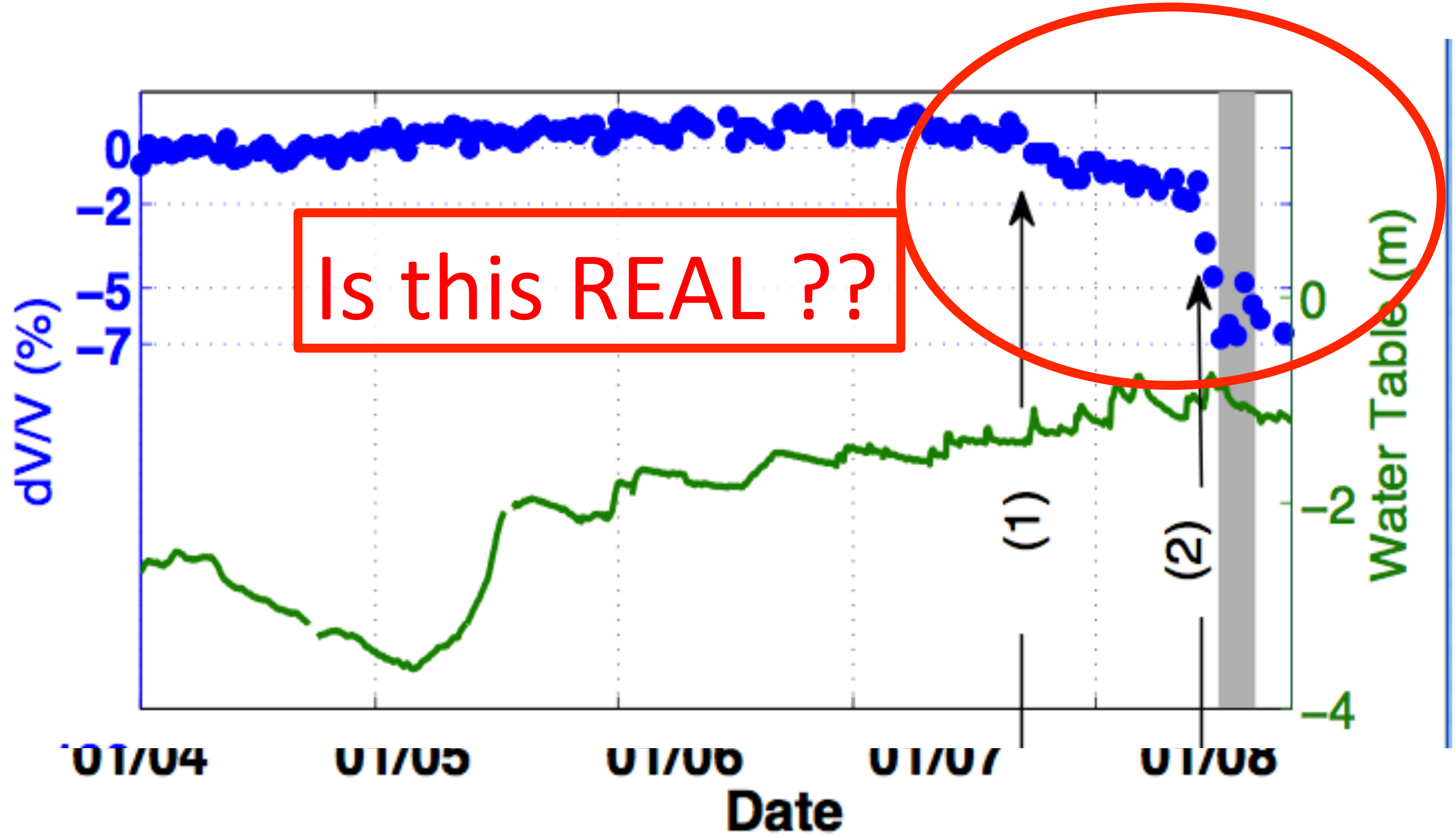
Numerical model :



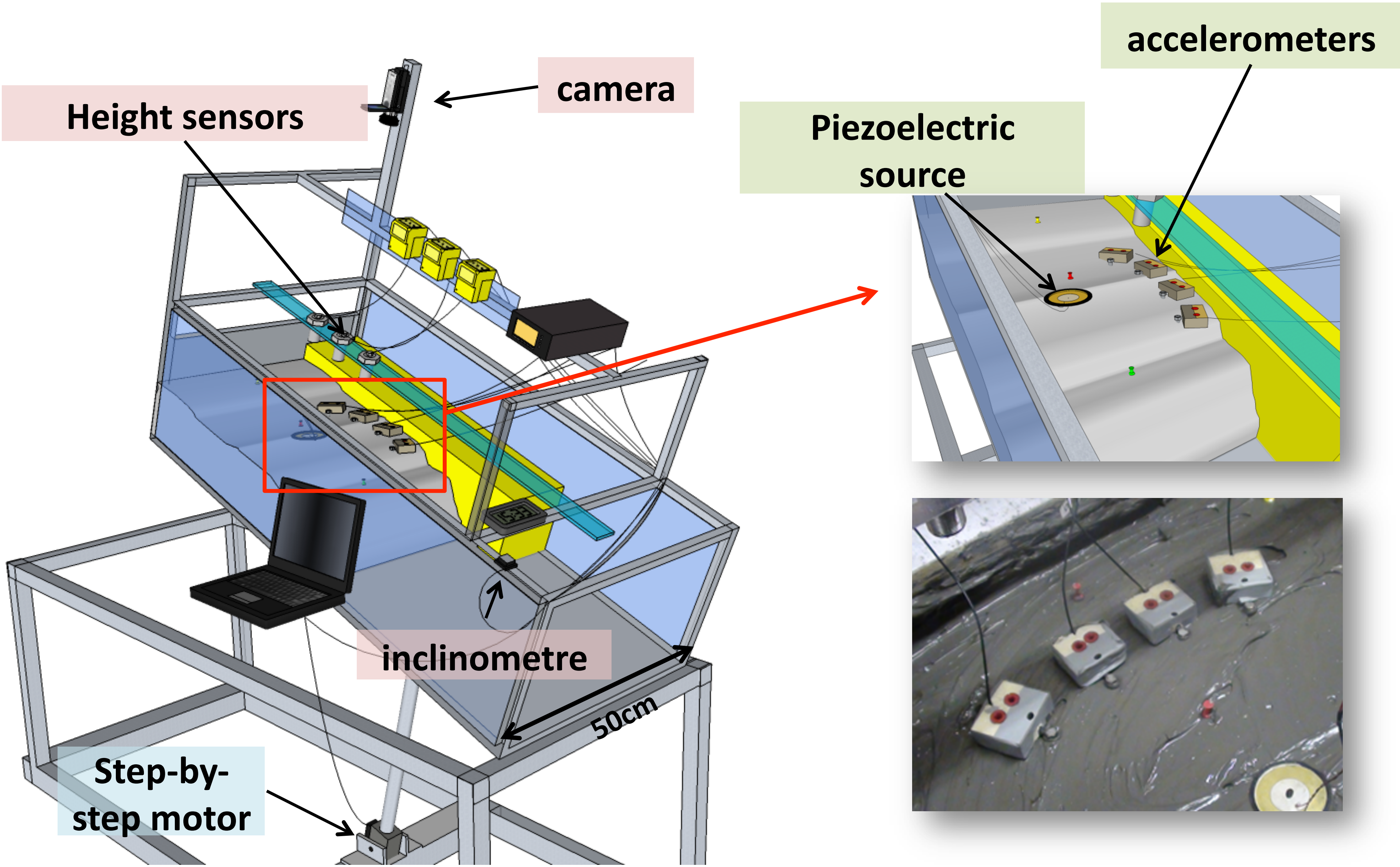
Numerical model :

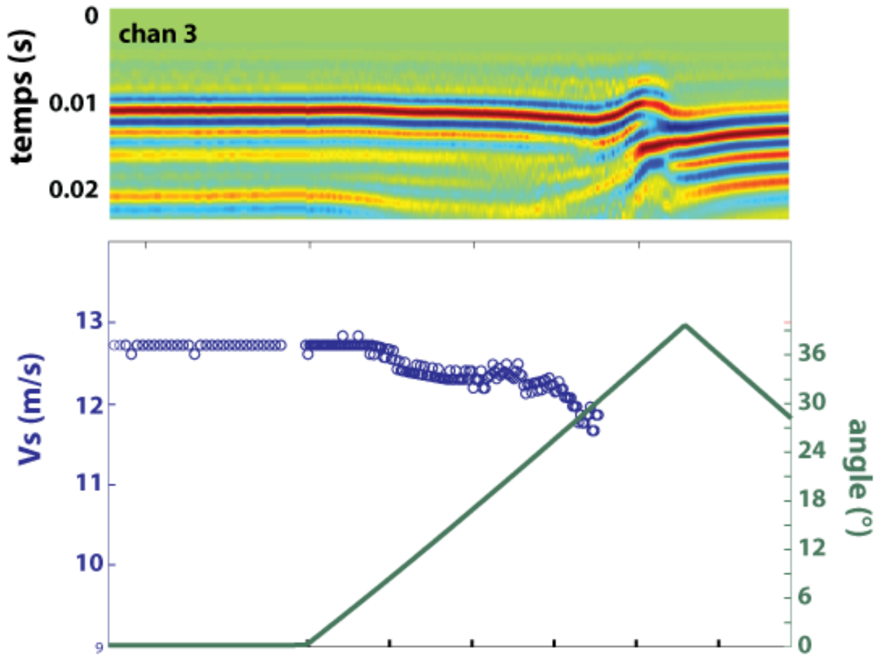


=> MOST PROBABLE MODEL

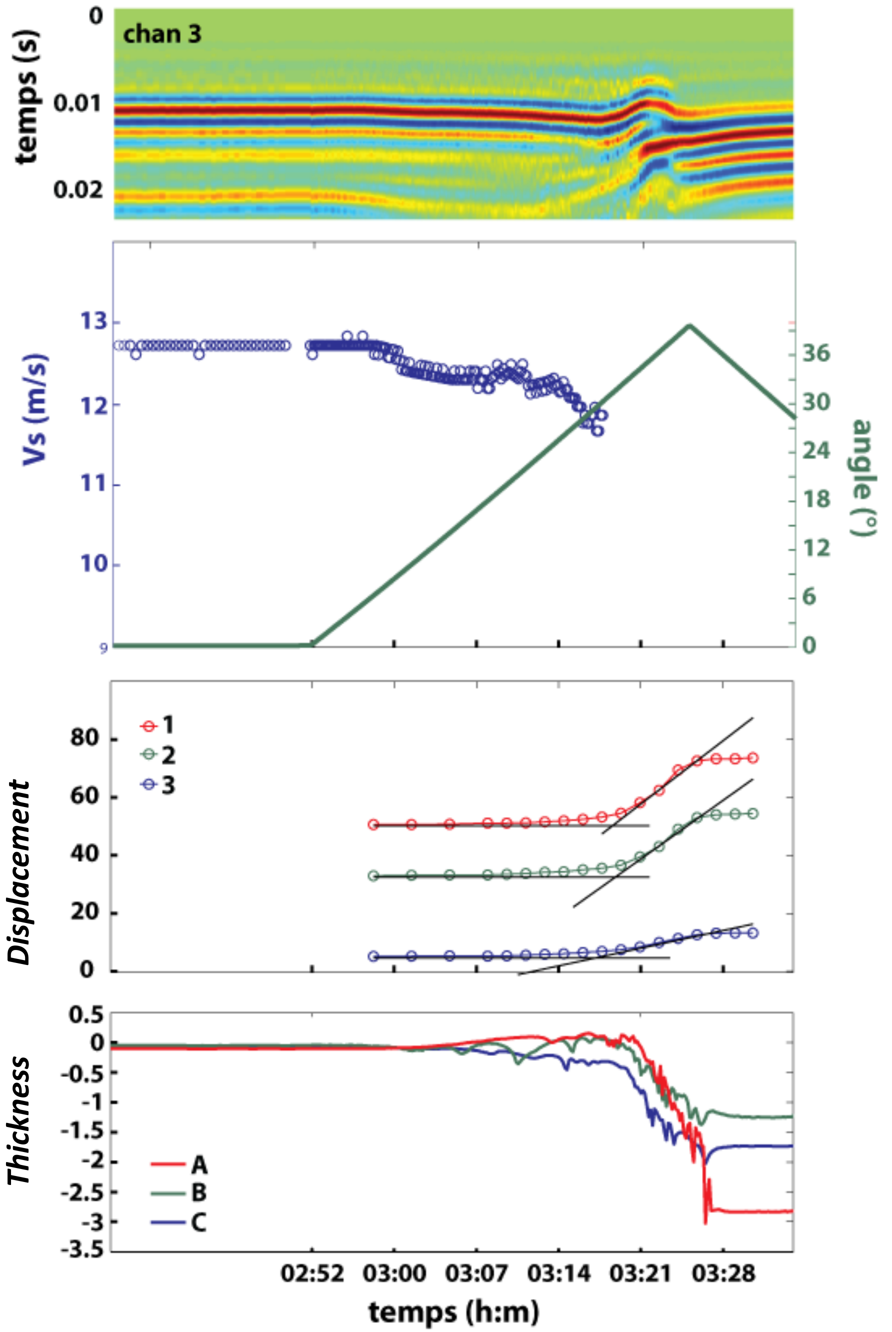


Mainsant et al, JGR (2011)


camera
Height sensors
Piezoelectric source
accelerometers
inclinometre
50cm
Step-by-step motor

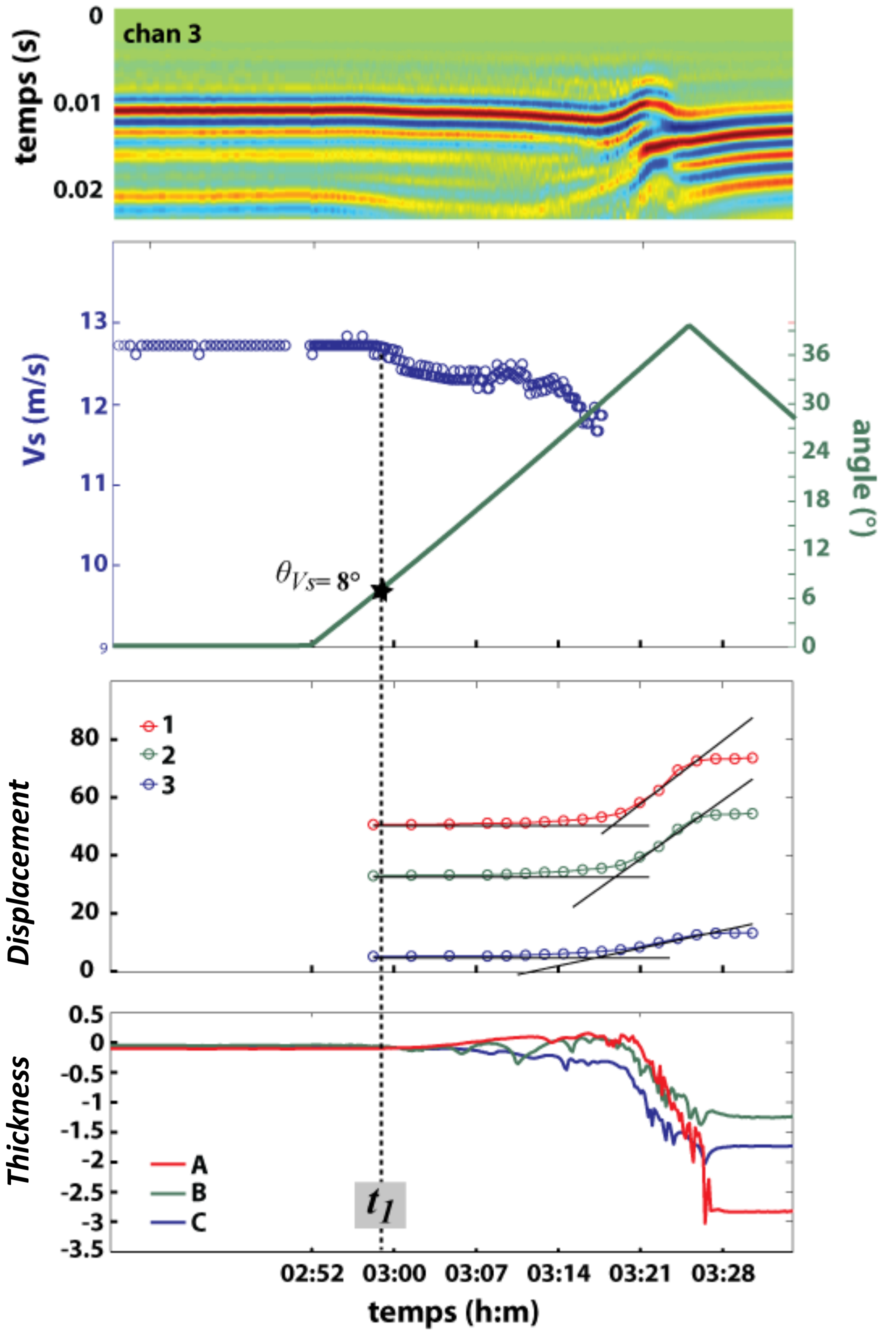


Vs & angles

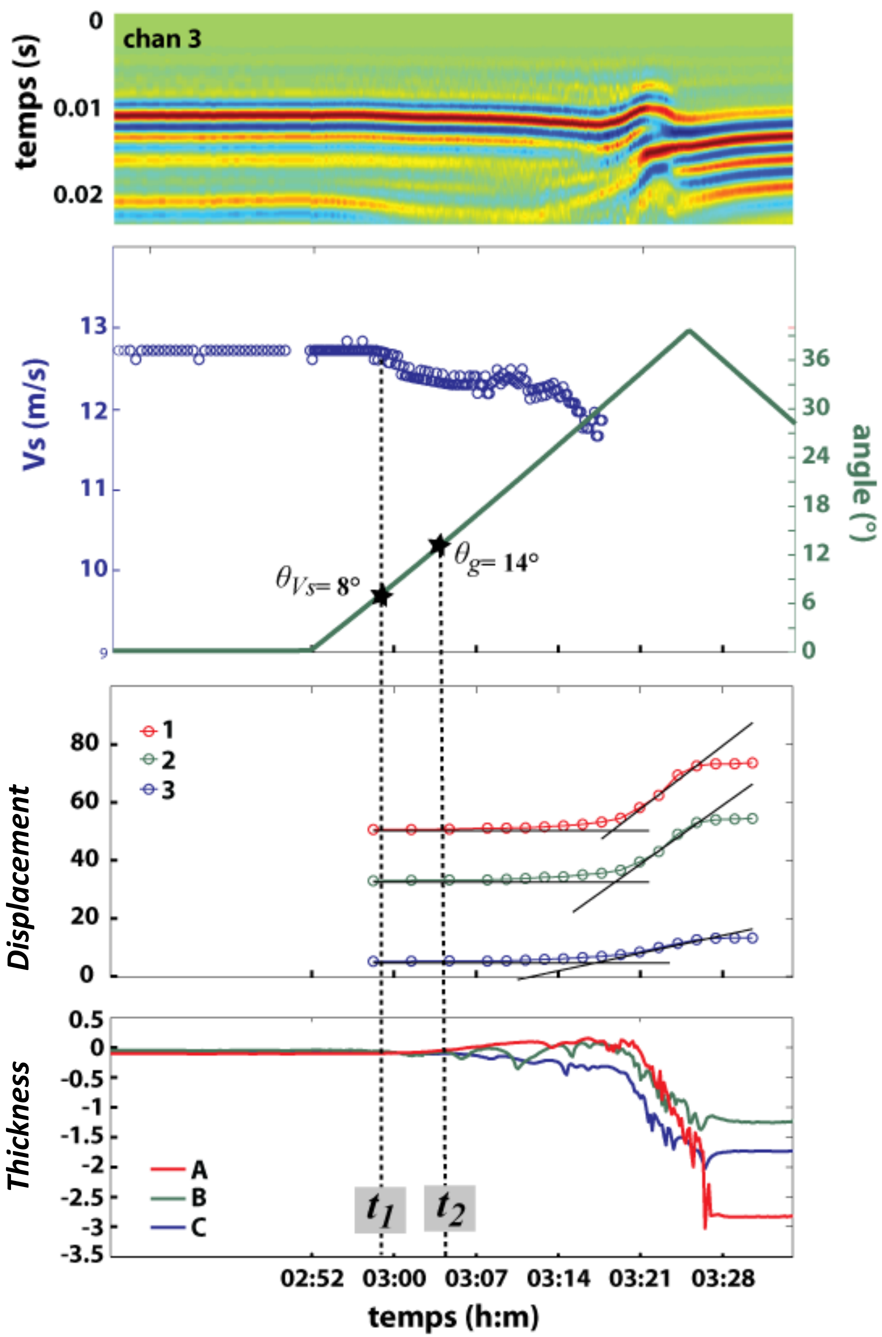


Vs & angles

Displacement

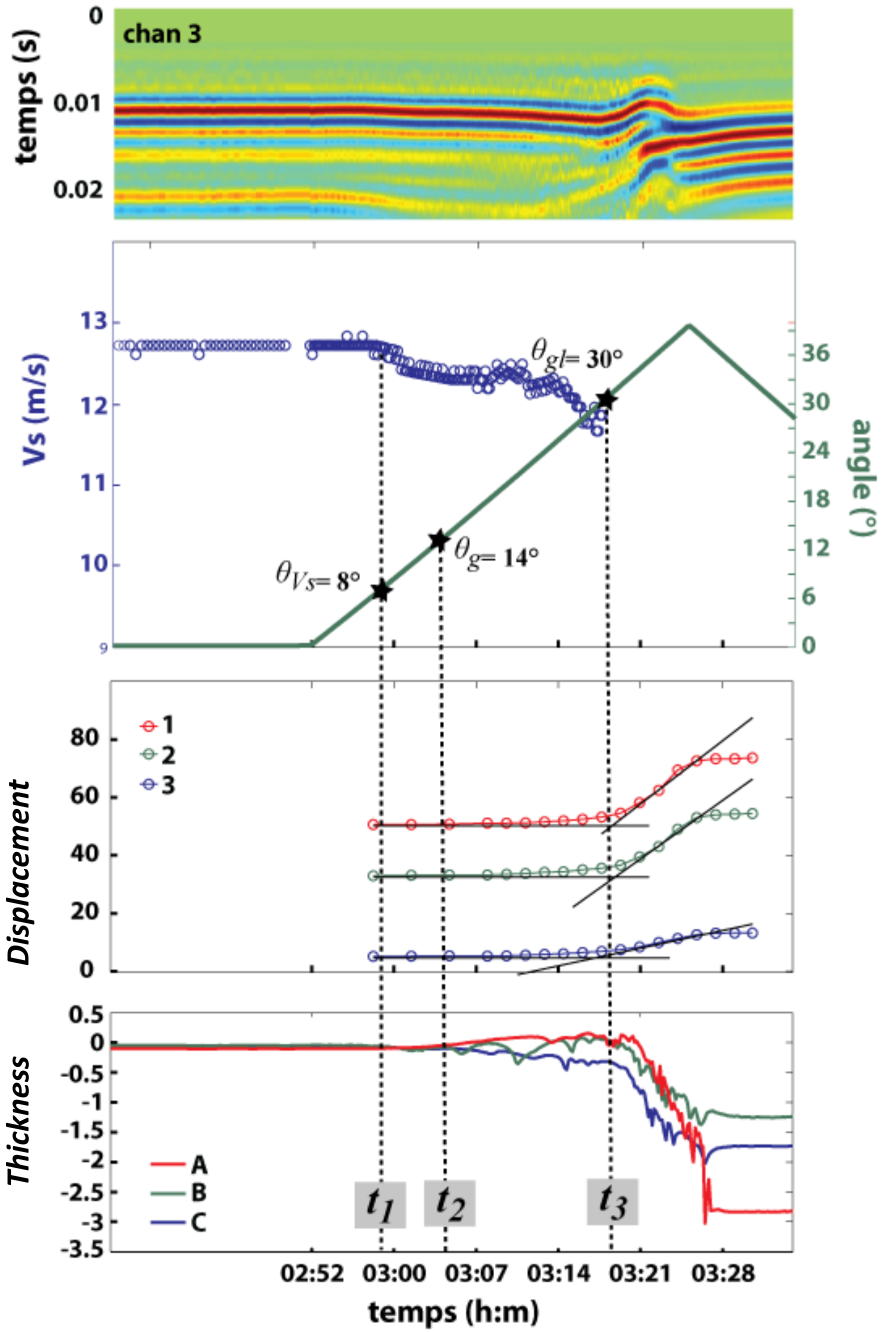


t1 : Vs decrease



t1 : Vs decrease

t2: surface change



t1 : Vs decrease

t2: surface change

t3: slope failure

t1 > t2 > t3

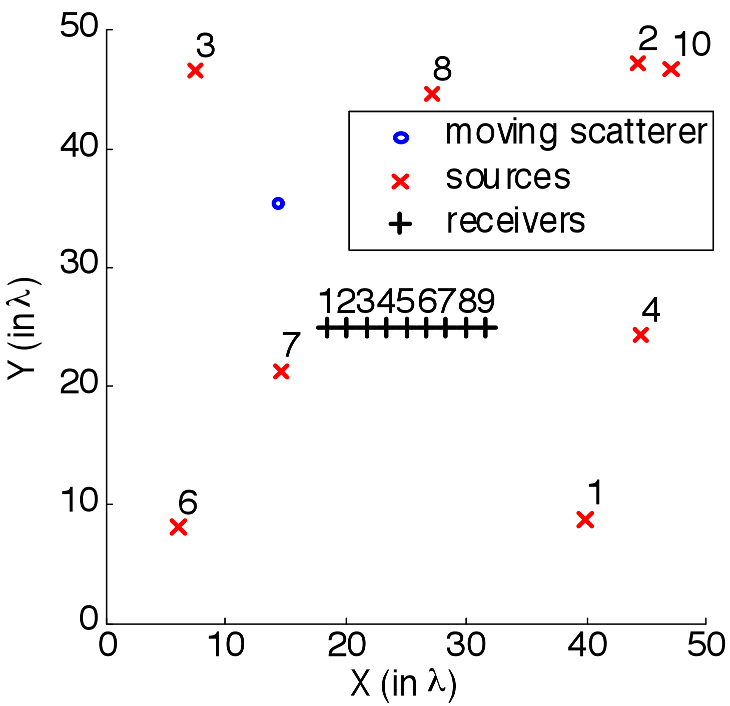
- PART 1.

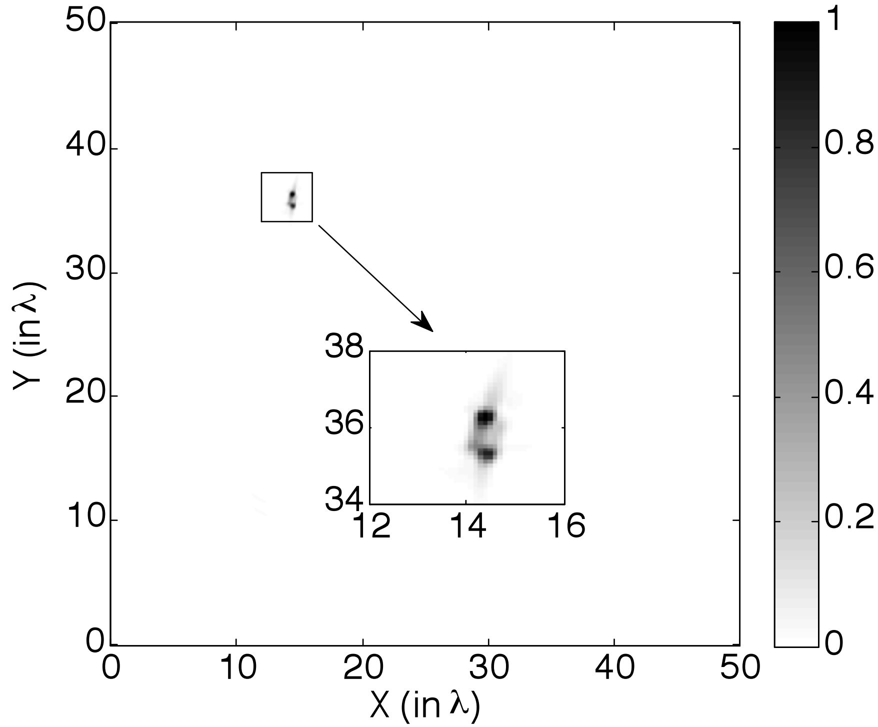
Detecting velocity dV/V change (Global)

- PART 2.

Locating changes (Local)

Single scattering ⇔ Born approx. ⇔ Conventional imaging



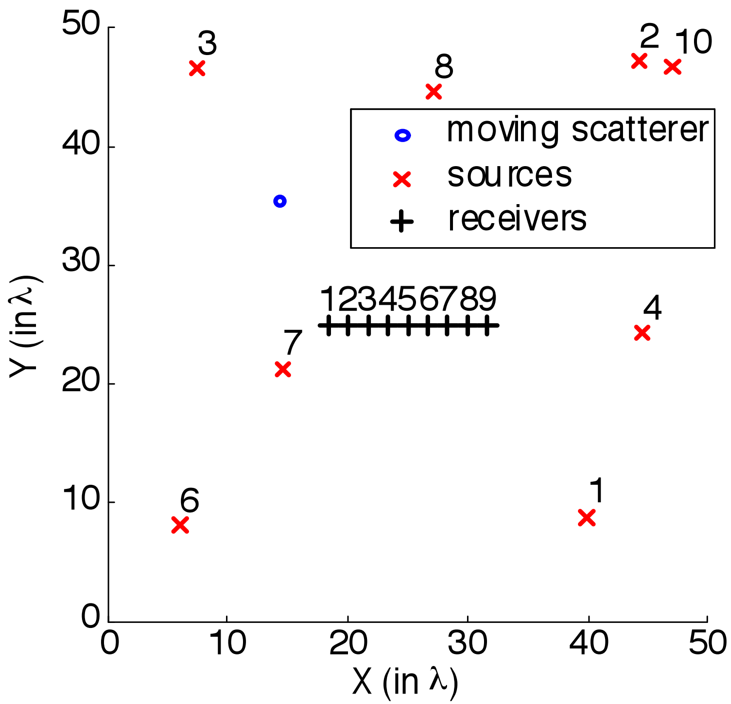


$$h_{state\ A}\ (S,R,t)$$

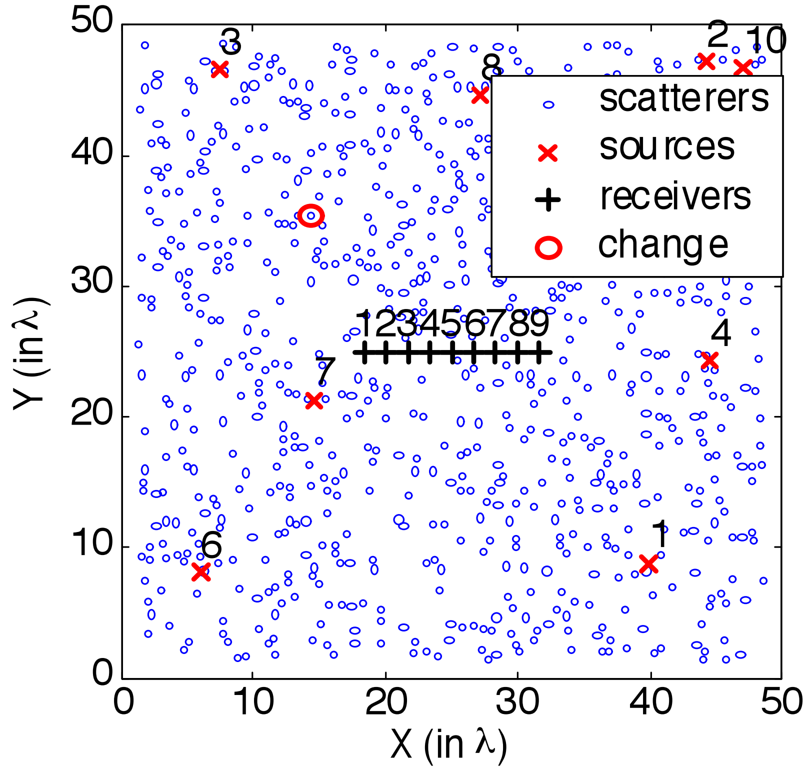
$$h_{state\ B}\ (S,R,t)$$

Image between two states (differential)

Single scattering medium:
1 changing scatterers
(ie metals)



Multiple scattering medium:
800 scatterers+ 1 change
(ie concrete)



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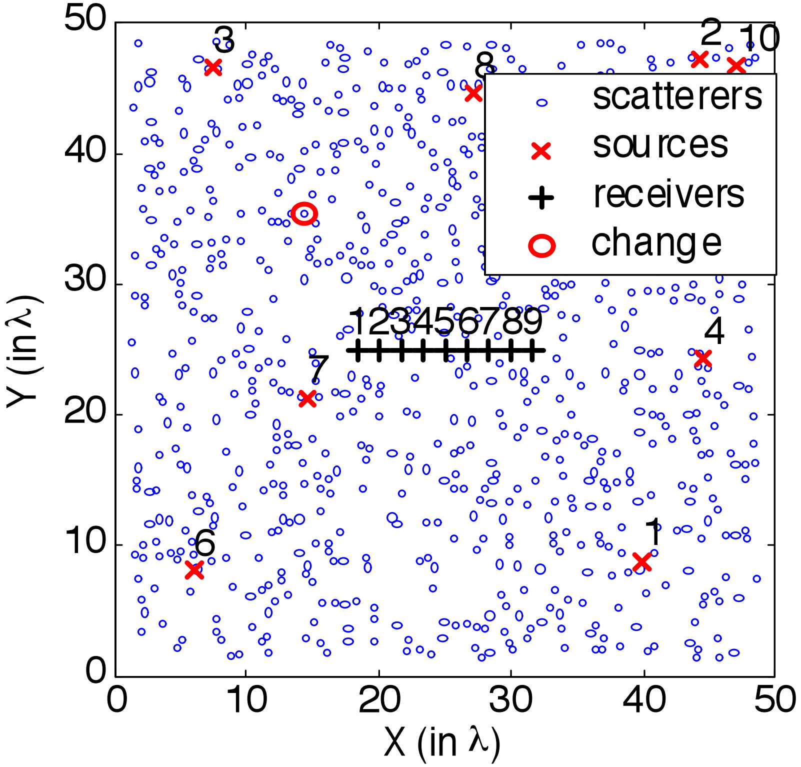
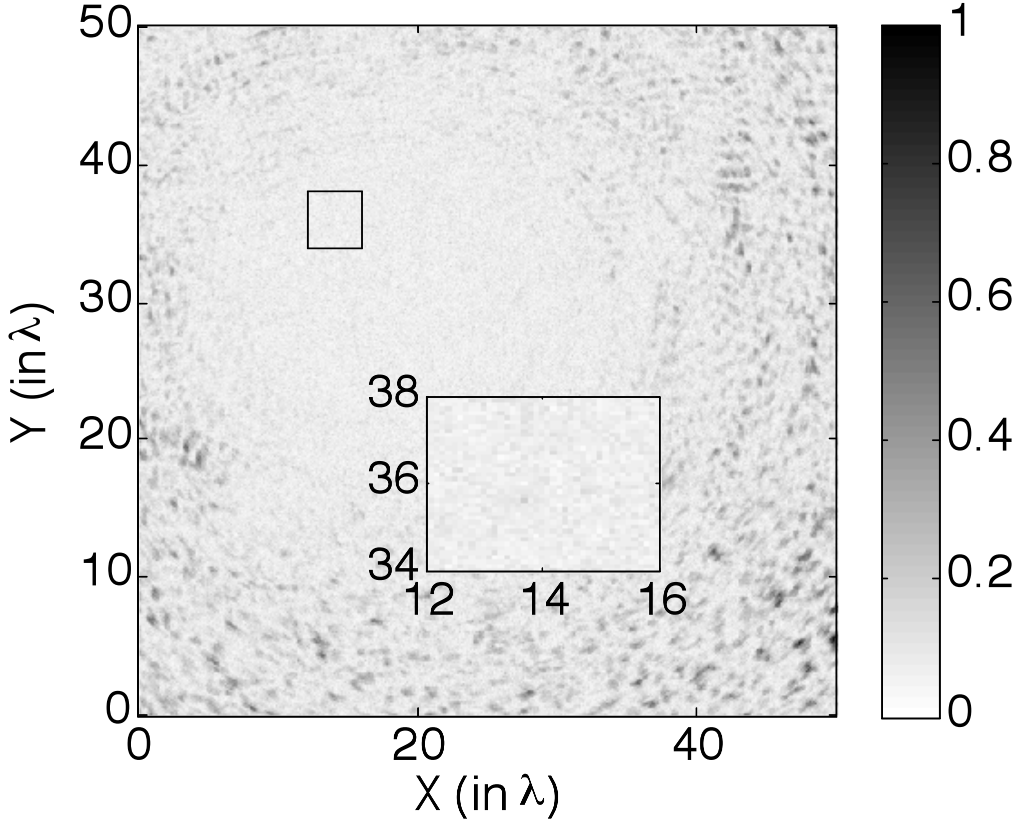
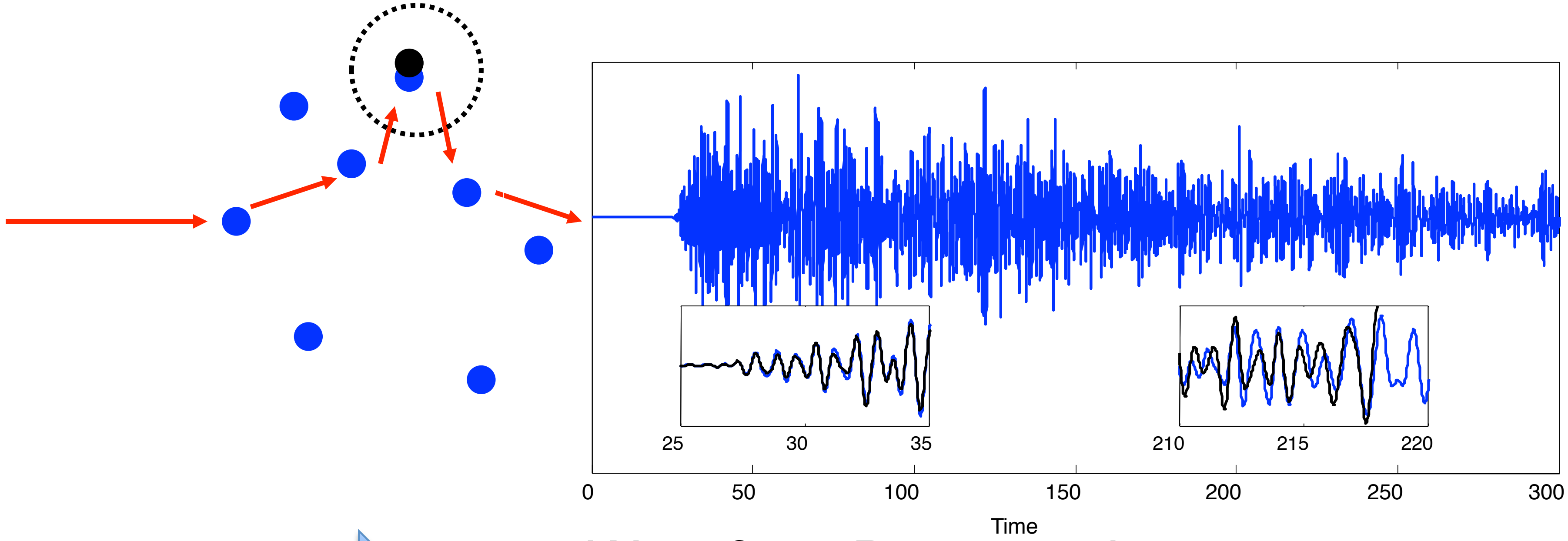




Conventional techniques…FAIL!

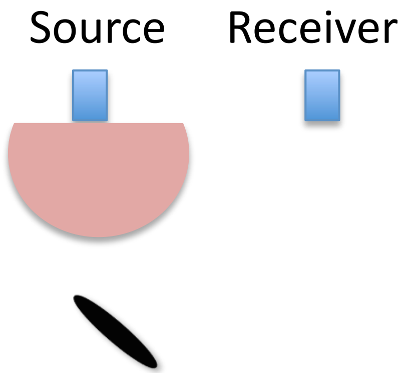
Compare the ultrasonic coda

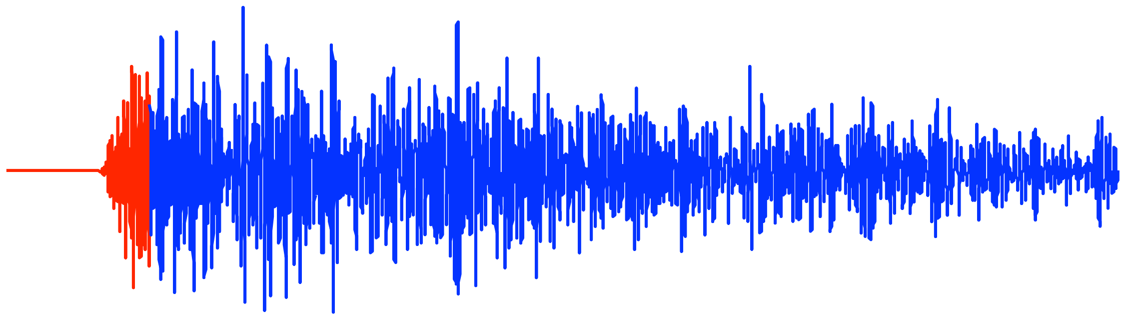


Waveform Decorrelation

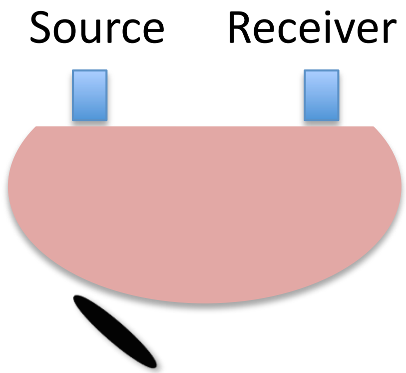
$$K^n(S,R,t) = 1 - \frac{\int \varphi_A(t)\varphi_B(t)dt}{\sqrt{\int \varphi_A{}^2(t)dt \int \varphi_B{}^2(t)dt}}$$

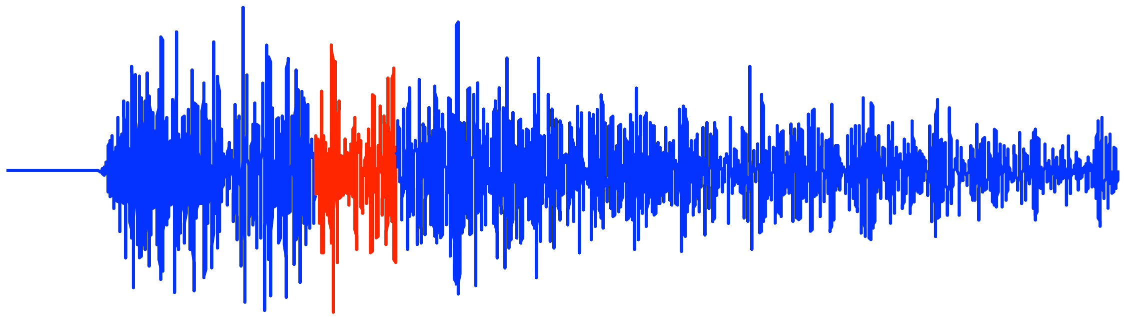
Depth sensitivity of coda waves



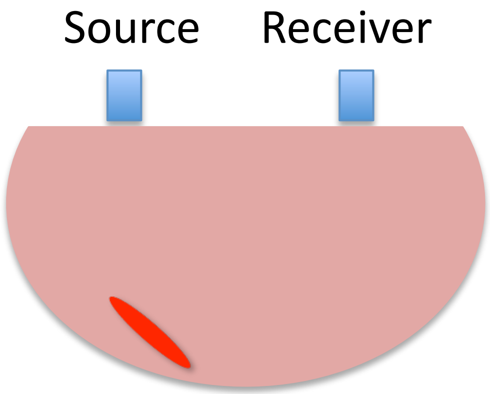


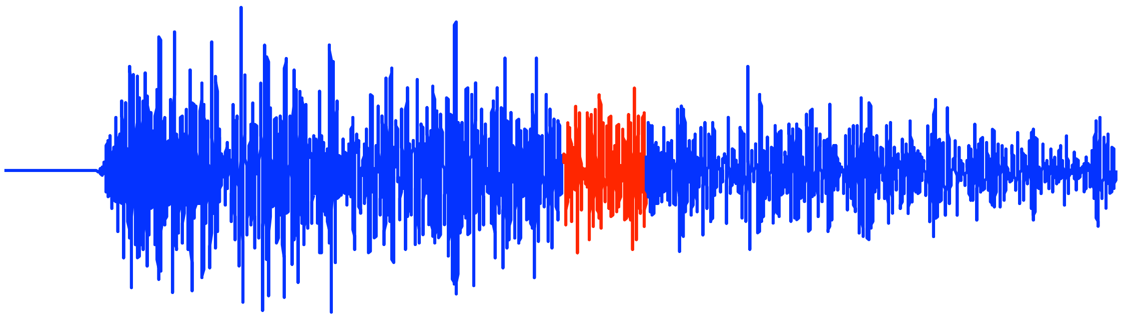
Depth sensitivity of coda waves



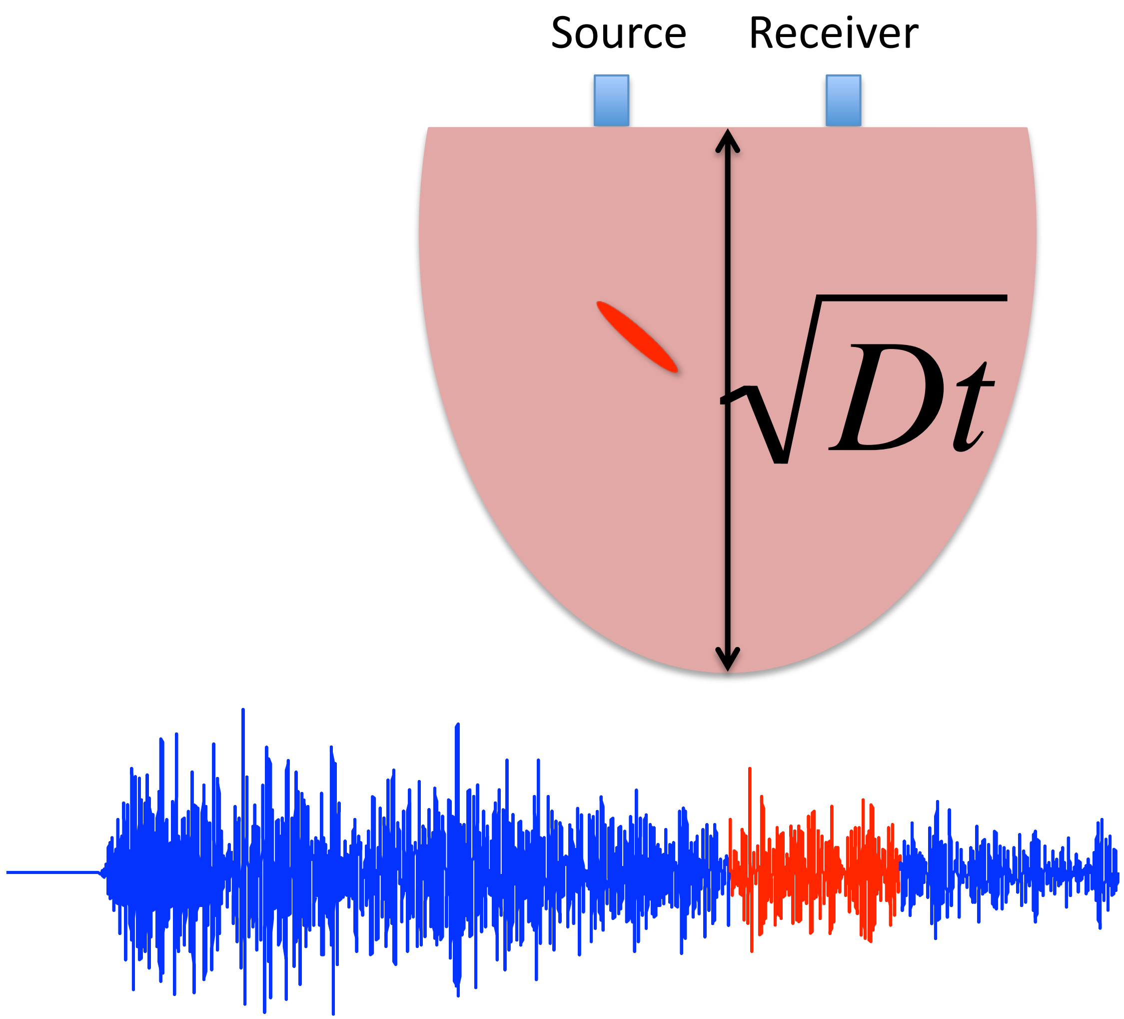


Depth sensitivity of coda waves





Depth sensitivity of coda waves



Theoretical prediction assuming:

- one isolated +local change
- diffusion constant D
- geometry of the medium

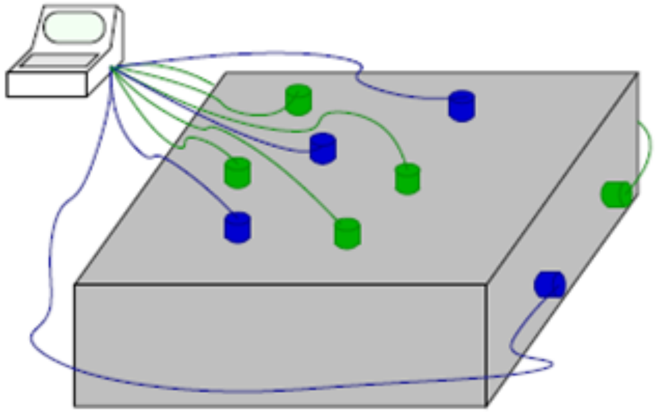
$$\left.\begin{matrix}\langle \varphi_A(S,R,t)\varphi_B(S,R,t)\rangle \\ K^d\end{matrix}\right\} = 1 - c\sigma \frac{\int g(S,x,\upsilon)g(x,R,t-\upsilon)d\upsilon}{g(S,R,t)}$$

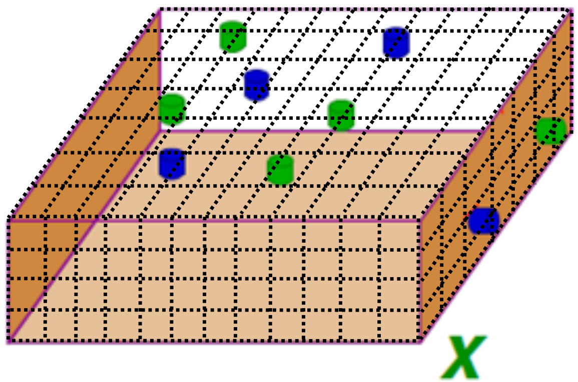
φ : Waveform (phase & amplitude)

g : transfert function ⇔ transport probability ⇔ average intensity

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 :

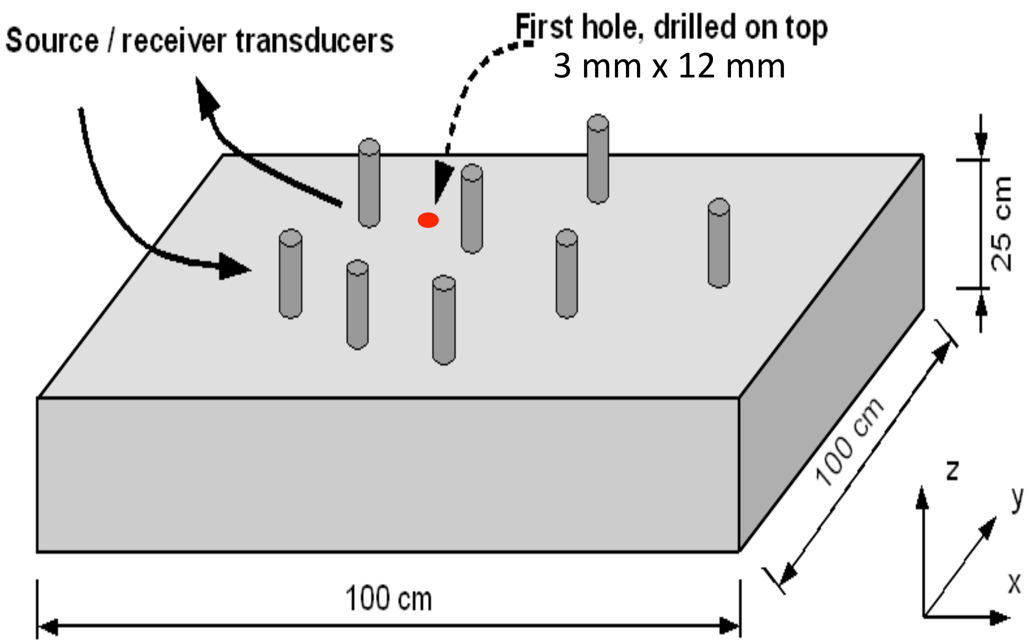
For each voxel x :

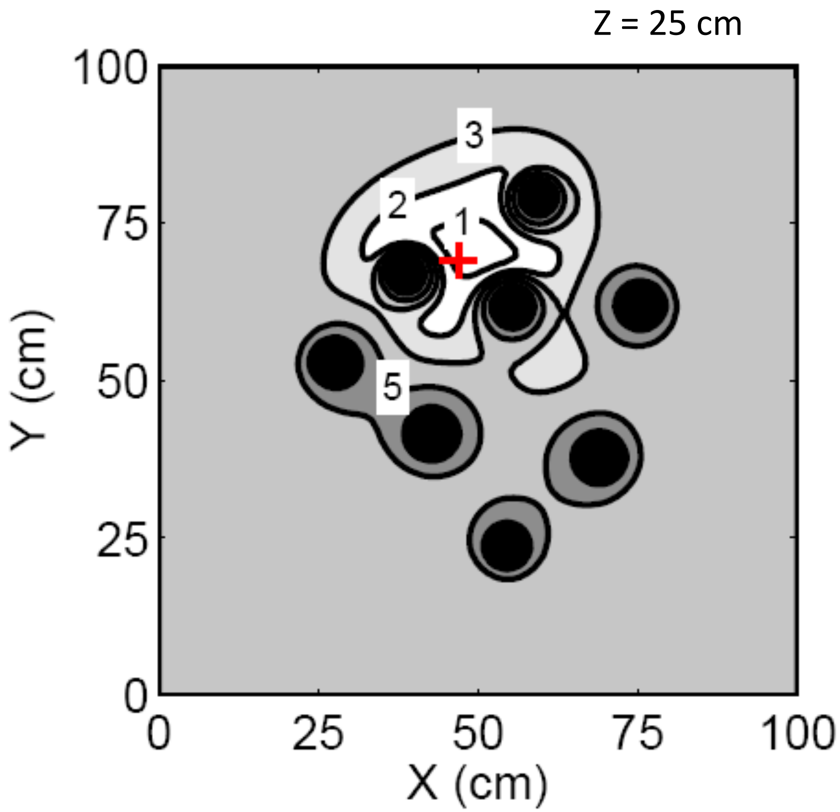
$\Rightarrow Q_{ij}^{th}(S_i, R_j, x, t)$

Theoretical decorrelation

(x, σ) that minimizes the misfit ?

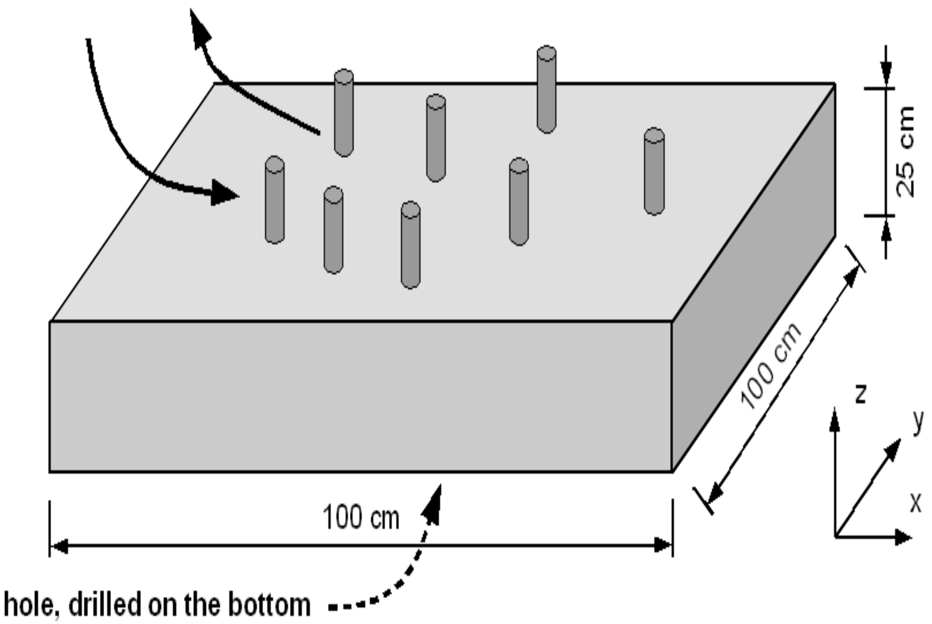
Application to concrete



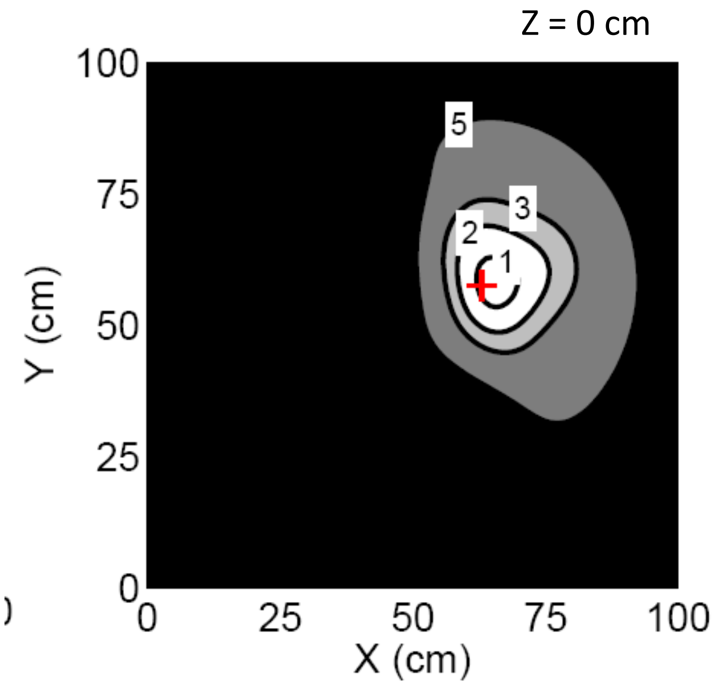


$$\chi^2(\mathbf{x}) = \sum_{i,j} \left(K_{ij}^d(t) - K_{ij}^n(\mathbf{x},t)\right)^2 / \epsilon^2$$

Application to concrete



10 mm x 10 mm

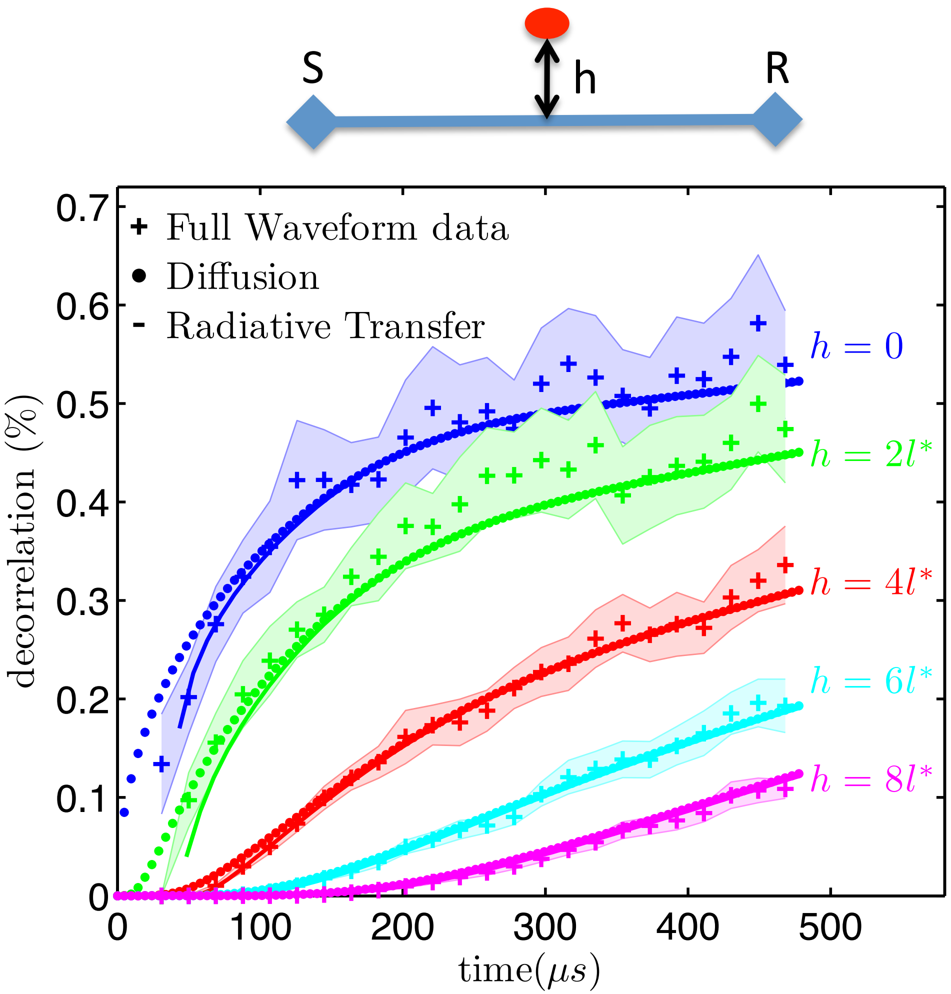


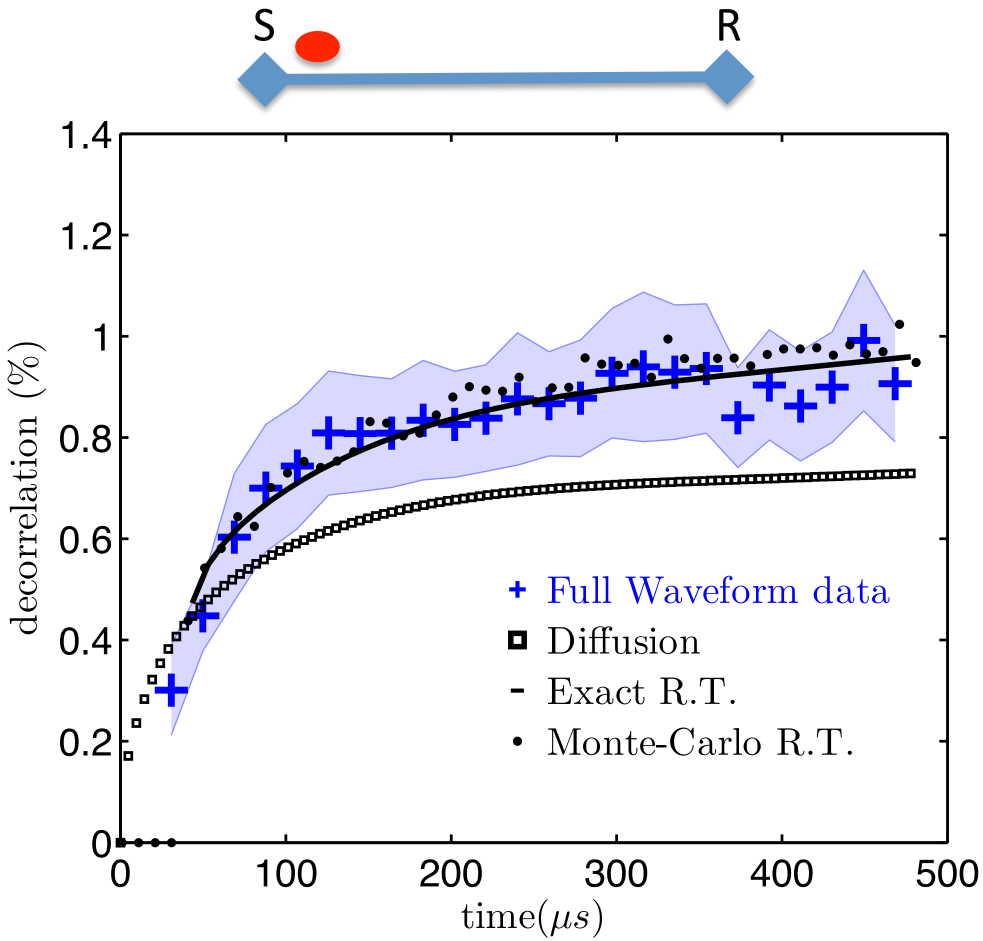
$$\chi^2(\mathbf{x}) = \sum_{i,j} \left(K^d_{ij}(t) - K^n_{ij}(\mathbf{x}, t) \right)^2 / \epsilon^2$$

Larose *et al*, Appl. Phys. Lett. (2010)
Rossetto *et al*, J. Appl. Phys. (2011)

T. Planès (PhD stud.)

Transfert function (intensity)





T. Planes (PhD 2013)
Planes et al (2013)

Inversion process

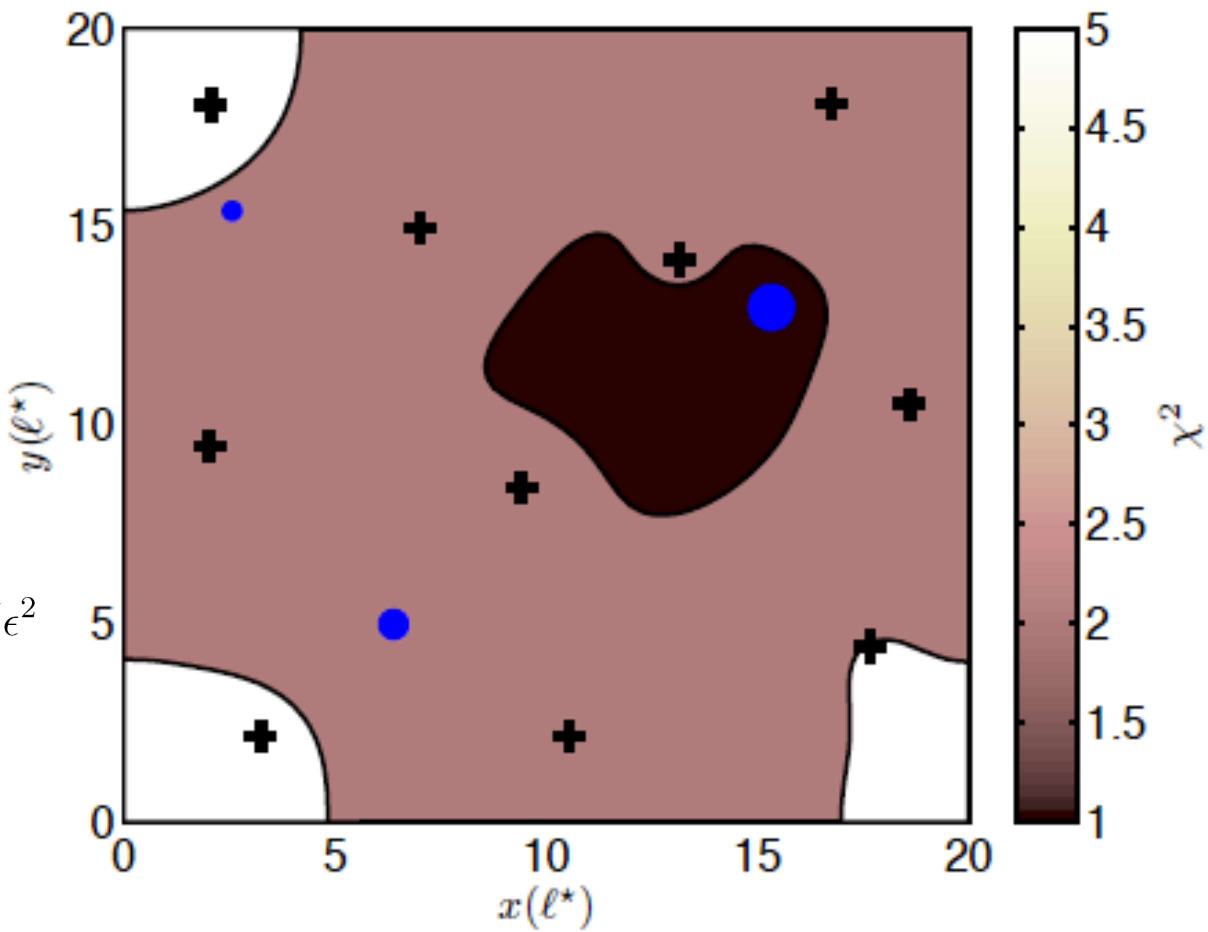
2D Acoustic Finite-Difference Simulation

Sensors

New defects :

$$\text{Radius} = \frac{\lambda}{5}; \frac{\lambda}{3}; \frac{\lambda}{2};$$

$$\chi^2(\mathbf{x}) = \sum_{i,j} \left(K_{ij}^d(t) - K_{ij}^n(\mathbf{x}, t) \right)^2 / \epsilon^2$$



T. Planes (PhD 2013)
Planes et al (2013)

Inversion process

2D Acoustic Finite-Difference Simulation

✚ Sensors

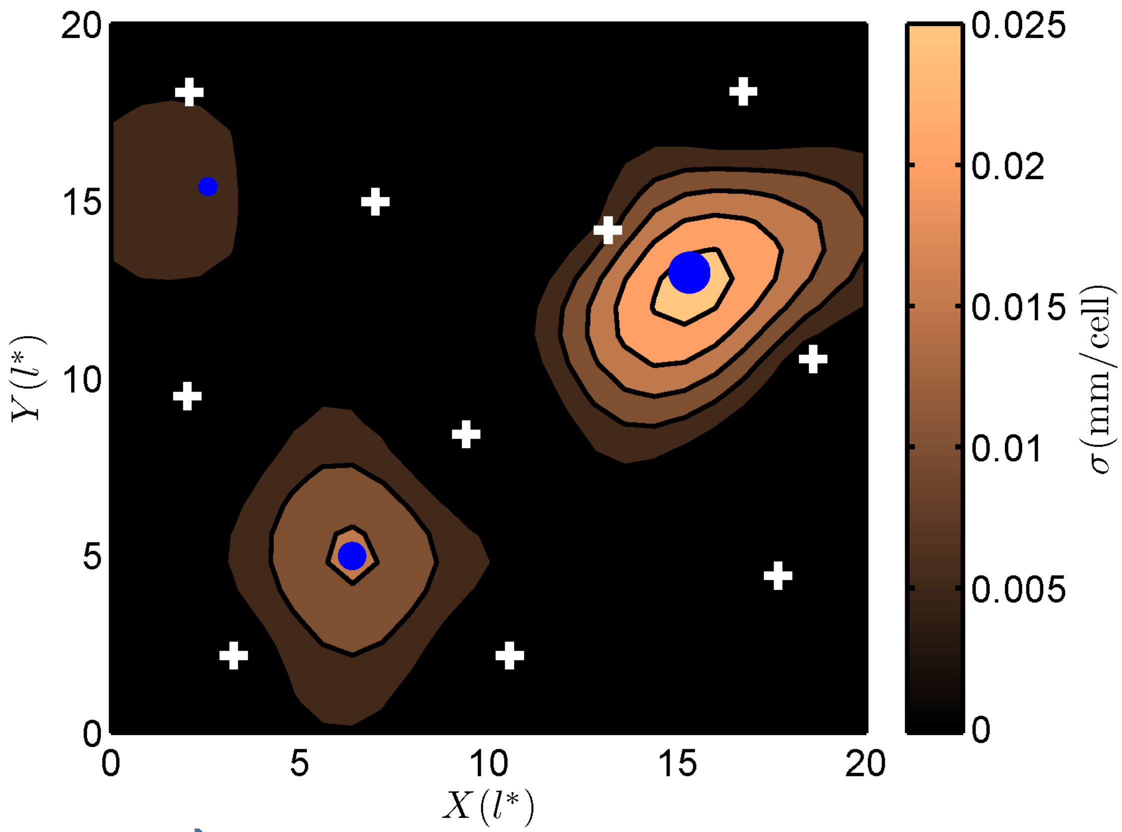
● New defects :

$$\mathrm{Radius} = \frac{\lambda}{5}; \frac{\lambda}{3}; \frac{\lambda}{2};$$

Linear forward problem :

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

Least square inversion
[Tarantola 2005] :



➡ $\tilde{\boldsymbol{\sigma}}$ Estimated cross section map

T. Planes (PhD 2013)
Planes et al (2013)

To be continued…. See Brenguier's presentation!