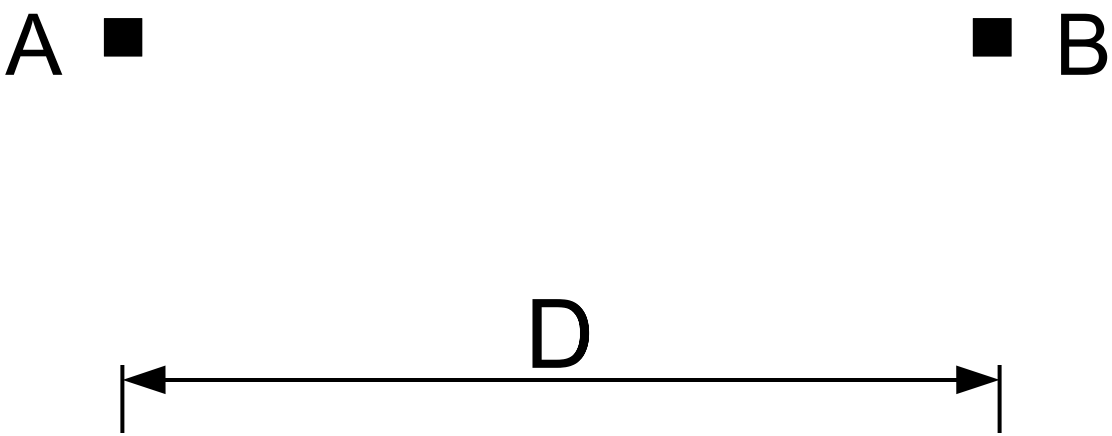
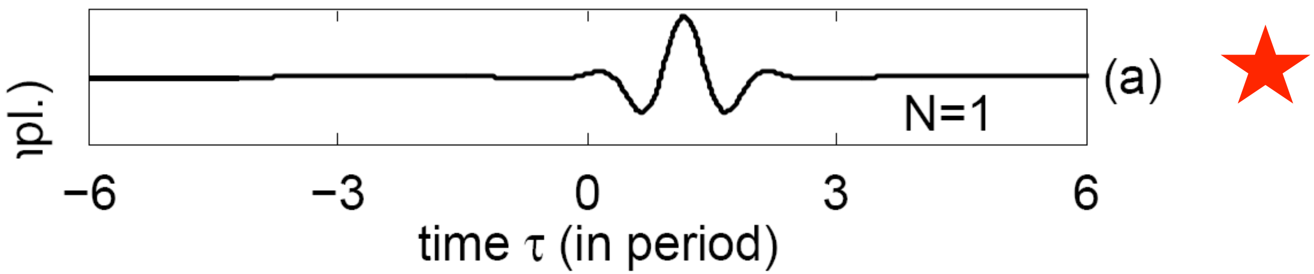
Ambient noise Cross-Correlations : convergence rate & monitoring…

Eric LAROSE
ISTerre – Grenoble
CNRS & Université J. Fourier

1. Convergence rate
2. Coda Wave Interferometry
3. Coda Wave Decorrelation


A
B
D

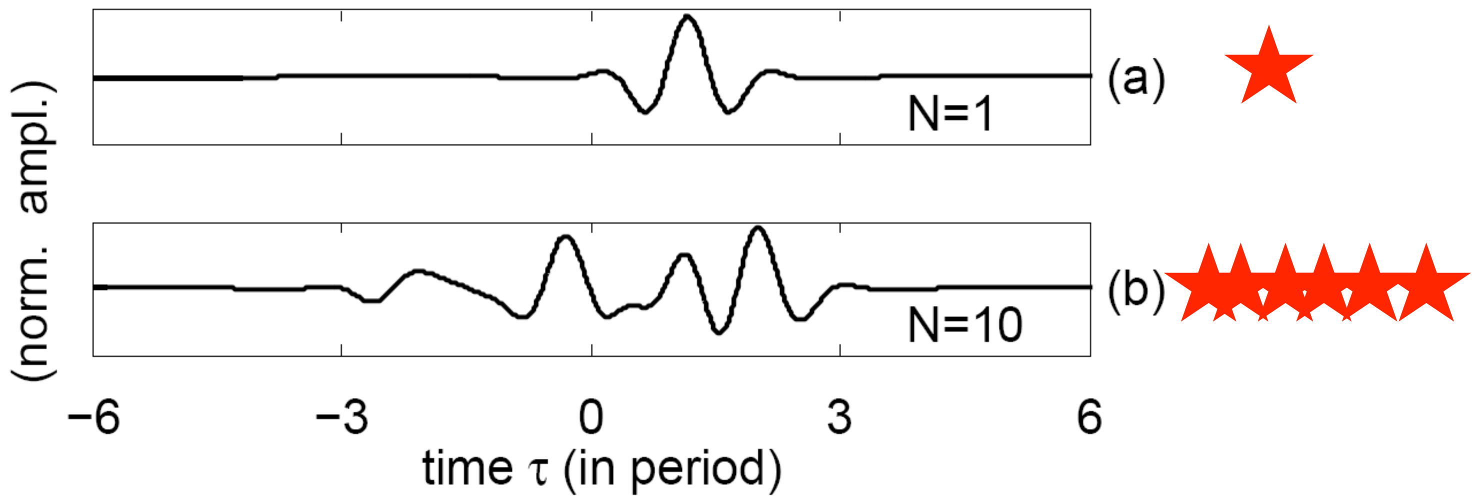
Convergence toward the Green function



D= 3 λ

Larose *et al*, J. Appl. Phys (2008)

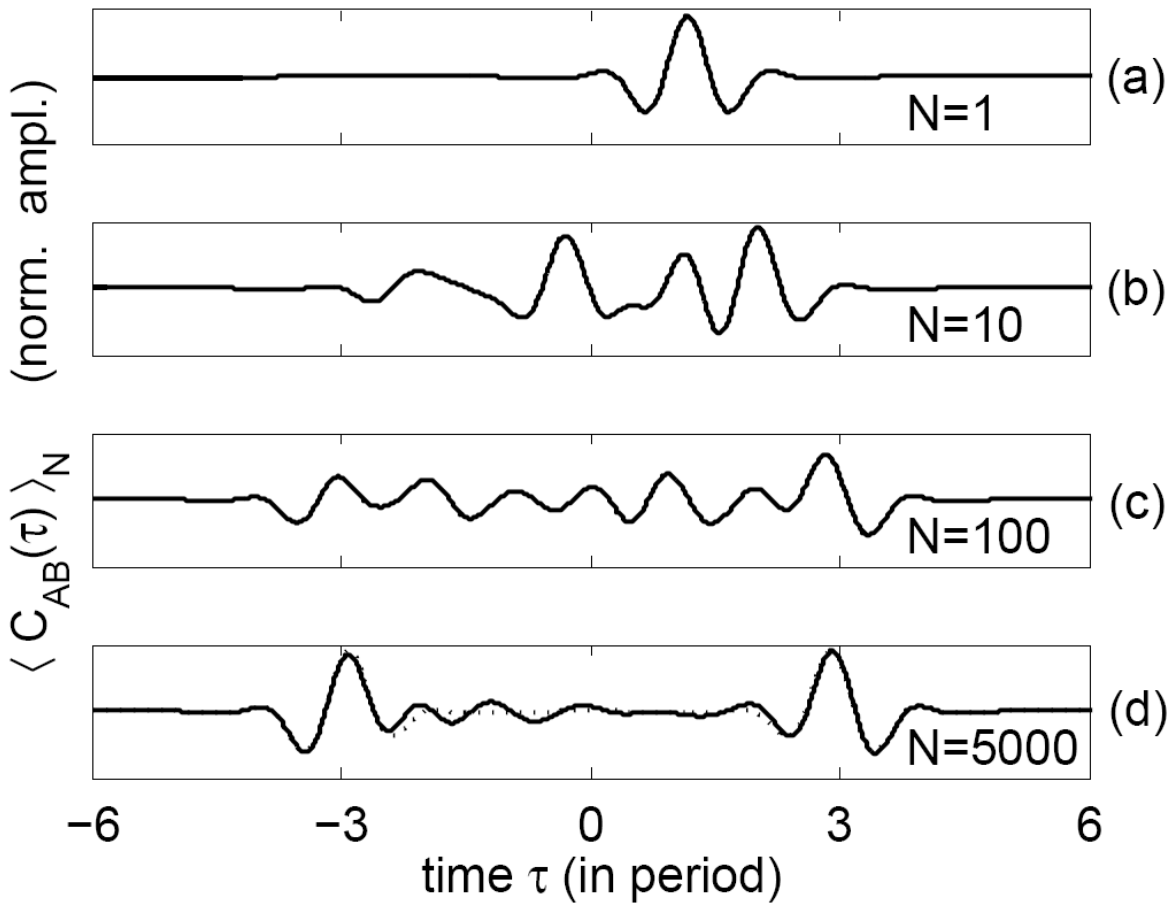
Convergence toward the Green function



D= 3 λ

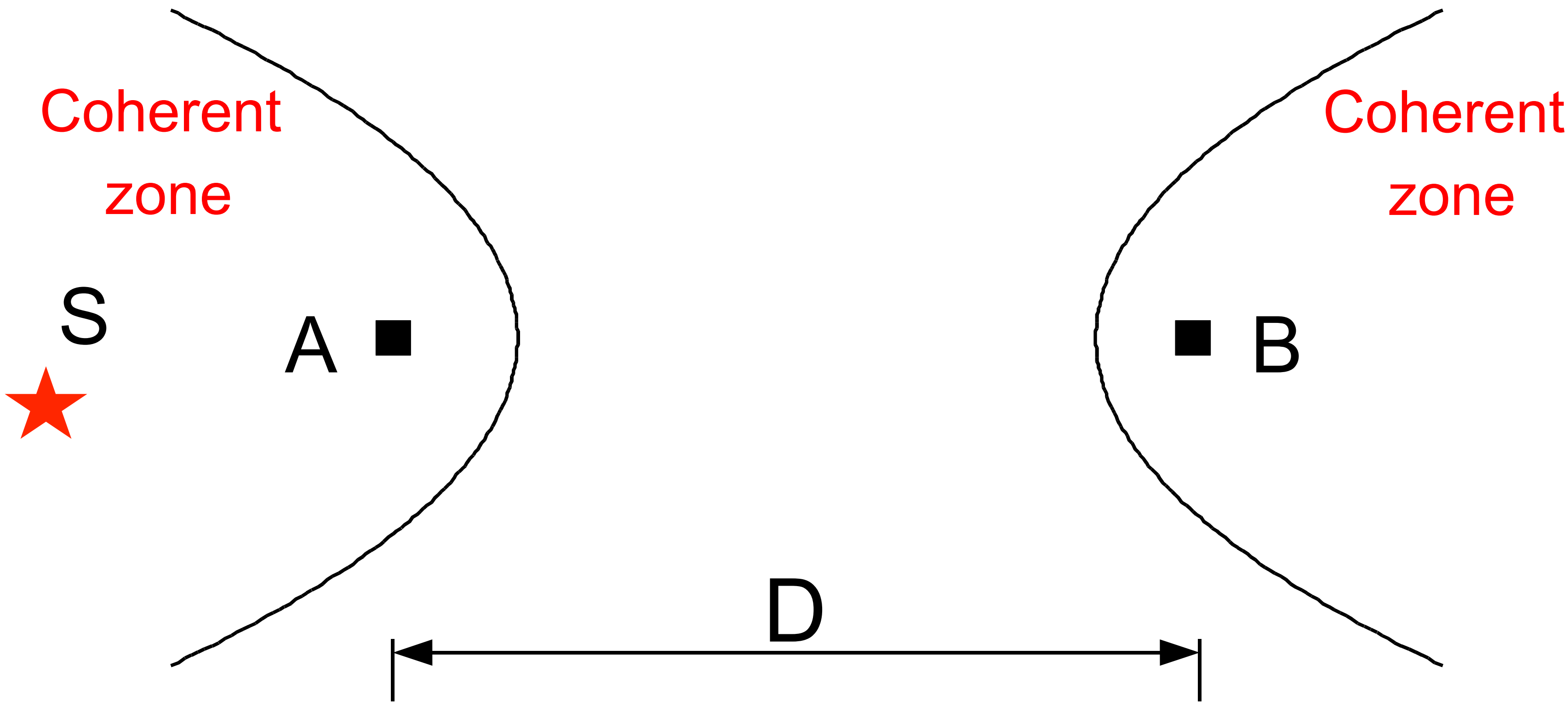
Larose *et al*, J. Appl. Phys (2008)

Convergence toward the Green function



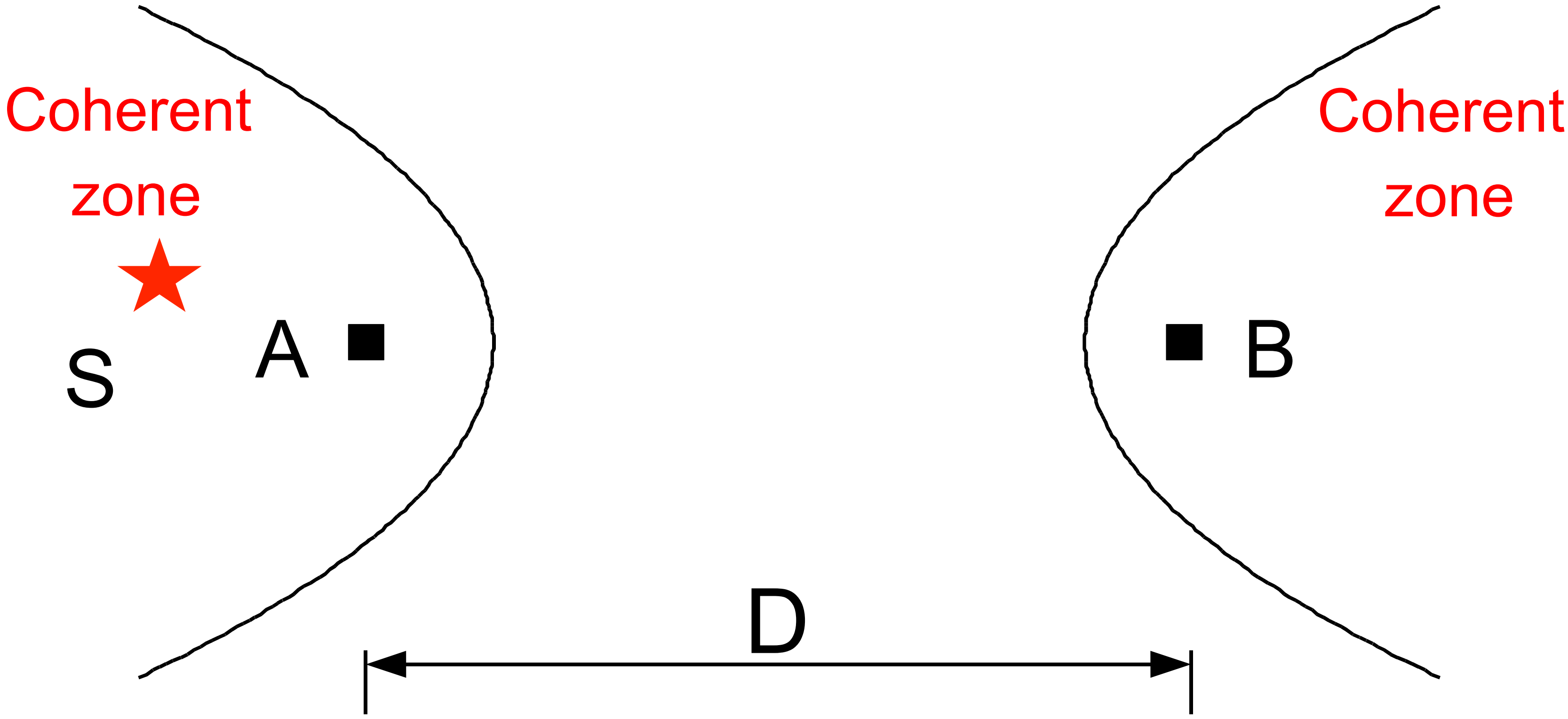
D= 3 λ

Larose *et al*, J. Appl. Phys (2008)



$\Sigma \sim N$

Roux *et al*, J. Acoust. Soc. Am. (2004)
Snieder, Phys. Rev. E (2004)
Larose, Ann. Phys. Fr (2006)



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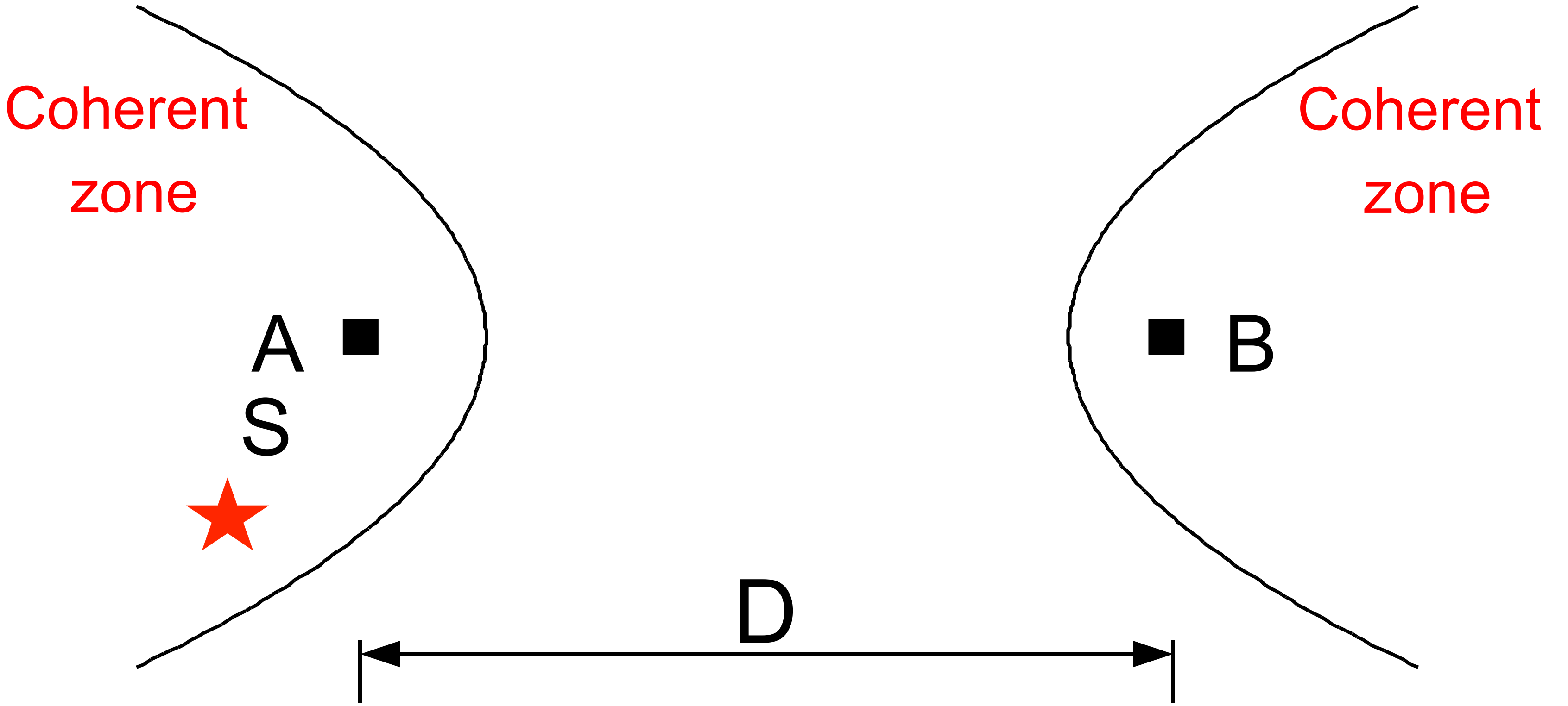

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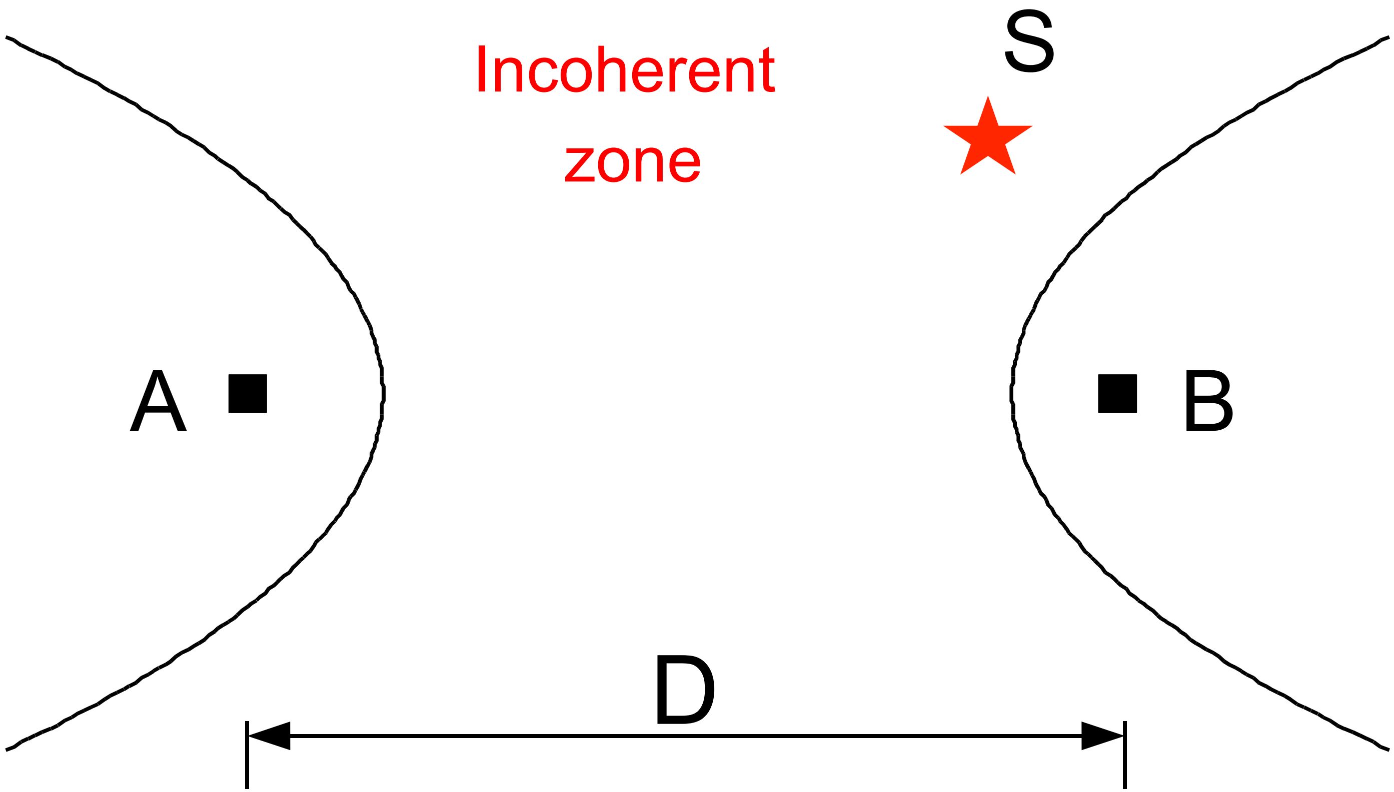
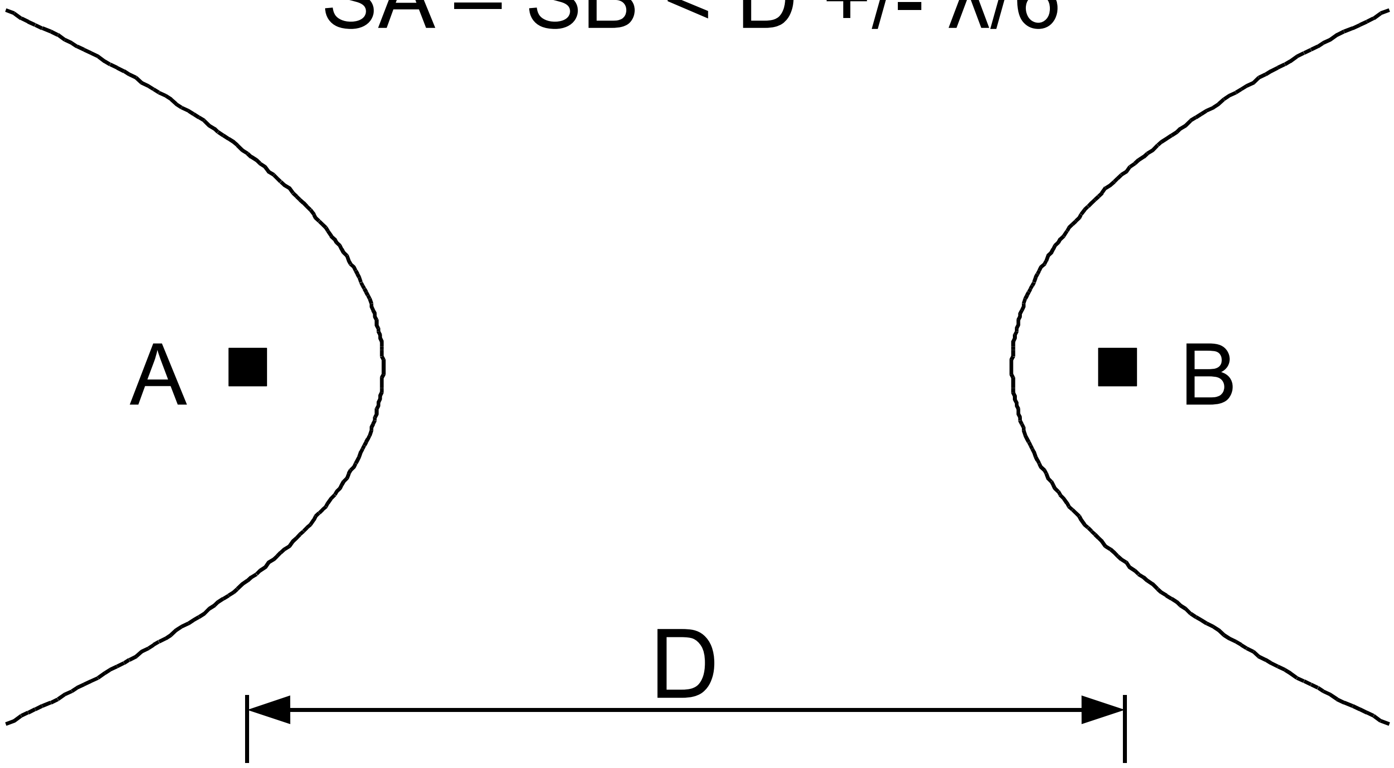


$\Sigma \sim \sqrt{N}$

Roux *et al*, J. Acoust. Soc. Am. (2004)
Snieder, Phys. Rev. E (2004)
Larose, Ann. Phys. Fr (2006)

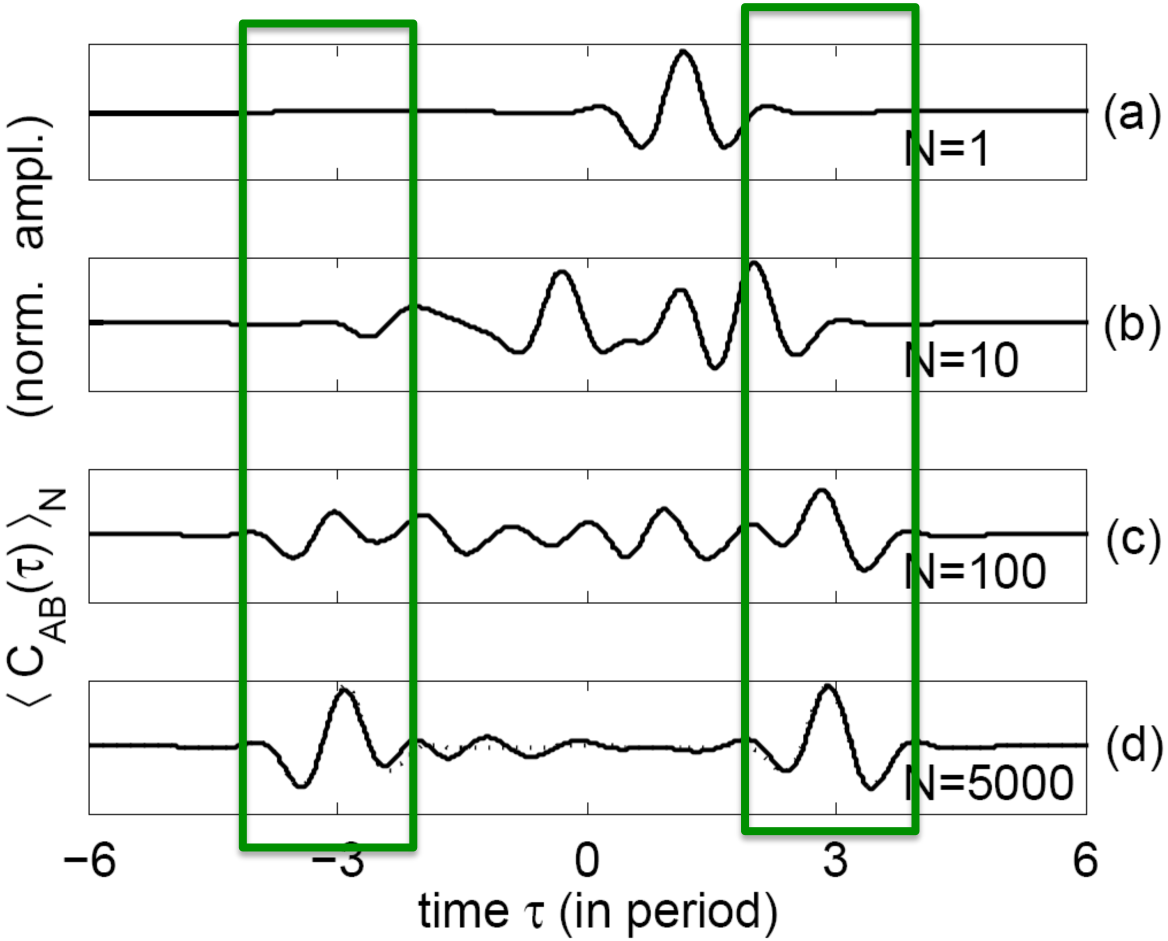
Condition of coherence:

SA – SB < D +/- λ/6



Larose, Ann. Phys. Fr (2006)

Definition of coherent zone and SNR

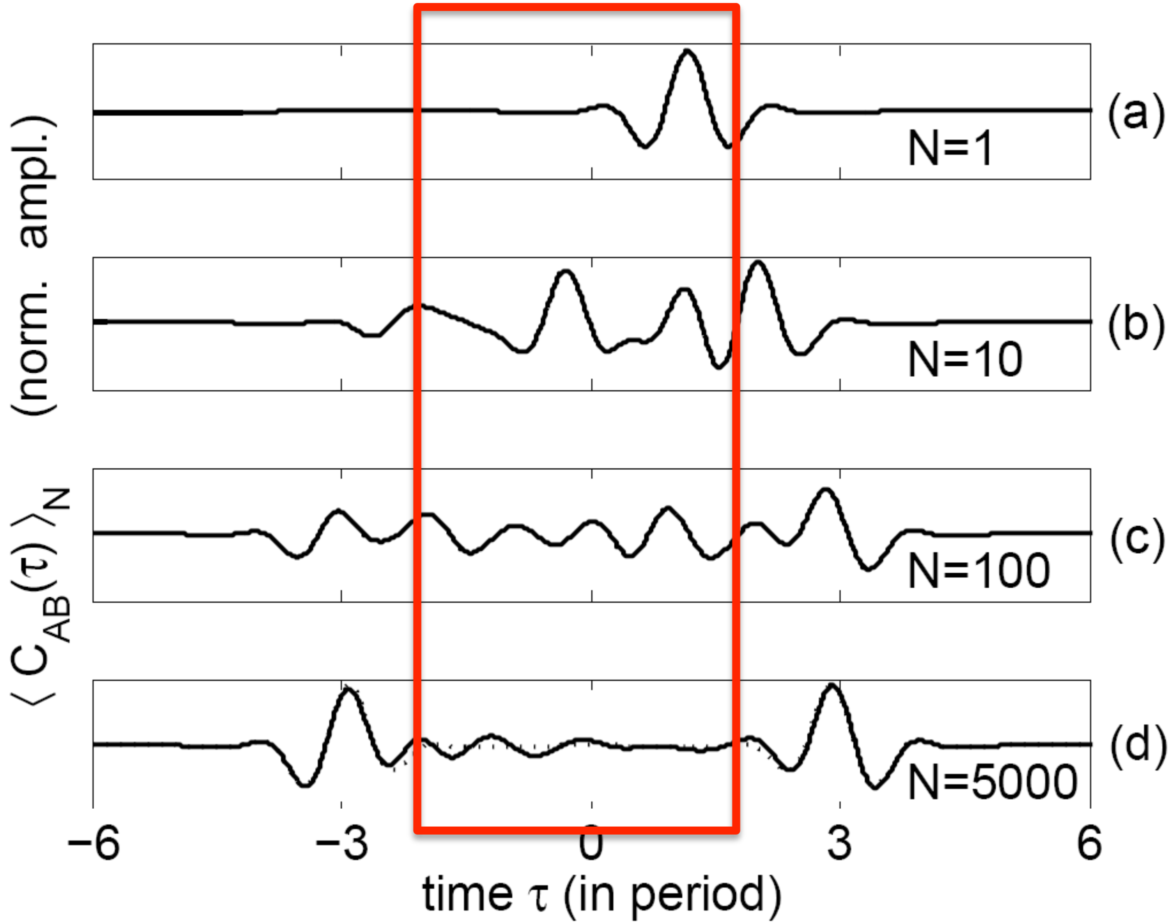


D= 3 λ

Amplitude of the signal

Larose *et al*, J. Appl. Phys (2008)

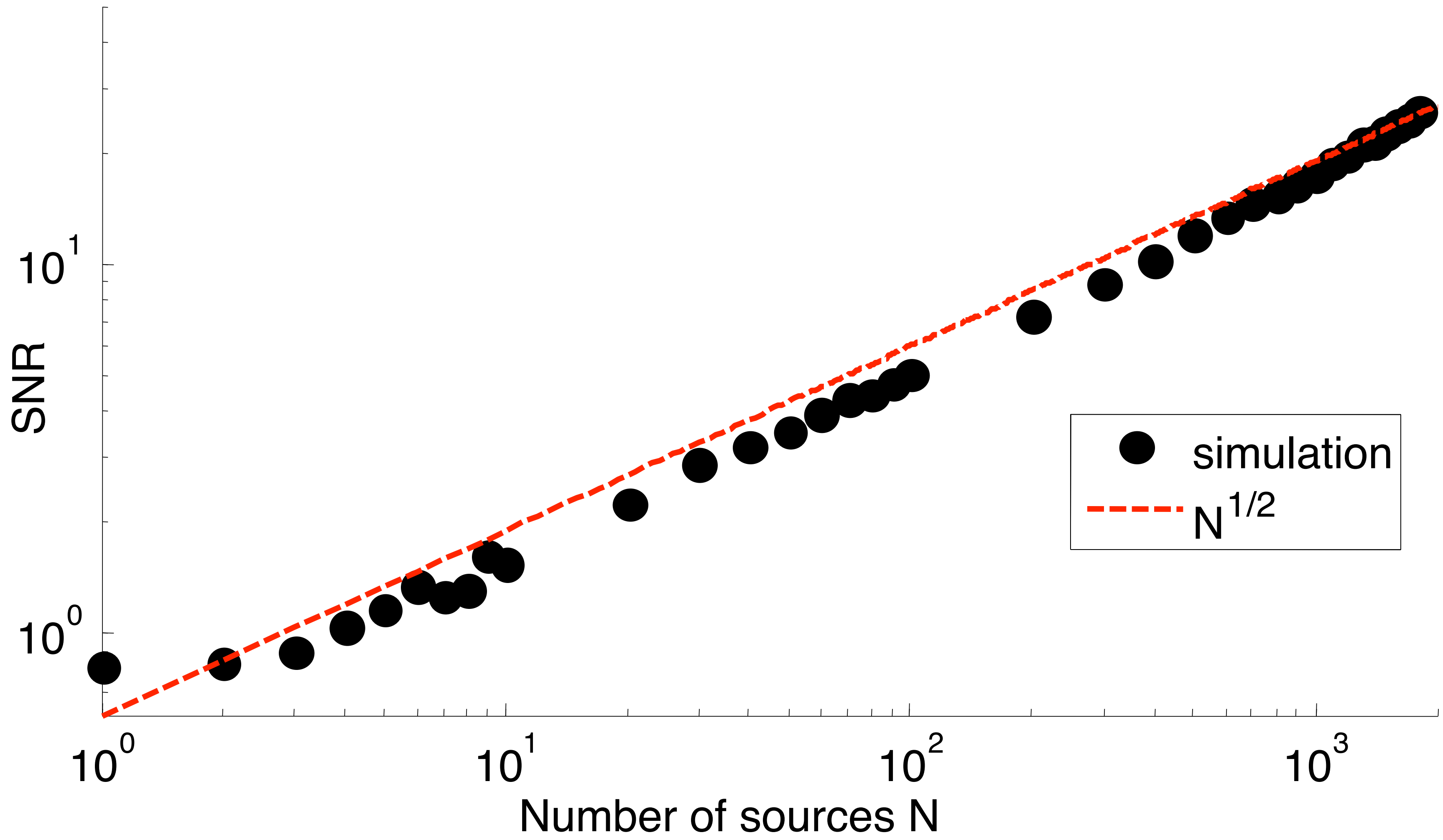
Definition of coherent zone and SNR



D= 3 λ

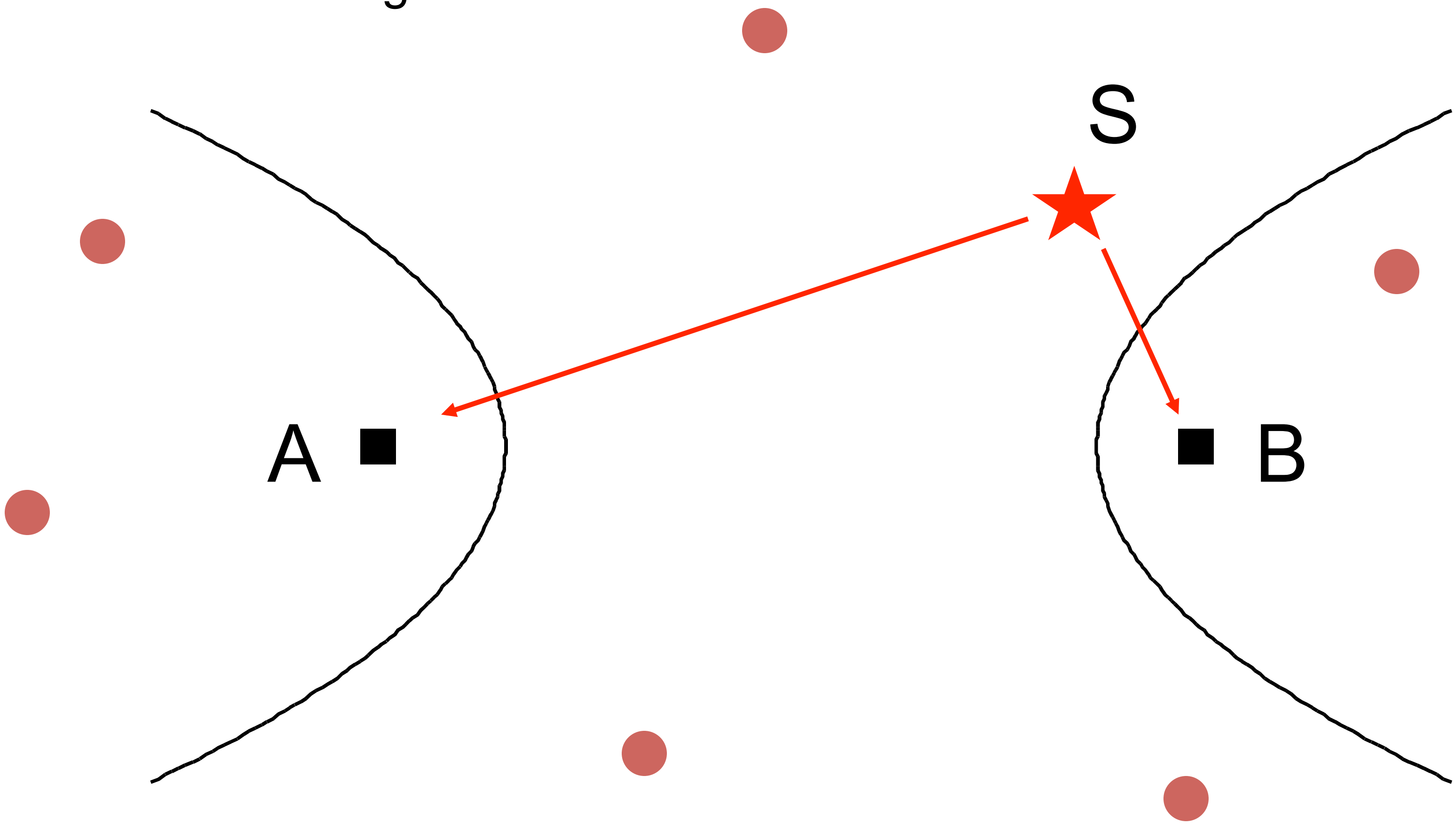
Amplitude of the noise

Larose *et al*, J. Appl. Phys (2008)



Larose *et al*, J. Appl. Phys (2008)

Role of scattering ?



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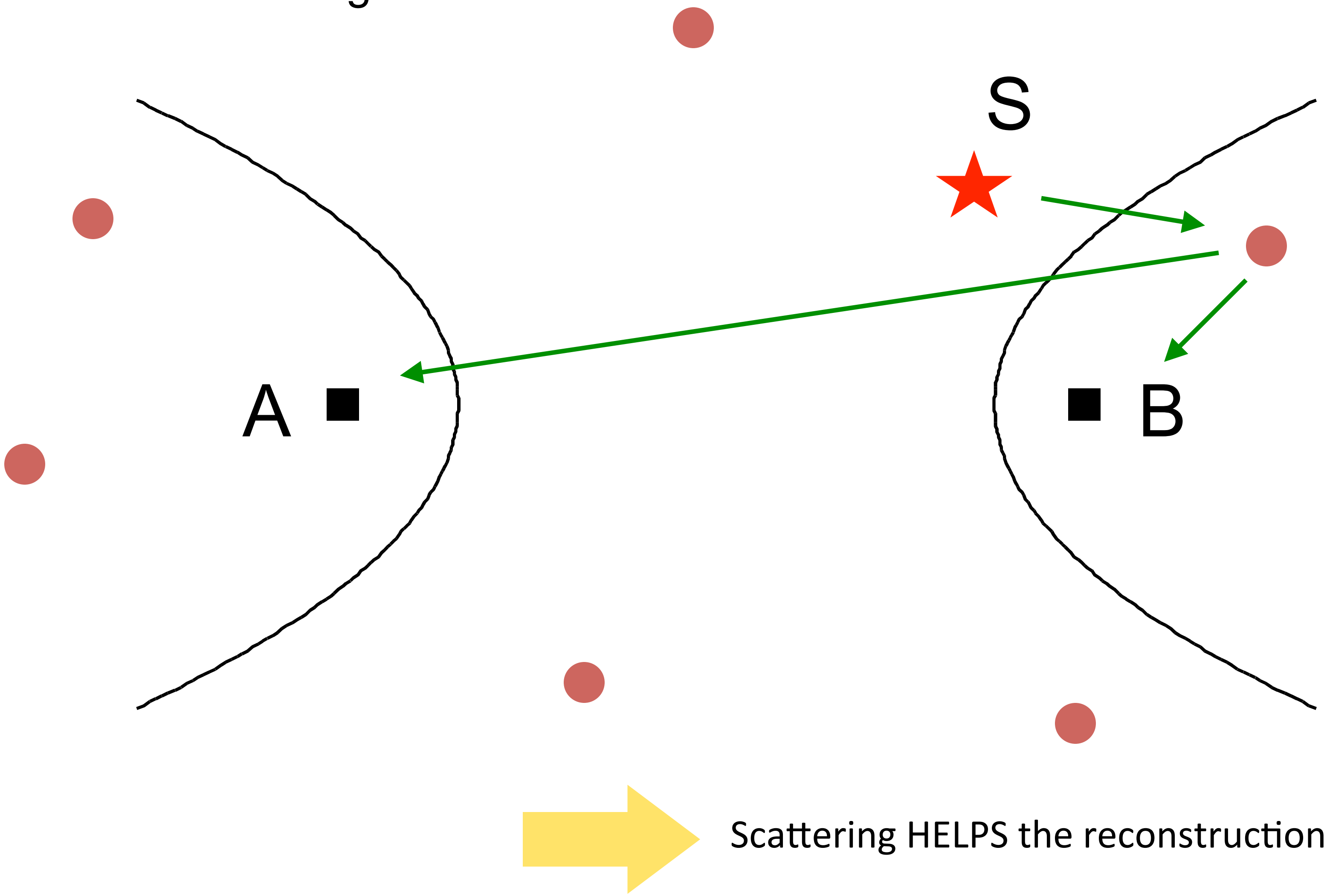
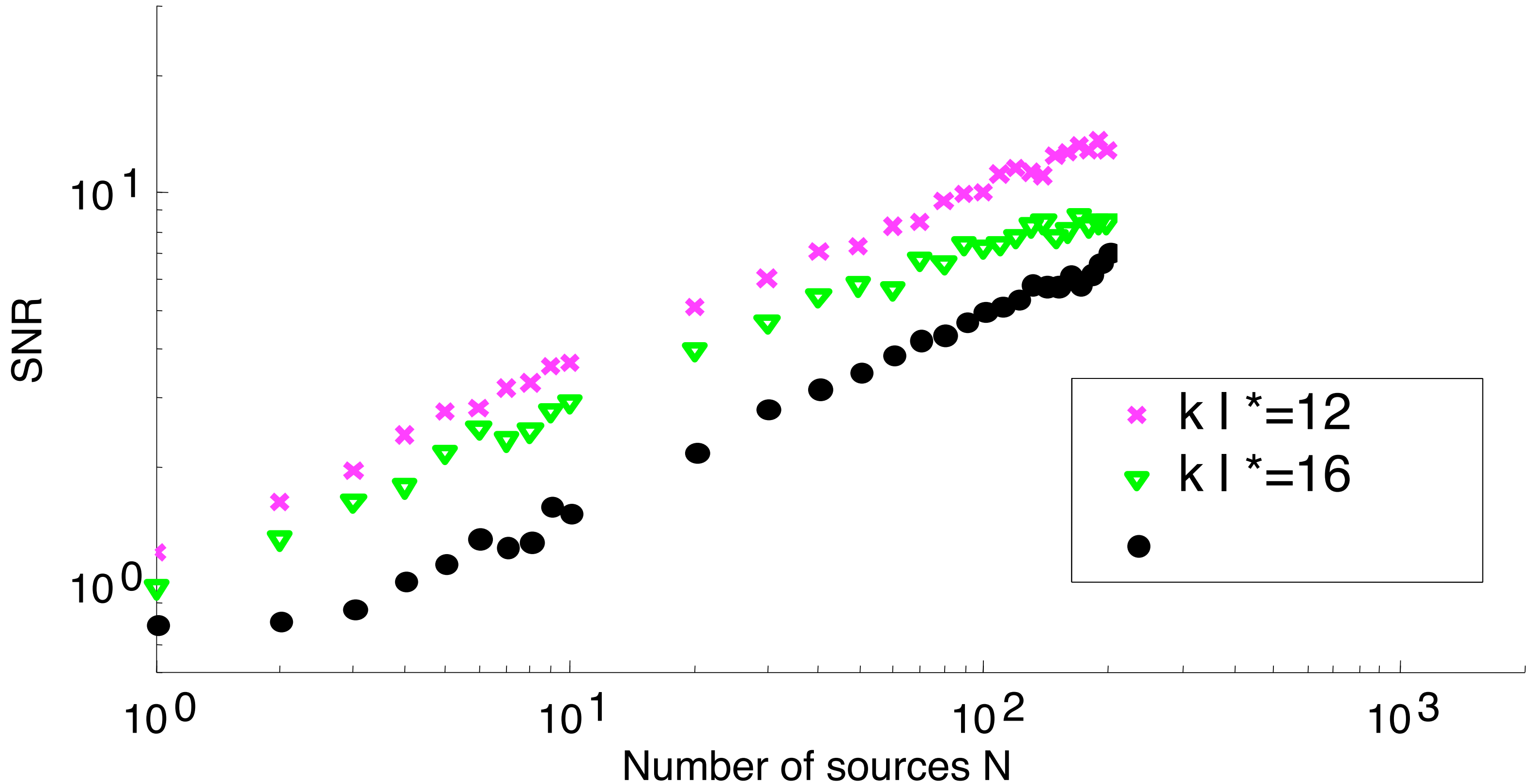


Scattering HELPS the reconstruction

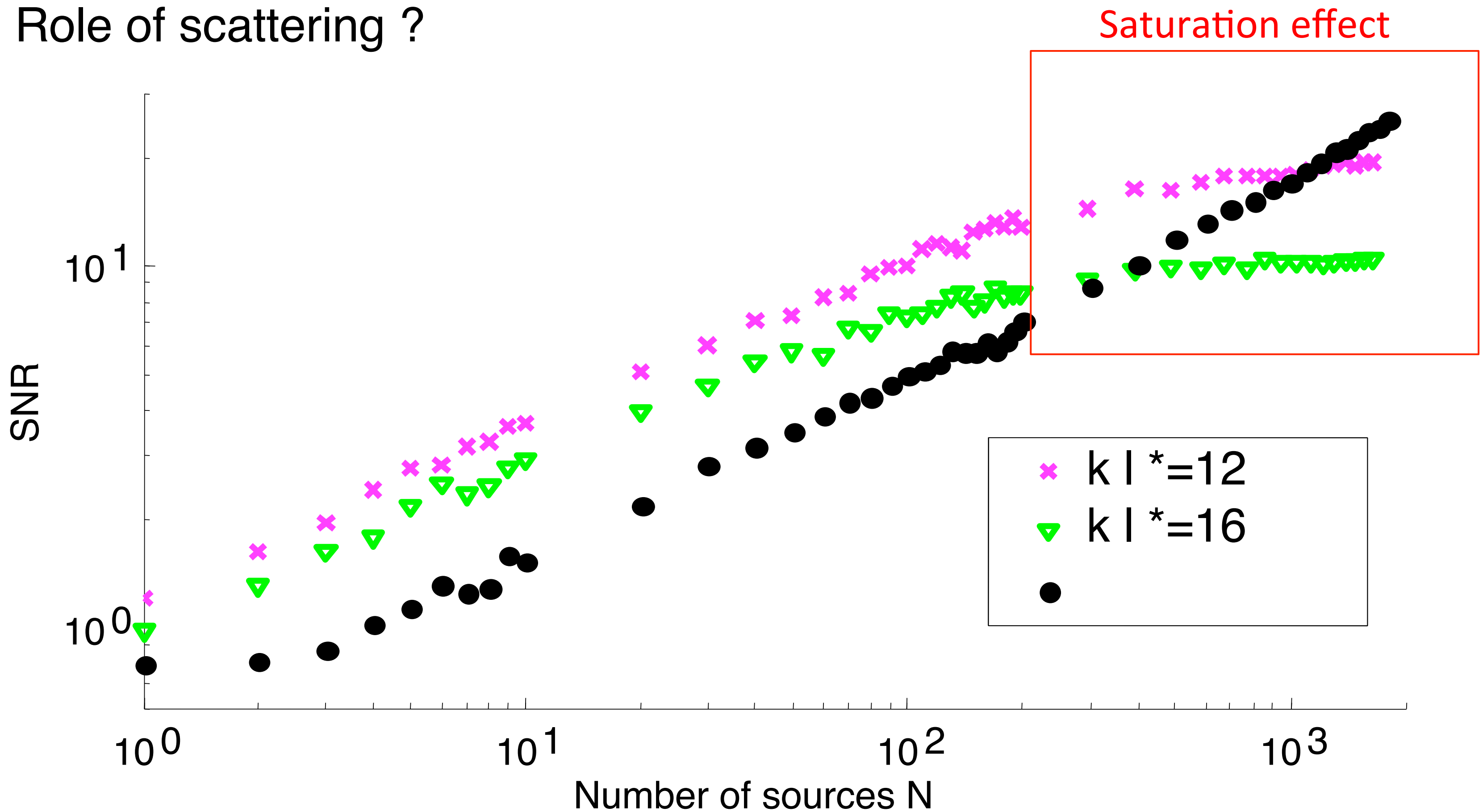
Role of scattering ?



Scattering HELPS the reconstruction

Larose *et al*, J. Appl. Phys (2008)

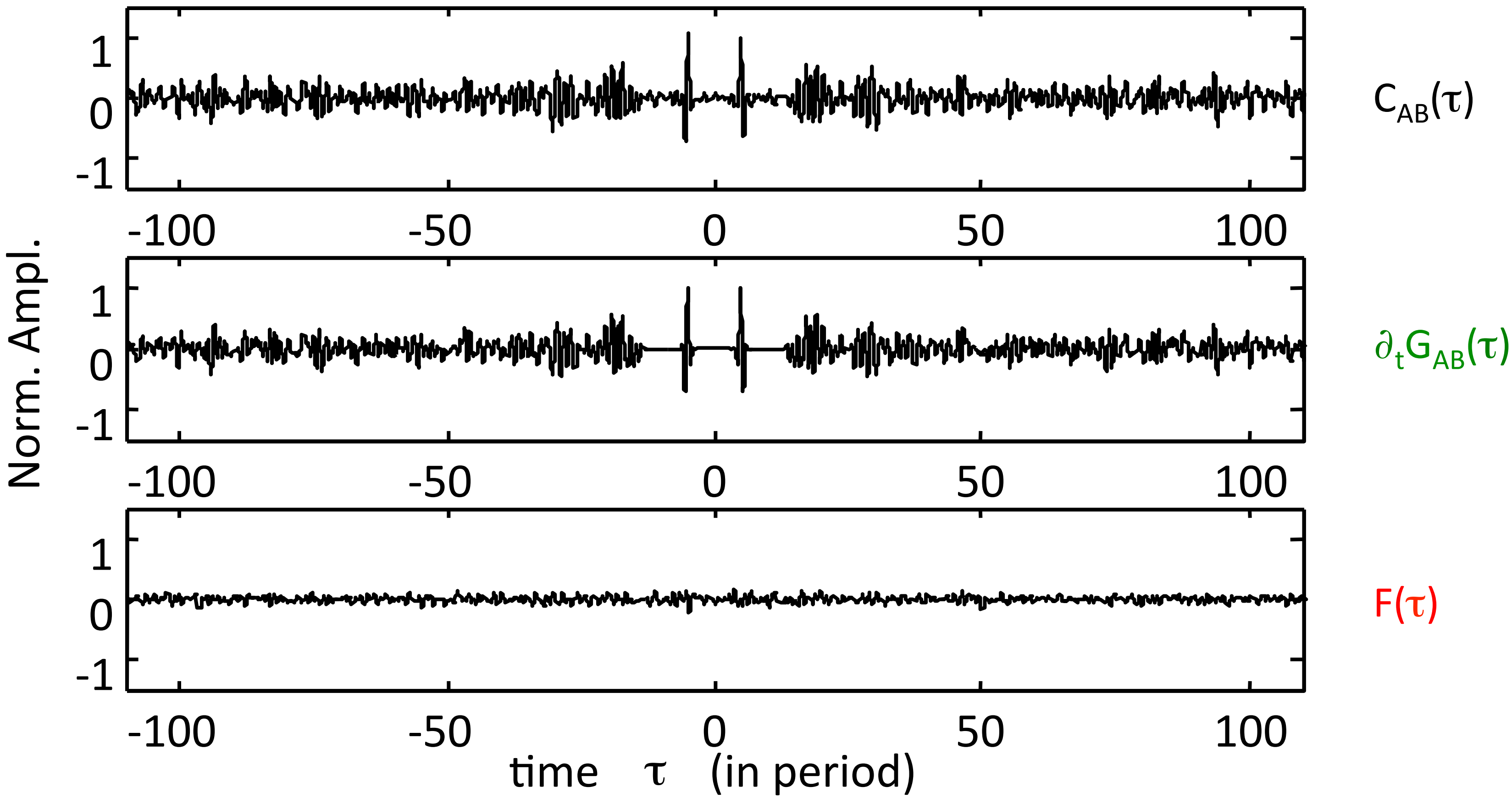
Role of scattering ?



Scattering HELPS the reconstruction

Larose *et al*, J. Appl. Phys (2008)

$C_{AB}(\tau)=\partial_t G_{AB}(\tau)+F(\tau)$



Establish a model for the AMPLITUDE of

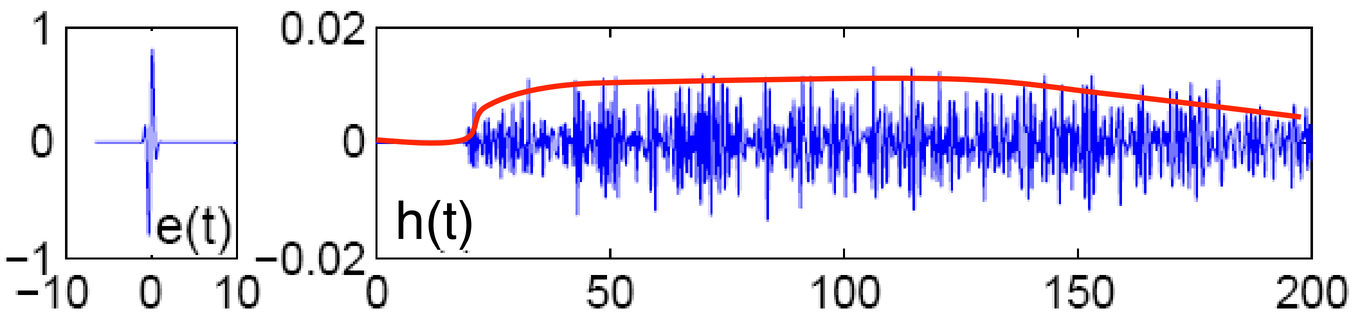
1) the « fluctuations » $F(\tau)$
2) the « signal » $\partial_t G_{AB}(\tau)$

« refocusing » energy in A at τ=0 ⇔ autocorrelation

$$C_{AA}(\tau=0) = \int_0^T h_A^2(t)dt$$

$$= \int_0^T \sigma^2(t)dt \; e(t) \otimes e(-t)$$

Envelope : σ(t)

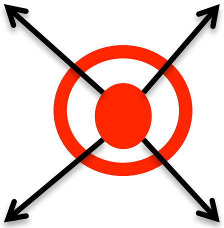


Derode et al, J. Appl. Phys 1999

Propagation of the energy from A at τ=0 ⇔ correlation in B at τ

$$C_{AB}(\tau) = \int_0^T h_A(t)h_B(t+\tau)dt$$

$$= \int_0^T \sigma^2(t)dt \; G_{AB}(\tau) \otimes e(t) \otimes e(-t)$$



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Amplitude at the focus

propagation

Source spectrum

Larose *et al*, J. Appl. Phys (2008)

Propagation of the energy from A at τ=0 ⇔ correlation in B at τ

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Amplitude at the focus — $\int_0^T \sigma(t)\sigma(t+\tau)dt$

propagation — $G_{AB}(\tau)$

Source spectrum — $e(t) \otimes e(-t)$

Amplitude of the signal

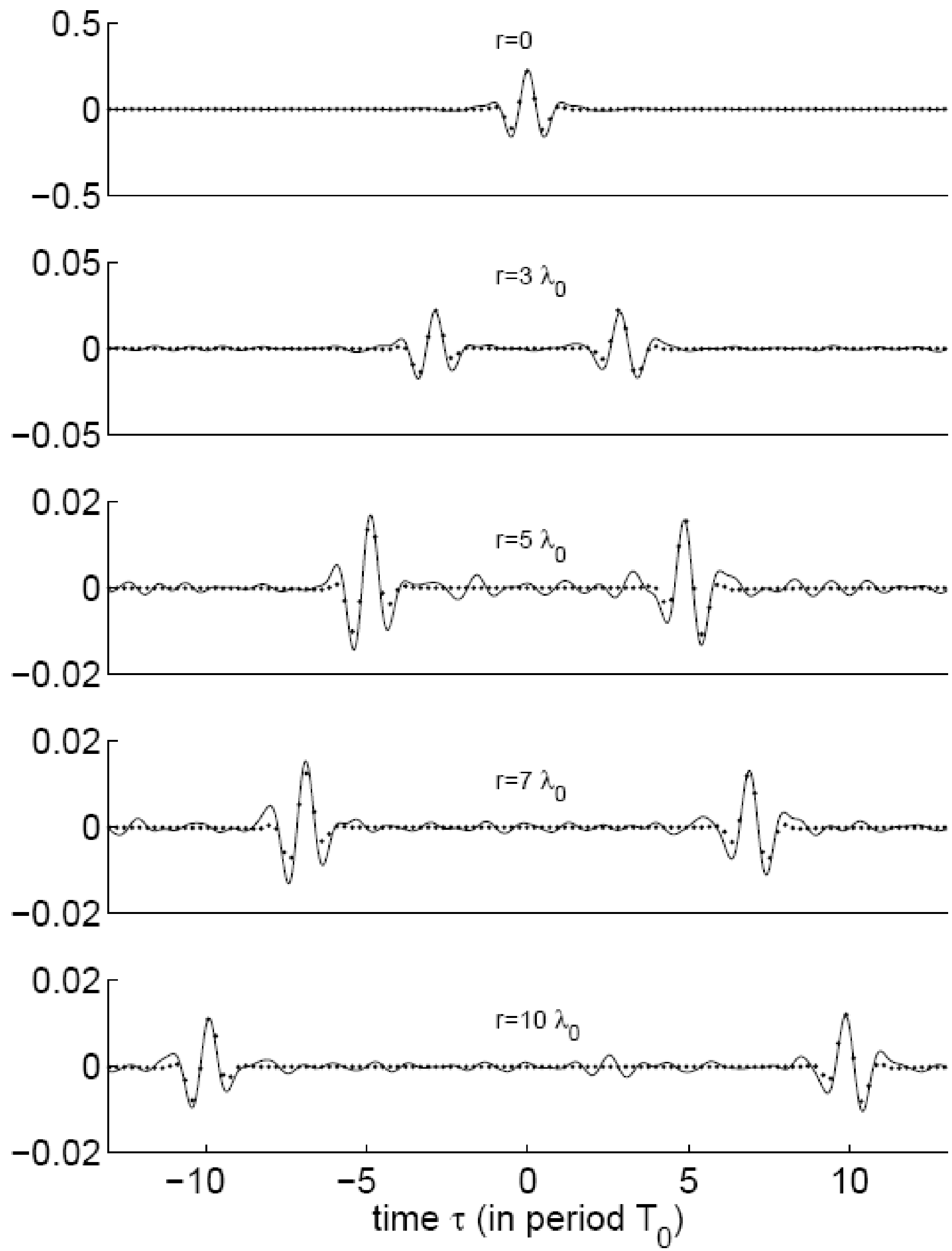
Larose *et al*, J. Appl. Phys (2008)

Numerical validation

Amplitude of the signal

$$\int_0^T \sigma(t)\sigma(t+\tau)dt$$
$$\times G_{AB}(\tau) \otimes e(t) \otimes e(-t)$$

- ➔ Geometrical spreading
- ➔
- ➔



Larose *et al*, J. Appl. Phys (2008)

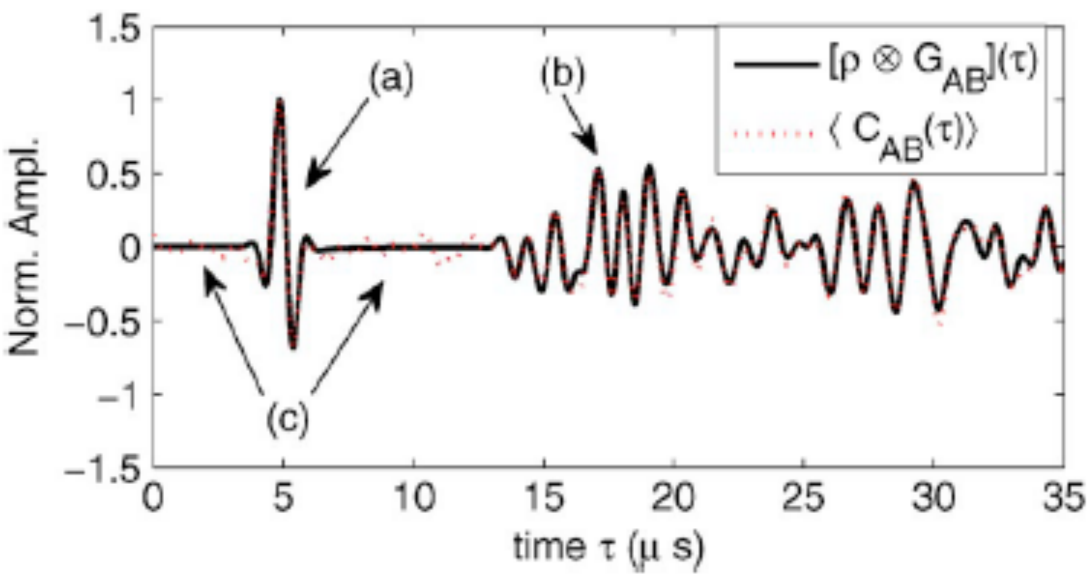
Numerical validation

Amplitude of the signal

$$\int_0^T \sigma(t)\sigma(t+\tau)dt$$

$$\times G_{AB}(\tau)\otimes e(t)\otimes e(-t)$$

- ➔ Geometrical spreading
- ➔ Scattered waves
- ➔



Larose *et al*, J. Appl. Phys (2008)

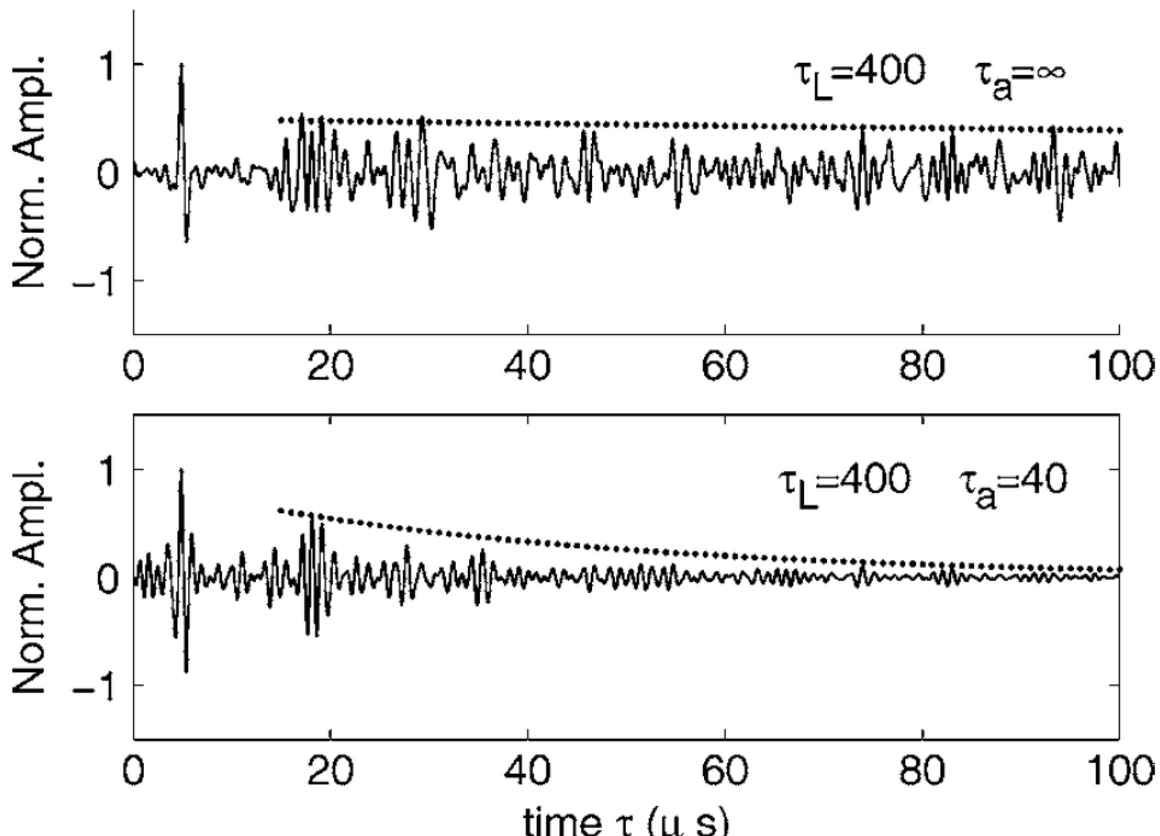
Numerical validation

Amplitude of the signal

$$\int_0^T \sigma(t)\sigma(t+\tau)dt$$

$$\times G_{AB}(\tau)\otimes e(t)\otimes e(-t)$$

→ Geometrical spreading
→ Scattered waves
→ Attenuation



Larose *et al*, J. Appl. Phys (2008)

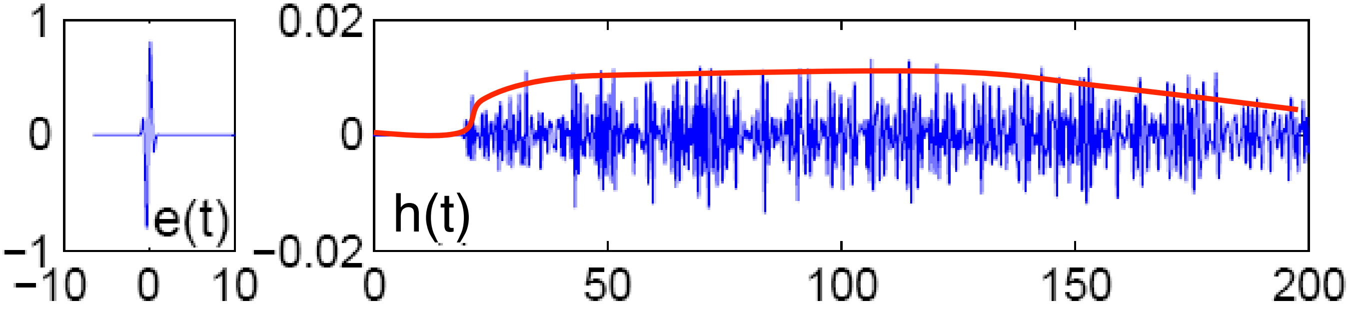
Fluctuations of correlations:

$$var\left\{C_{AB}\right\} = \left\langle C_{AB}^2(\tau)\right\rangle - \left\langle C_{AB}(\tau)\right\rangle^2$$

We assume:
Coda = succession of independent information grain = « shot noise » model
AND independent sources

$$var_{theo} \approx \int_0^T \sigma^2(\theta)\sigma^2(\theta+\tau)d\theta \int \rho^2(q)dq$$

Envelope : σ(t)



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$$var_{theo} \approx \int_0^T \sigma^2(\theta)\sigma^2(\theta+\tau)d\theta \int \rho^2(q)dq$$

$$SNR_{theo} = \frac{S_{theo}}{\sqrt{var_{theo}}} \qquad SNR_{num} = \frac{S_{num}}{\sqrt{var_{num}}}$$

$$SNR_{theo}(\tau, d) = \frac{[\rho \otimes G_{AB}](\tau)}{\sqrt{\int \rho^2(t)dt}} \times \frac{\int_0^T \sigma(t)\sigma(t+\tau)dt}{\sqrt{\int_0^T \sigma^2(t)\sigma^2(t+\tau)dt}}$$

$$SNR_{theo}(\tau, d) = \frac{[\rho \otimes G_{AB}](\tau)}{\sqrt{\int \rho^2(t)dt}} \times \frac{\int_0^T \sigma(t)\sigma(t+\tau)dt}{\sqrt{\int_0^T \sigma^2(t)\sigma^2(t+\tau)dt}}$$

SNR depends on:

➔The Green function (geometrical spreading, attenuation…)

$$\sqrt{\frac{1}{(kr)^{d-1}}}$$

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SNR depends on:

➔ The Green function (geometrical spreading, attenuation…)

➔ Source Bandwidth

$$\sqrt{\int \rho^2(t)dt} = \sqrt{\frac{1}{\Delta\omega}}$$

$$SNR_{theo}(\tau,d) = \frac{[\rho \otimes G_{AB}](\tau)}{\sqrt{\int \rho^2(t)dt}} \times \frac{\int_0^T \sigma(t)\sigma(t+\tau)dt}{\sqrt{\int_0^T \sigma^2(t)\sigma^2(t+\tau)dt}}$$

SNR depends on:

- ➔ The Green function (geometrical spreading, attenuation…)
- ➔ Source Bandwidth
- ➔ Duration and envelope of the record

In the case of stable noise…

$$\frac{\int_0^T \sigma(t)\sigma(t+\tau)dt}{\sqrt{\int_0^T \sigma^2(t)\sigma^2(t+\tau)dt}} \approx \frac{T}{\sqrt{T}}$$

Larose *et al*, J. Appl. Phys (2008)

$$SNR_{theo}(\tau,d)=\frac{[\rho\otimes G_{AB}](\tau)}{\sqrt{\int\rho^2(t)dt}}\times\frac{\int_0^T\sigma(t)\sigma(t+\tau)dt}{\sqrt{\int_0^T\sigma^2(t)\sigma^2(t+\tau)dt}}$$

SNR depends on:

- ➔ The Green function (geometrical spreading, attenuation…)
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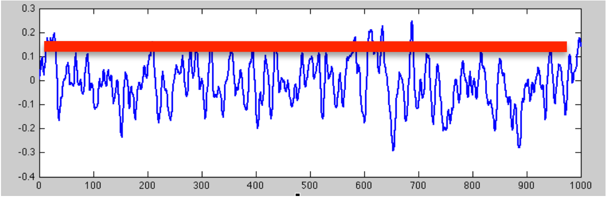

$$SNR_{theo}\propto\sqrt{T.\Delta\omega}\sqrt{\frac{1}{(kr)^{d-1}}}$$

Larose *et al*, J. Appl. Phys (2008)

Cf also: Sabra et al. JASA 2005
& Richard Weaver's papers

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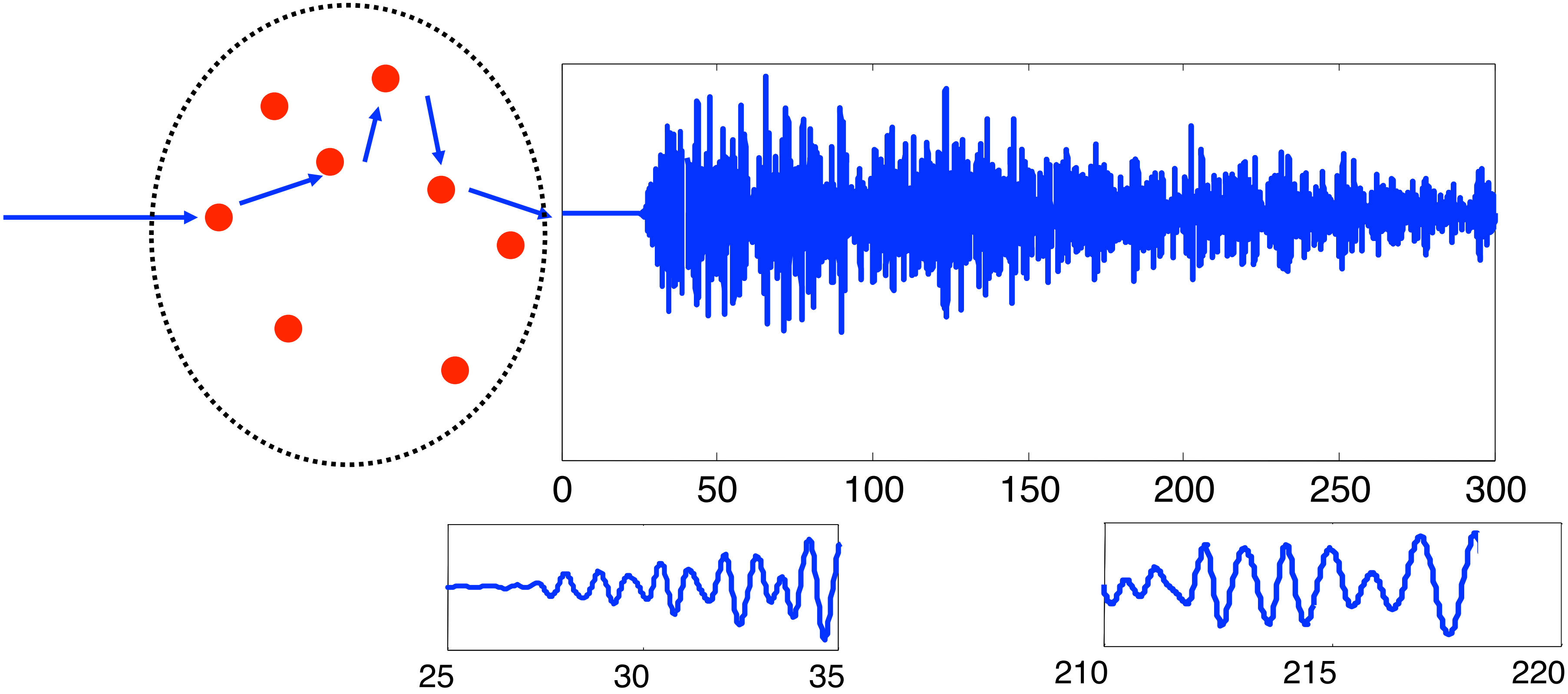
Coda Wave Interferometry

- Poupinet et al 1984
- Snieder et al 2002
- …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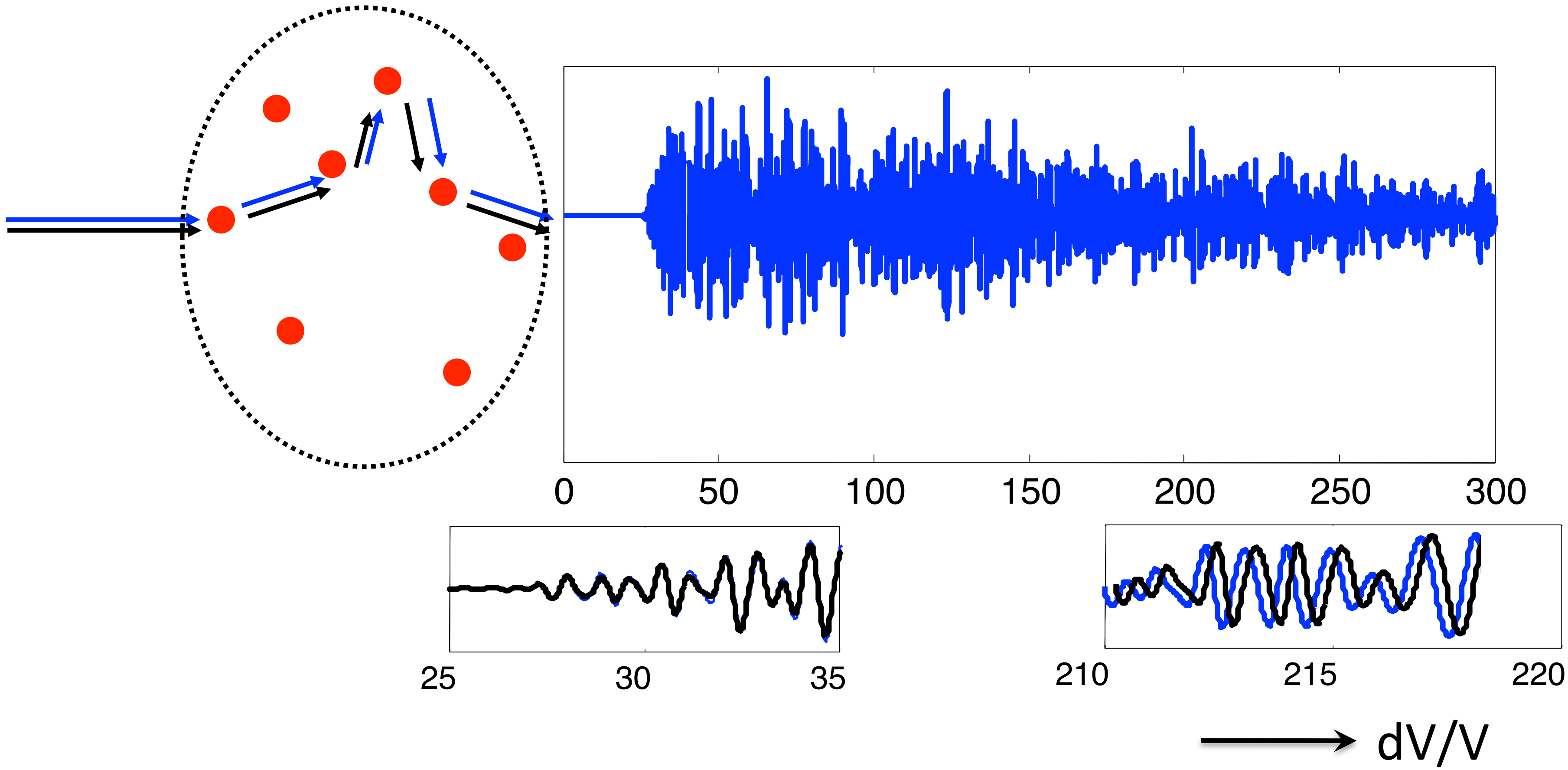
0
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215
220
dV/V

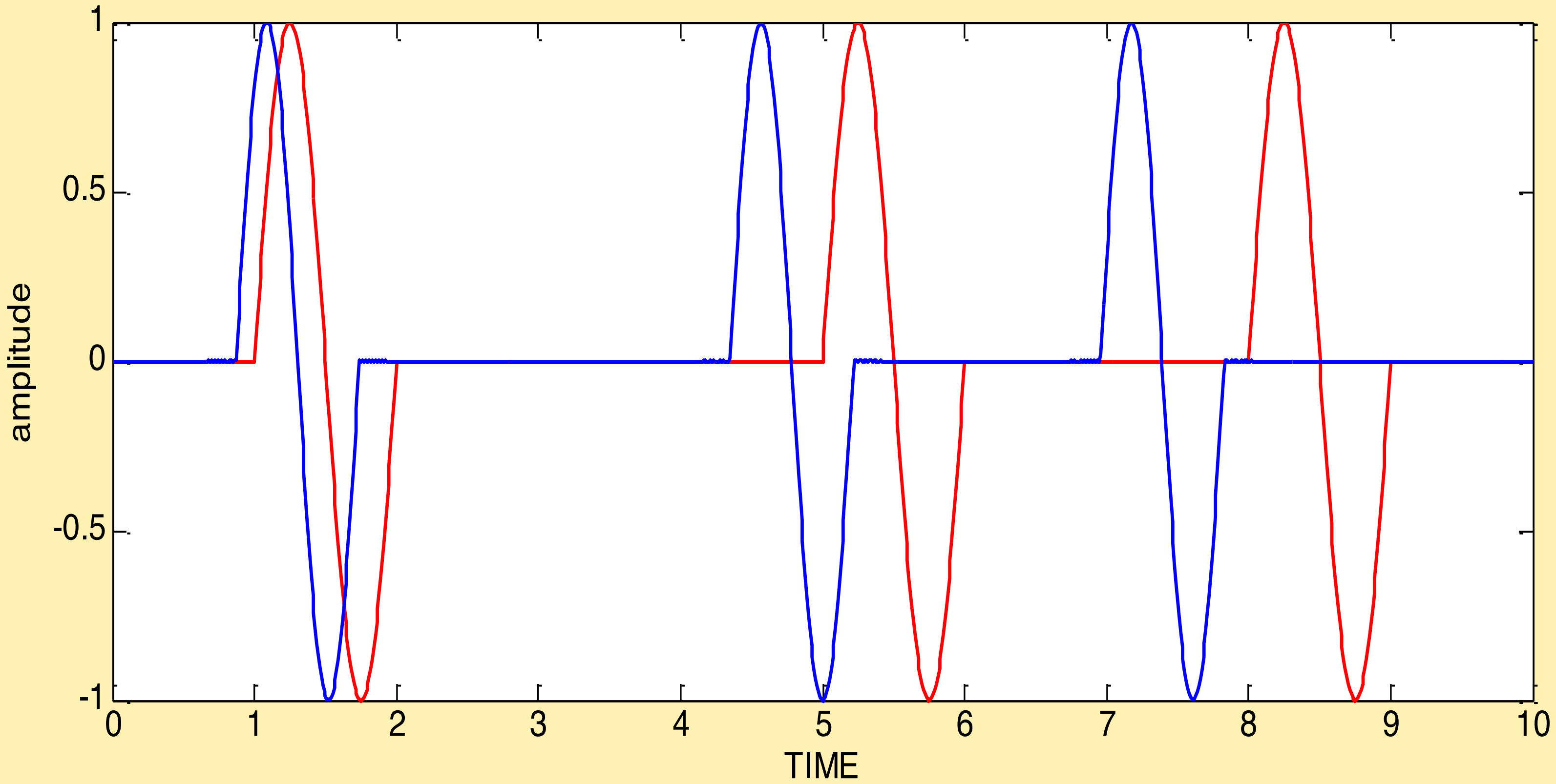
simulation

Date #1

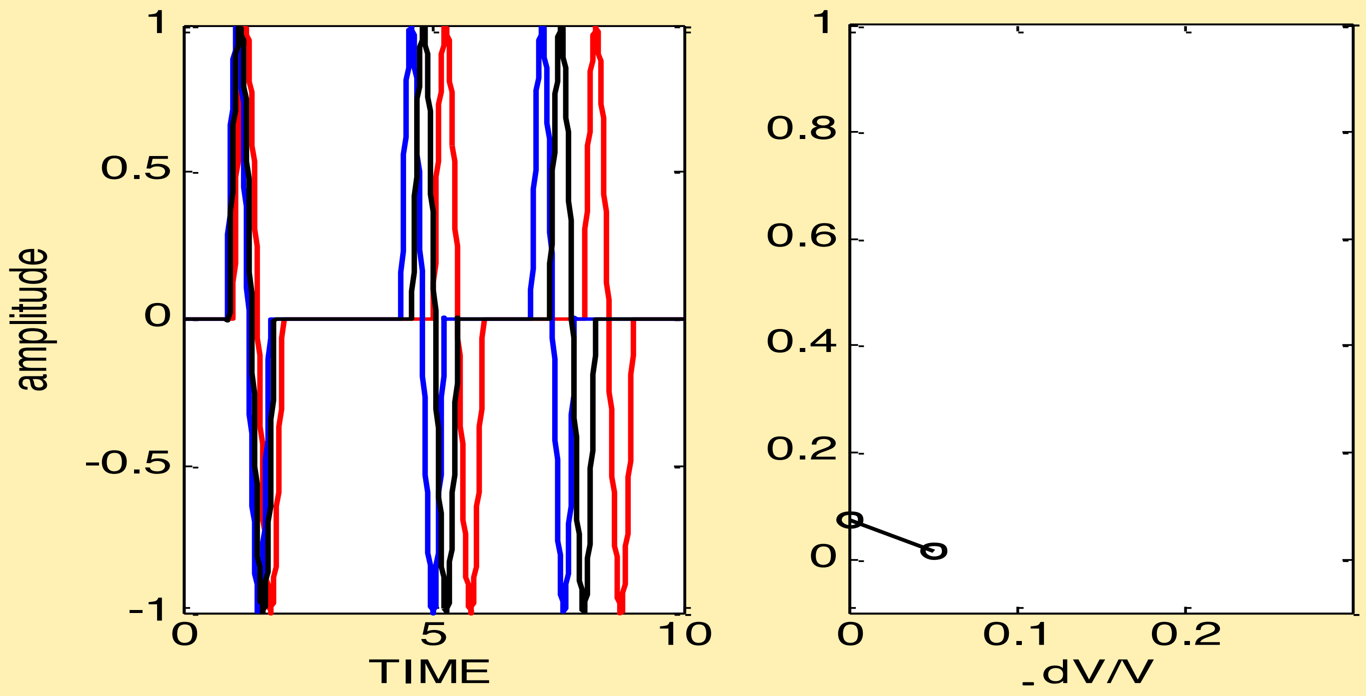
Froid = RAPIDE

Date #2

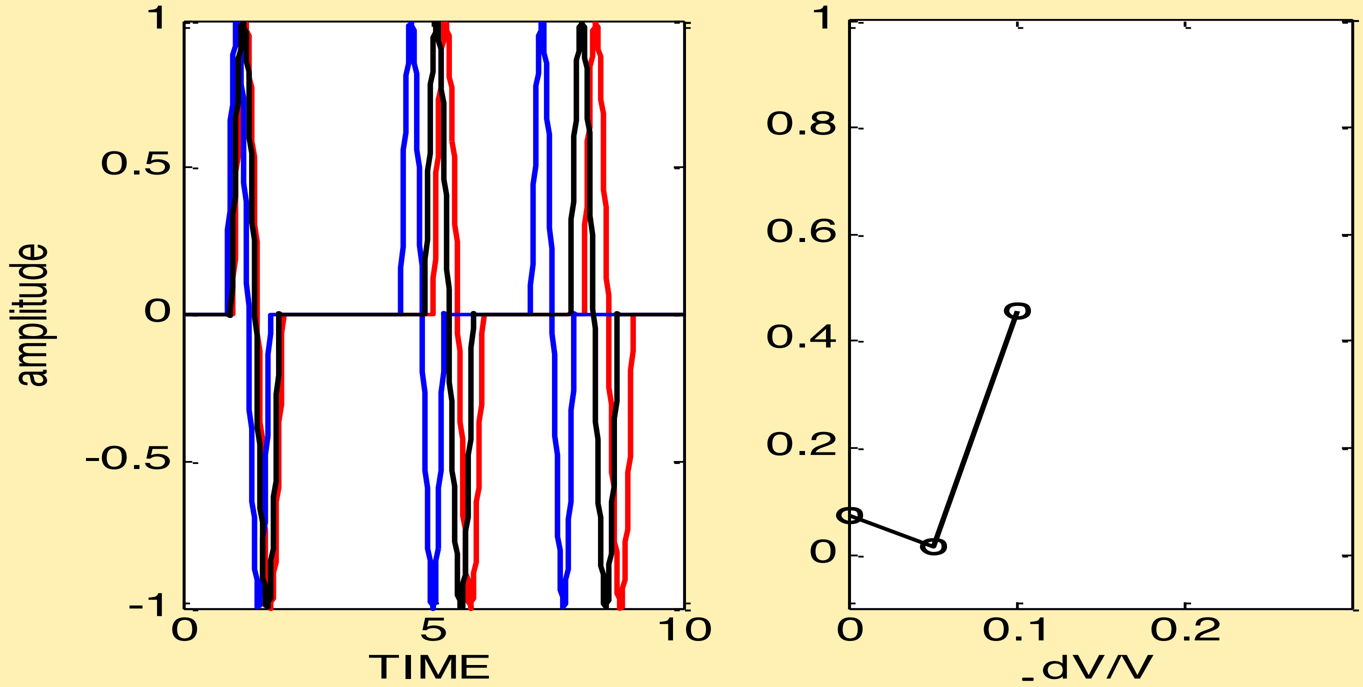
Chaud = LENT



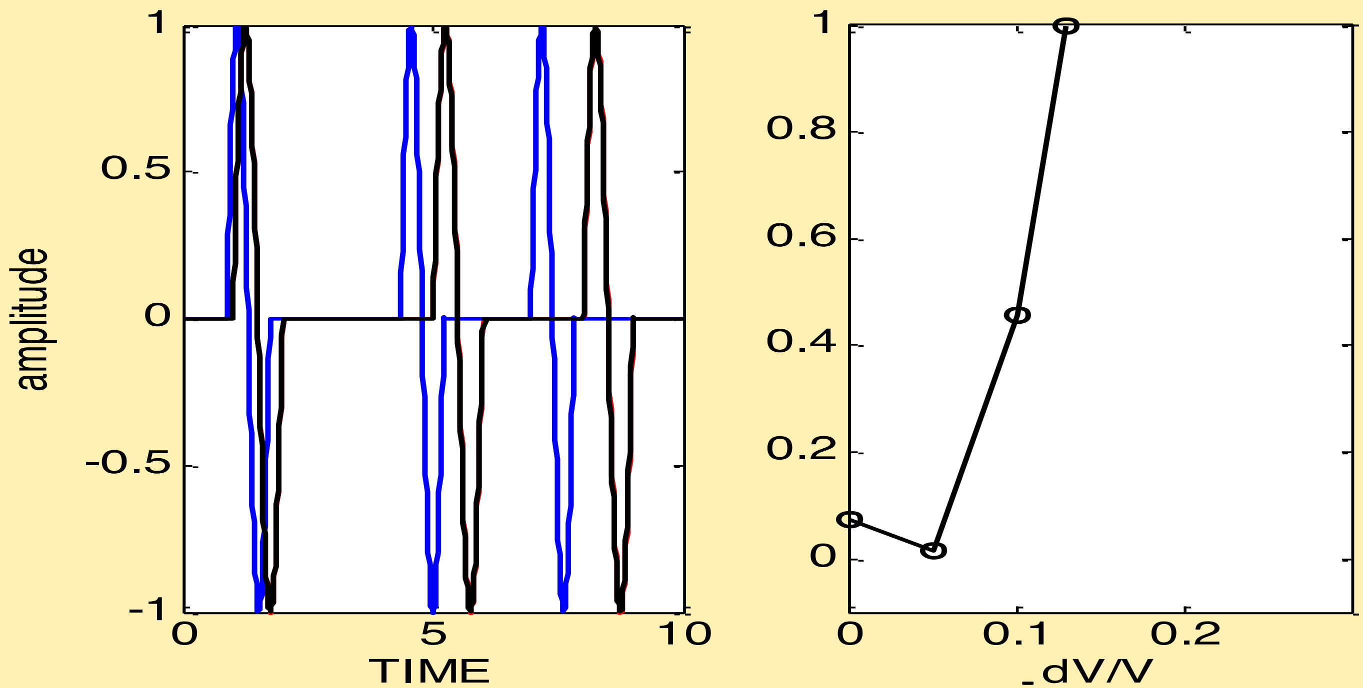
simulation



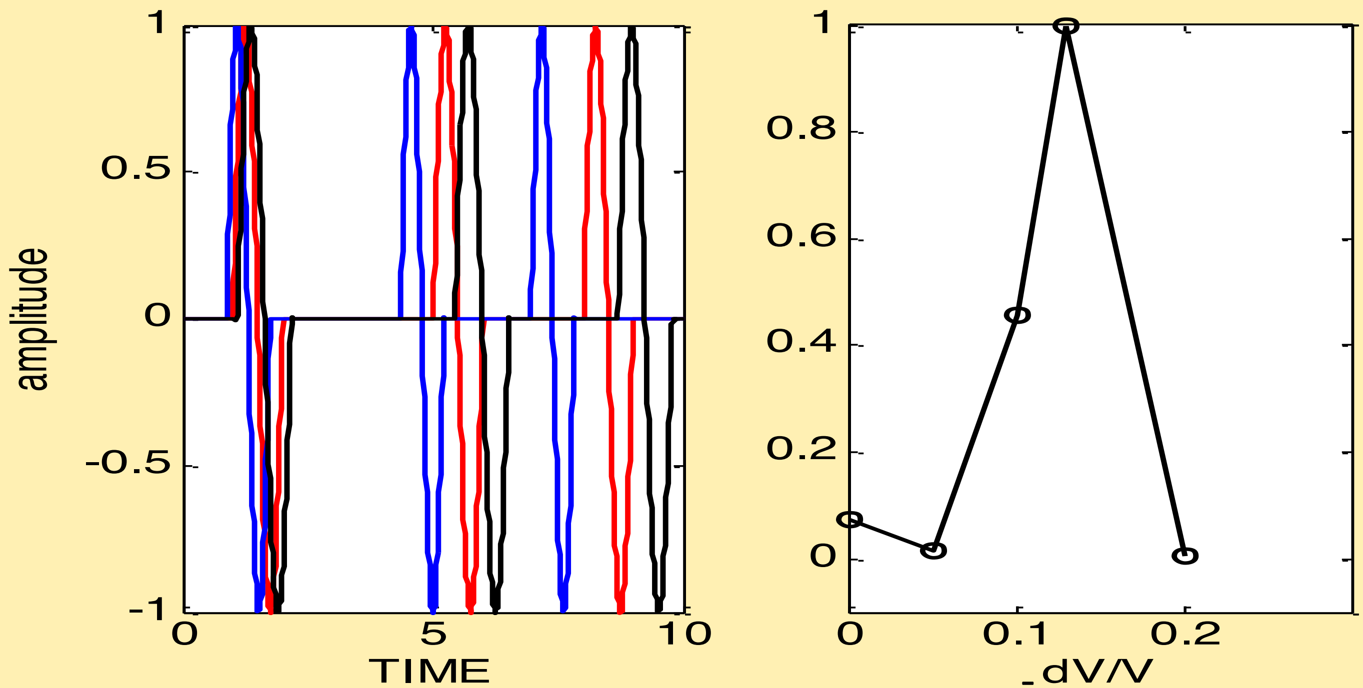
simulation



simulation



simulation



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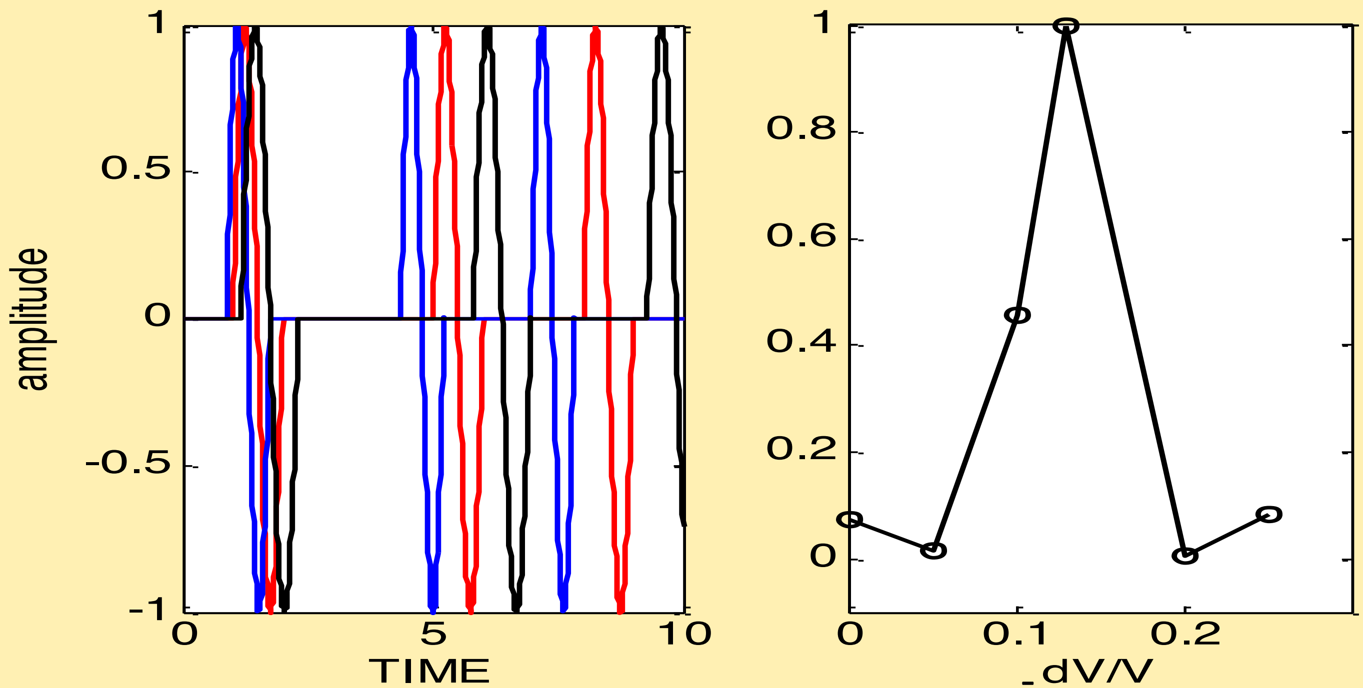

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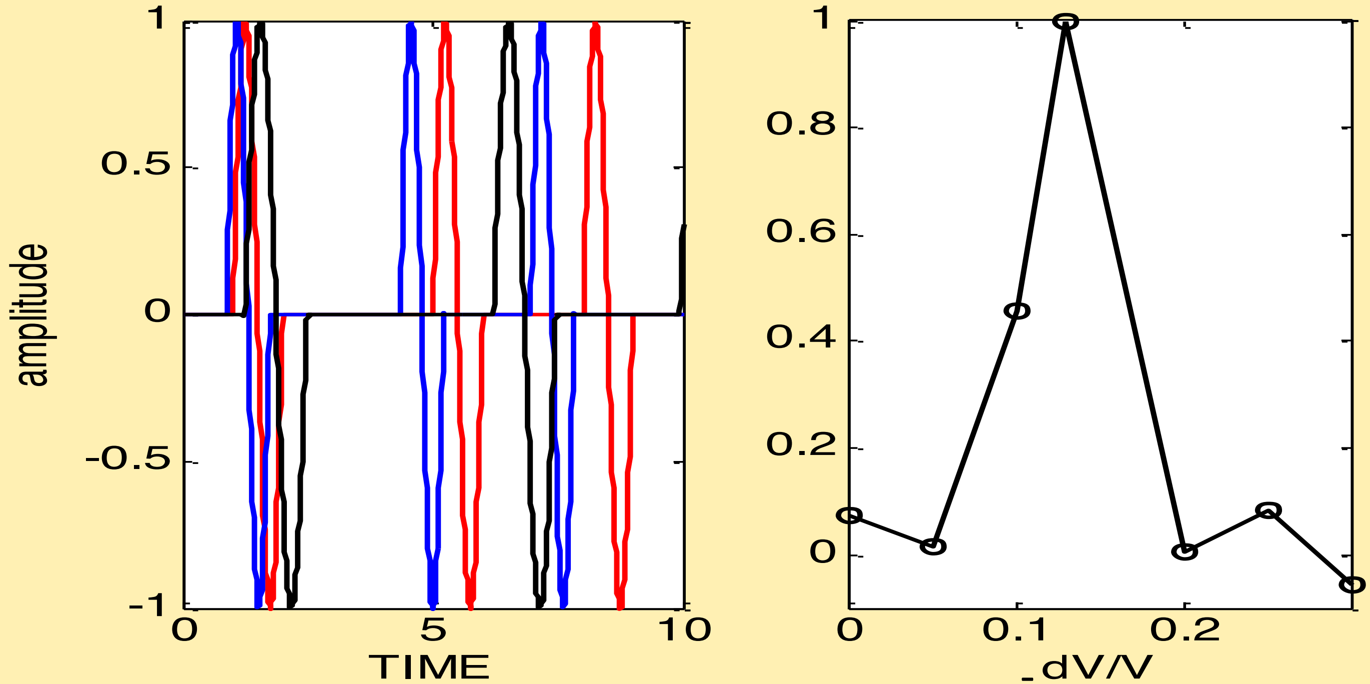
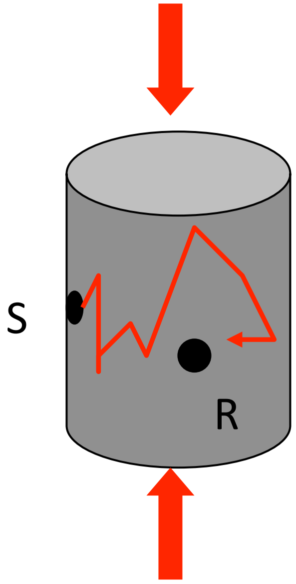
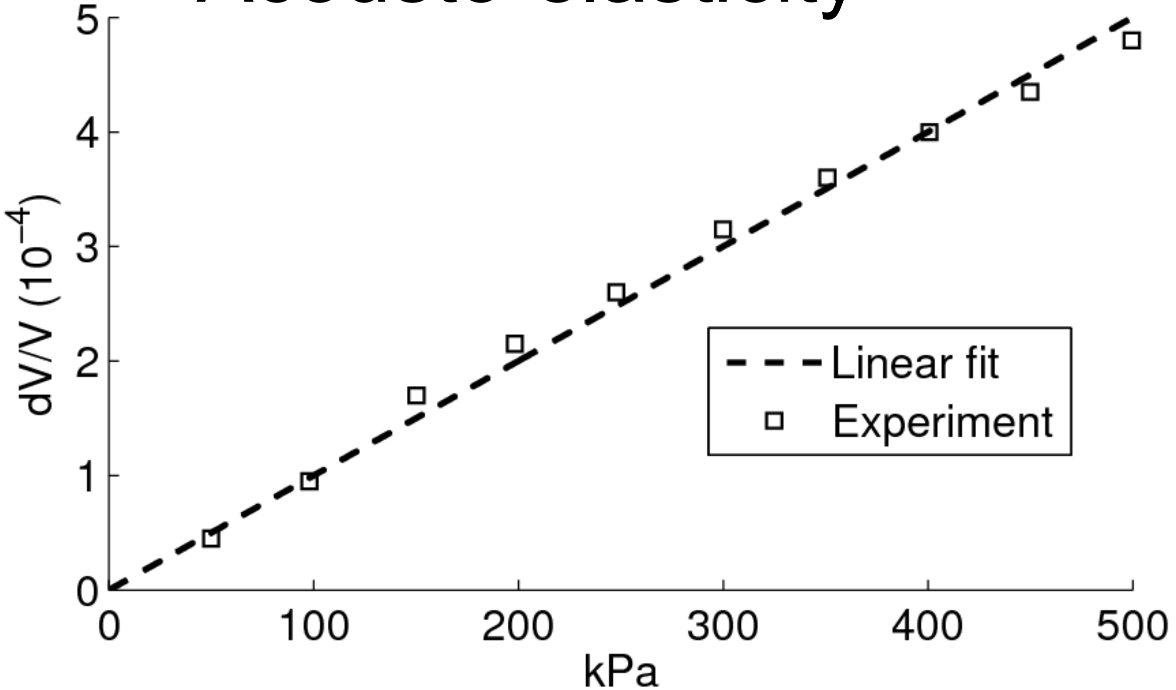
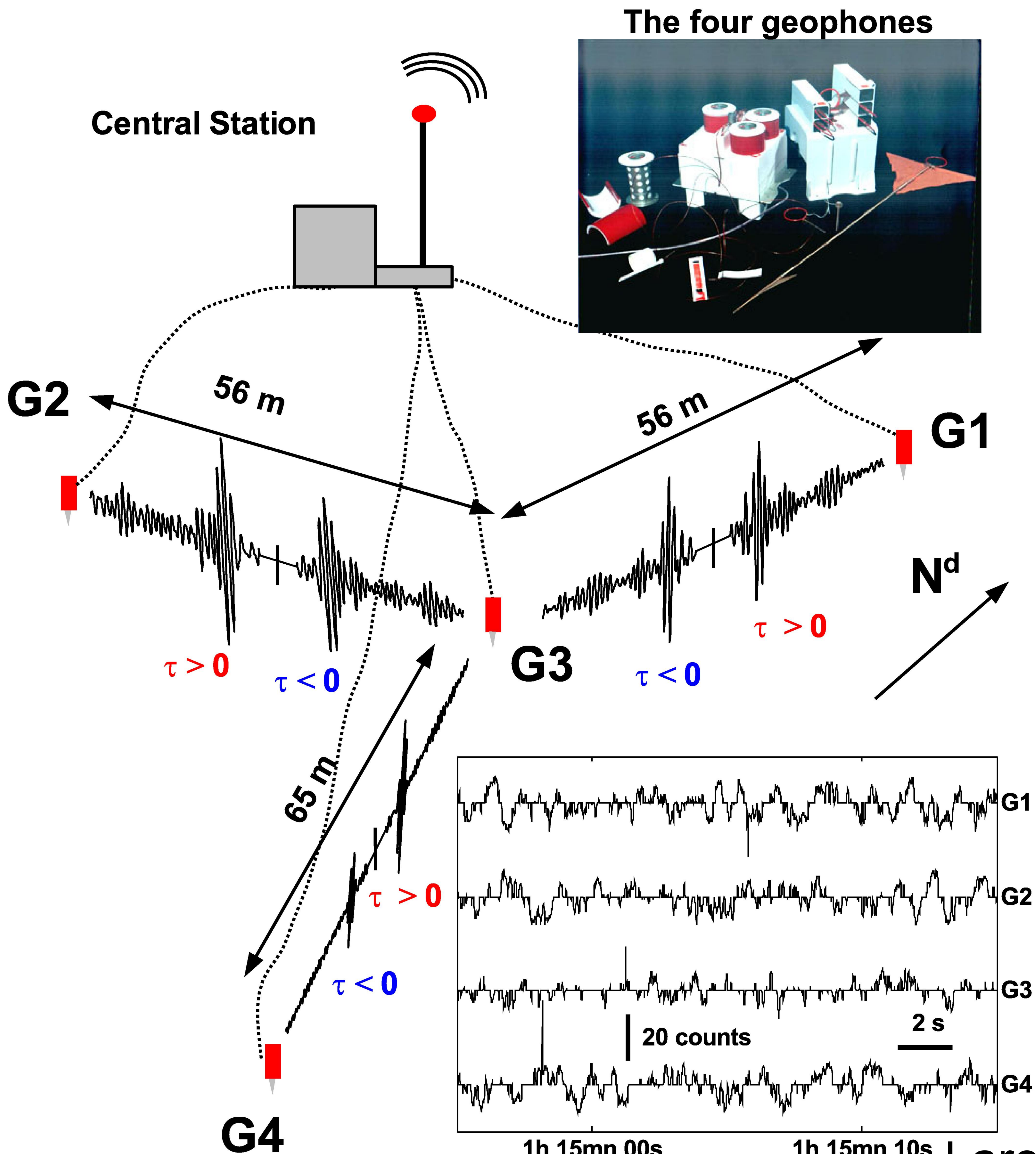


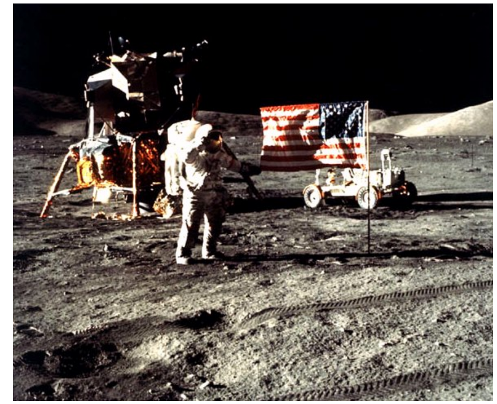
Acousto-elasticity



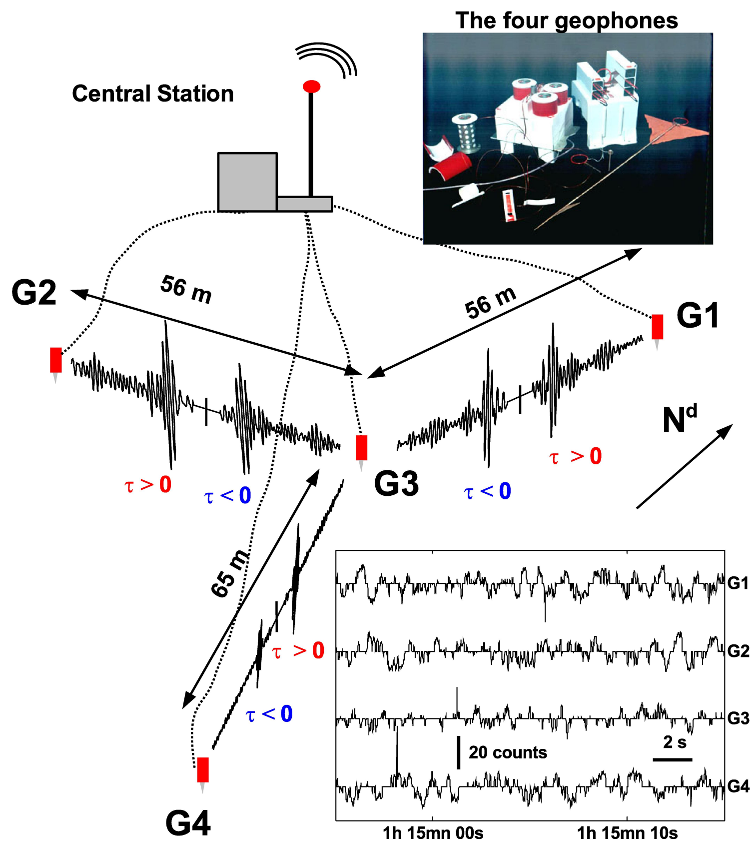


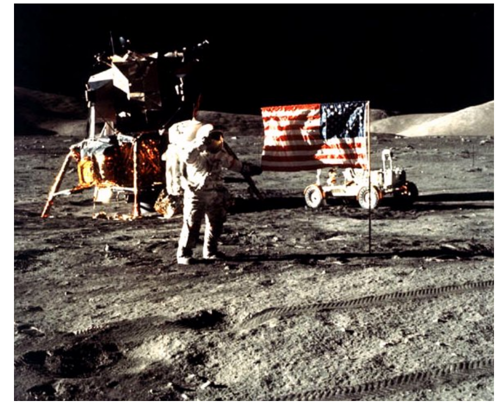
Larose & Hall, J. Acoust. Soc. Am (2009)

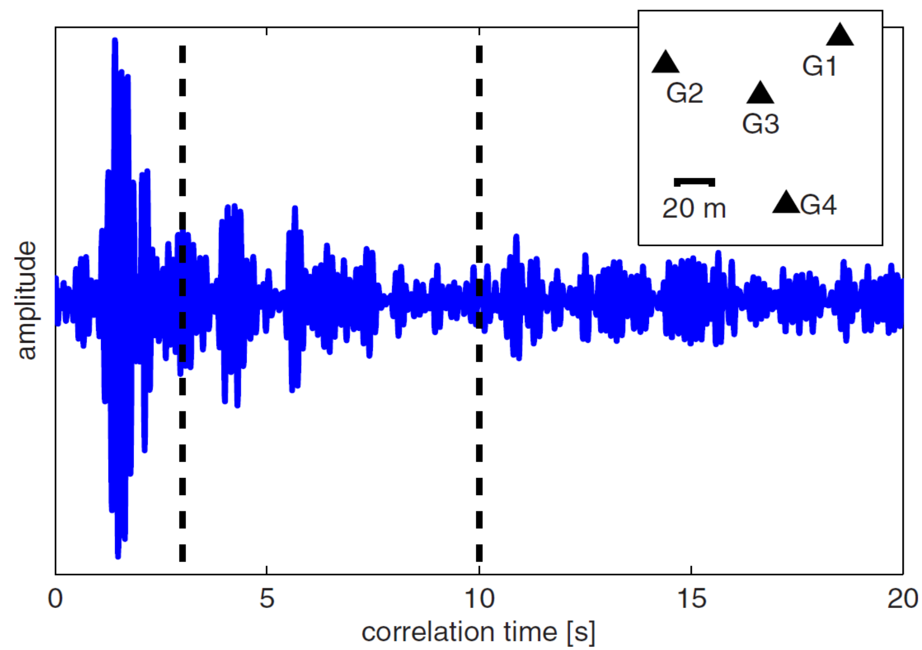




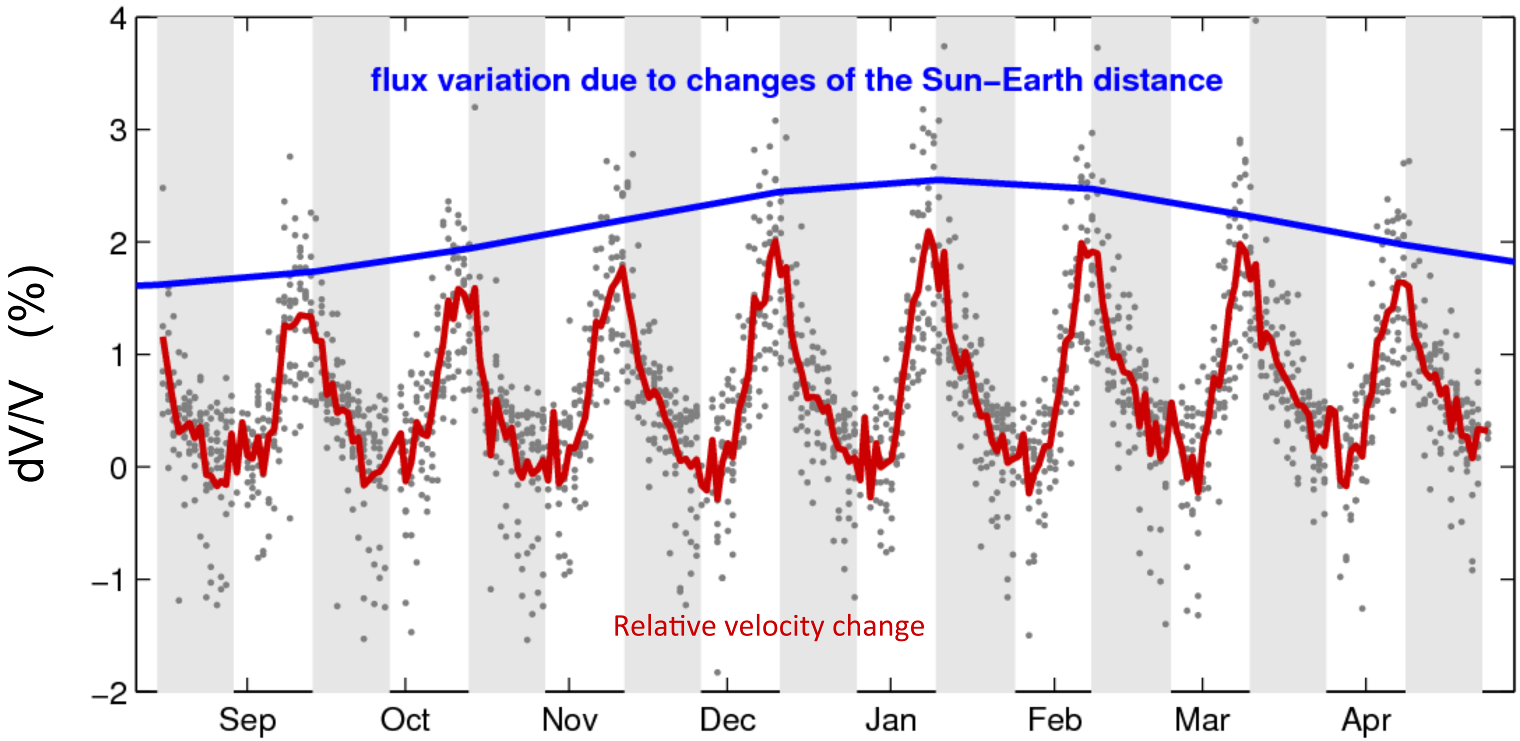
Larose *et al.*, Geophys. Res. Lett. (2005)







Larose *et al.*, Geophys. Res. Lett. (2005)

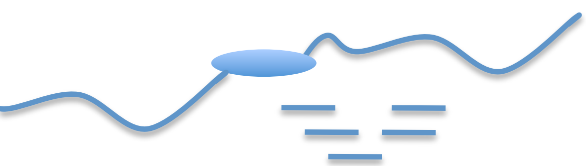


Sens-schönfelder & Larose, Phys. Rev. E (2008)

The role of Moisture

Water content change

Seismic velocity change



Apparent time delay in the records

The role of Moisture

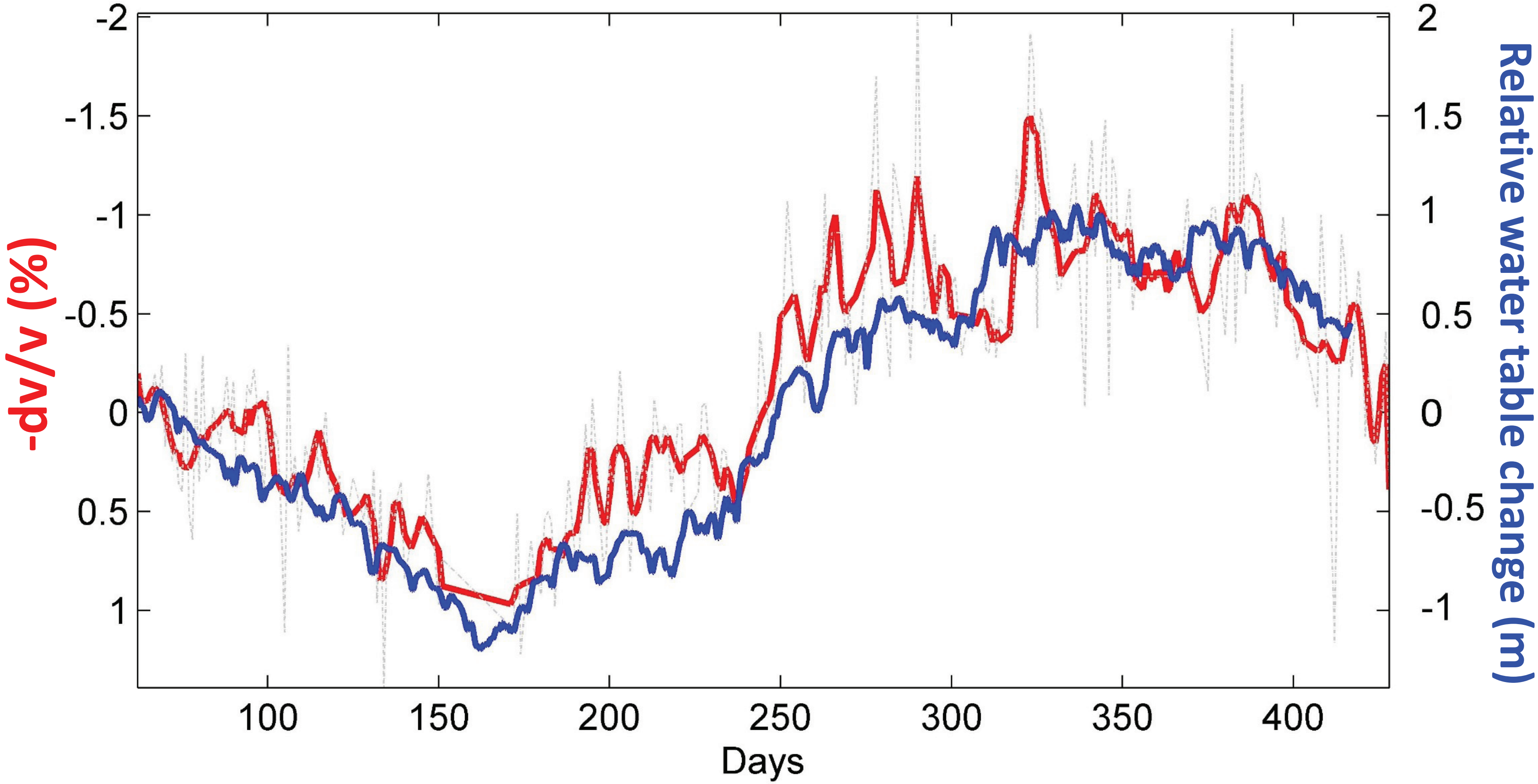
Water content change

Soill rigidity reduction

Seismic velocity change

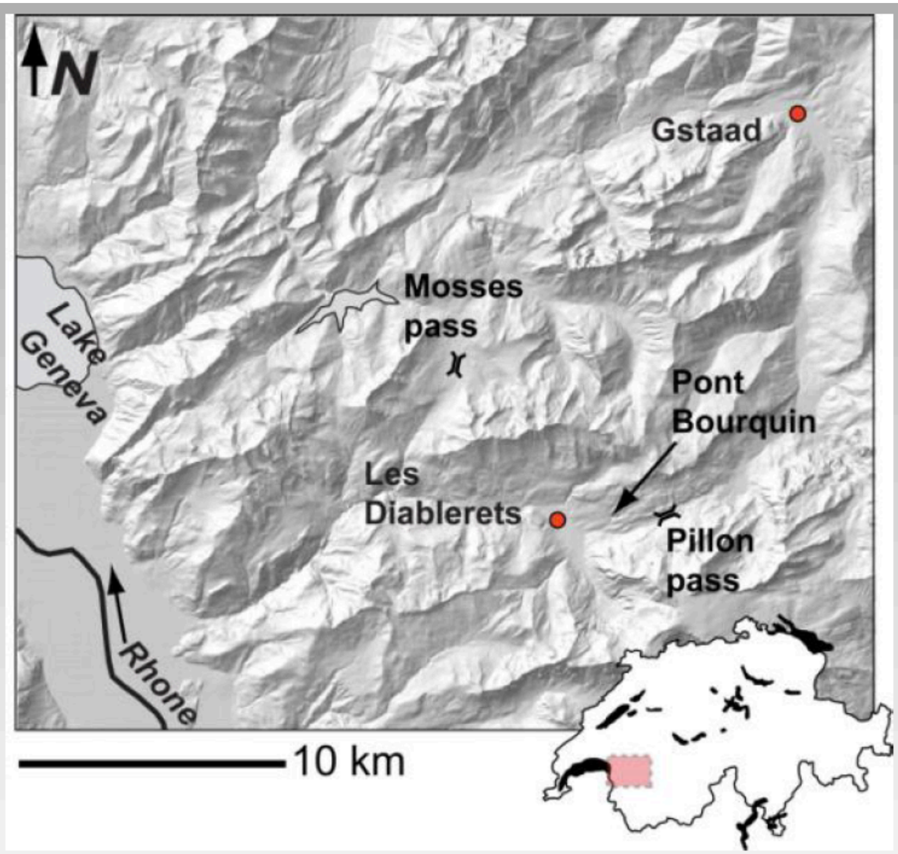
Apparent time delay in the records

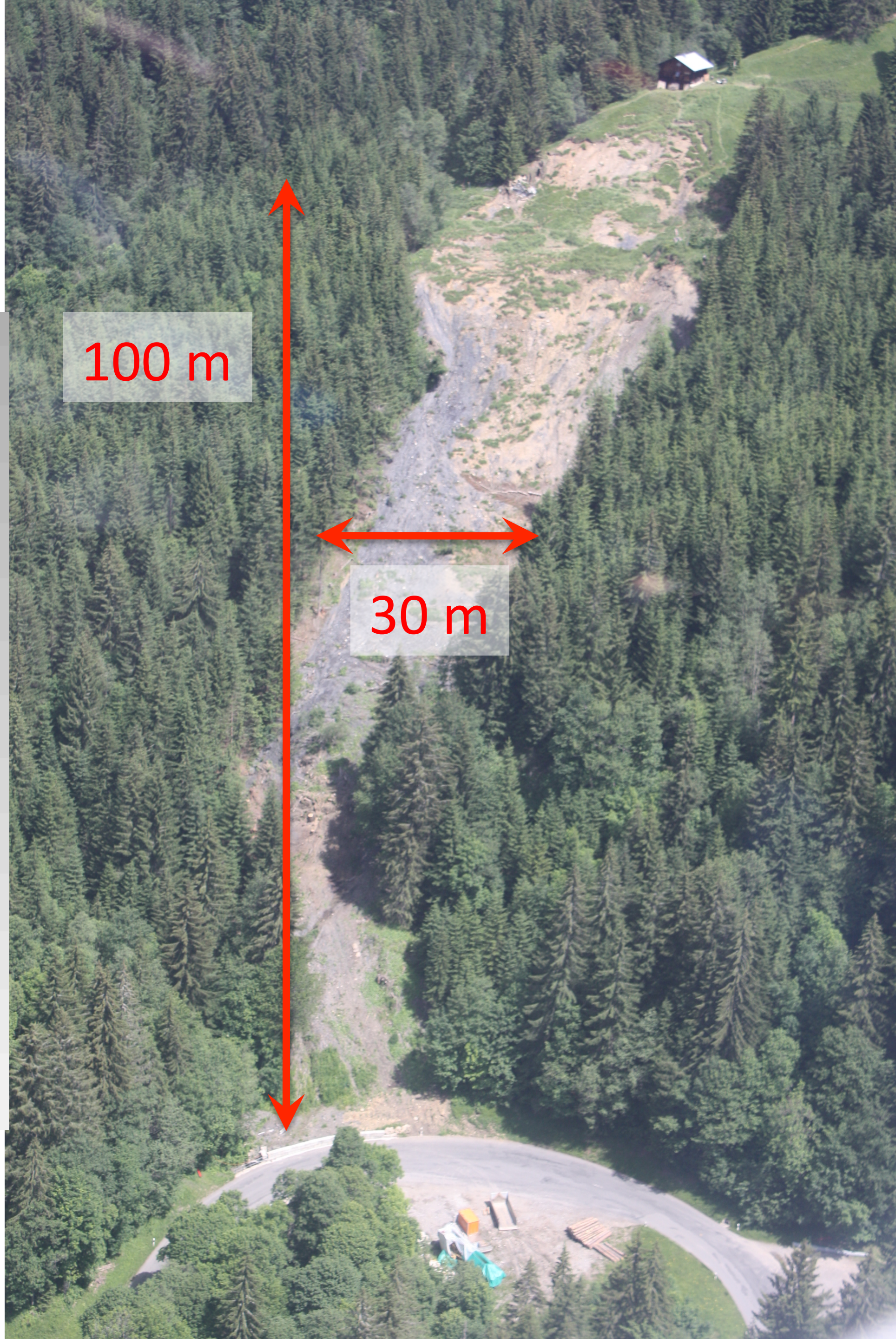
Utiku - NZ

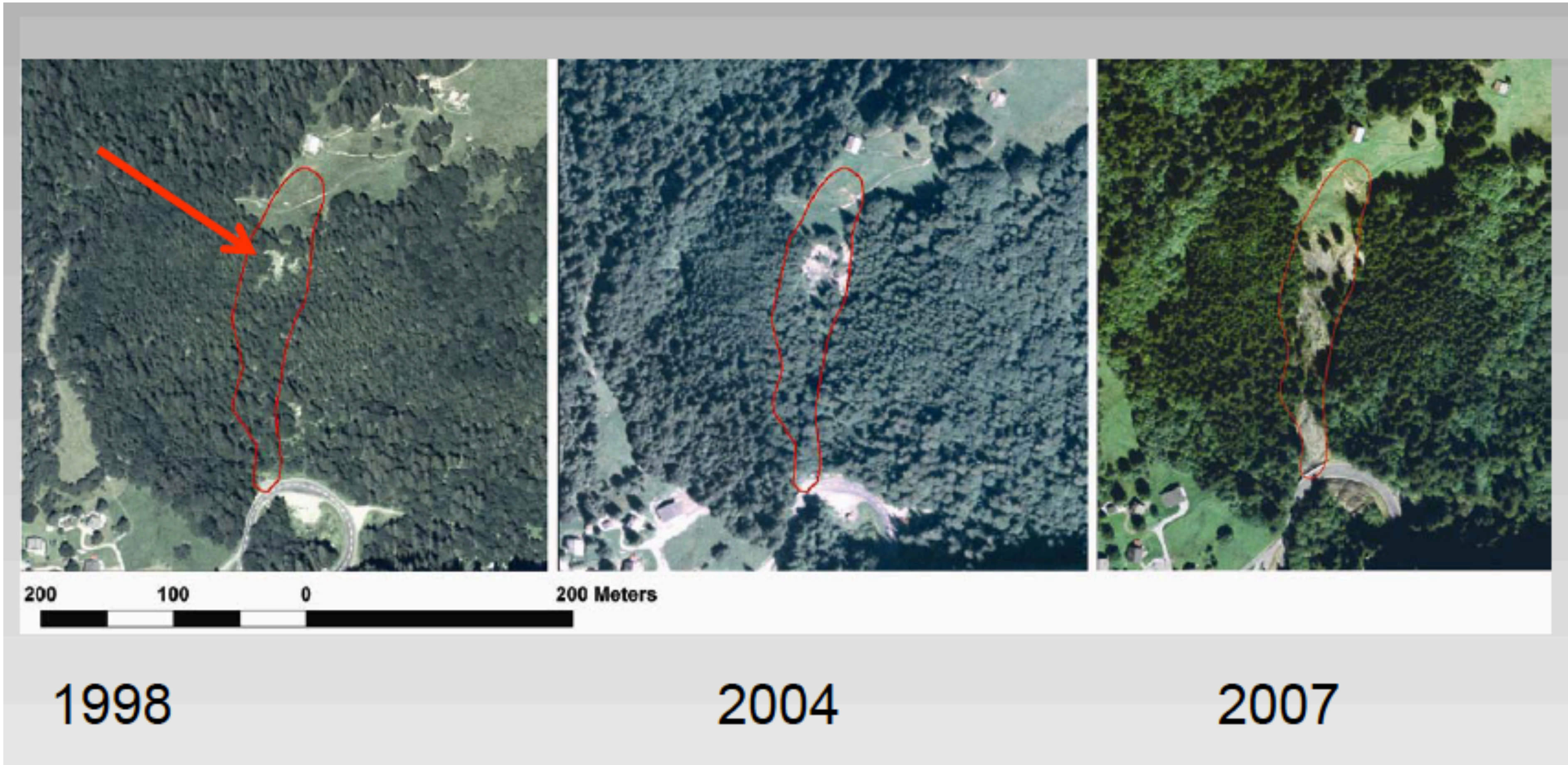


Courtesy of Voisin & Garambois

Les Diablerets (Suisse)



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200 Meters
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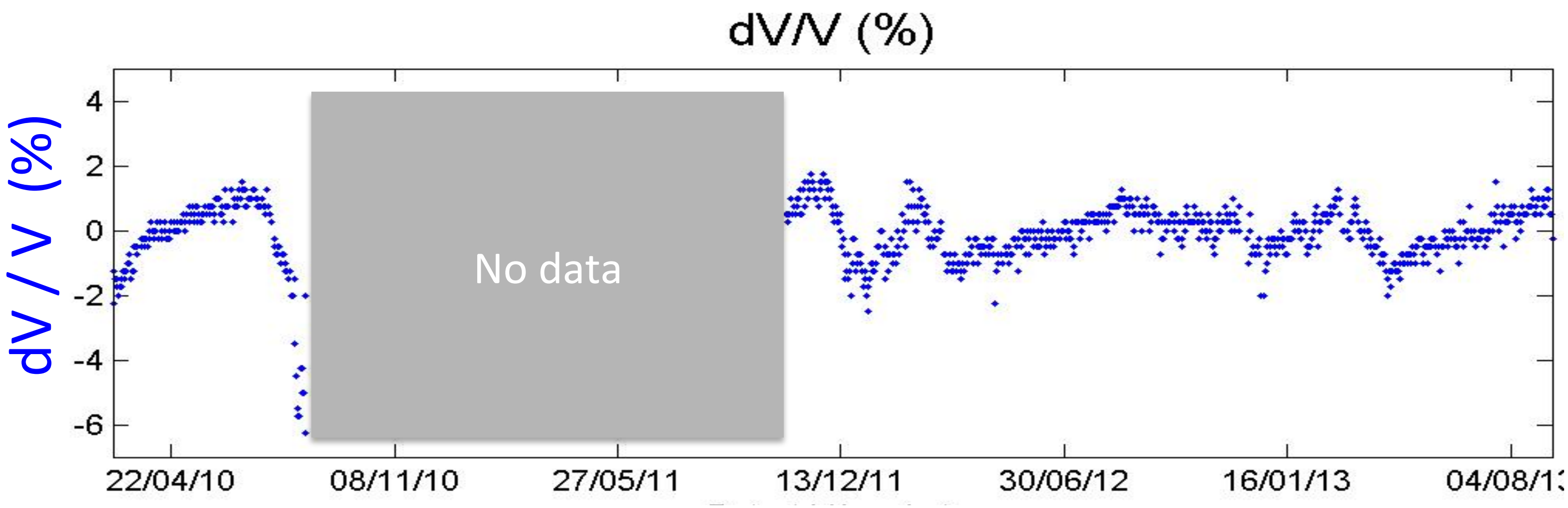
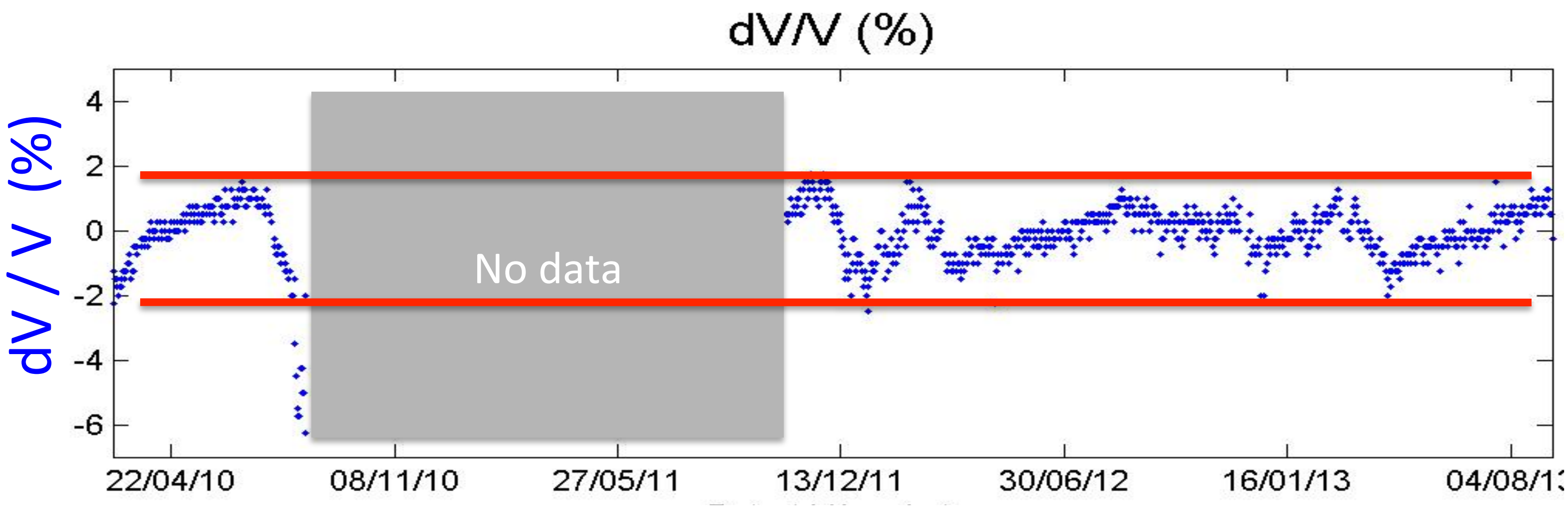
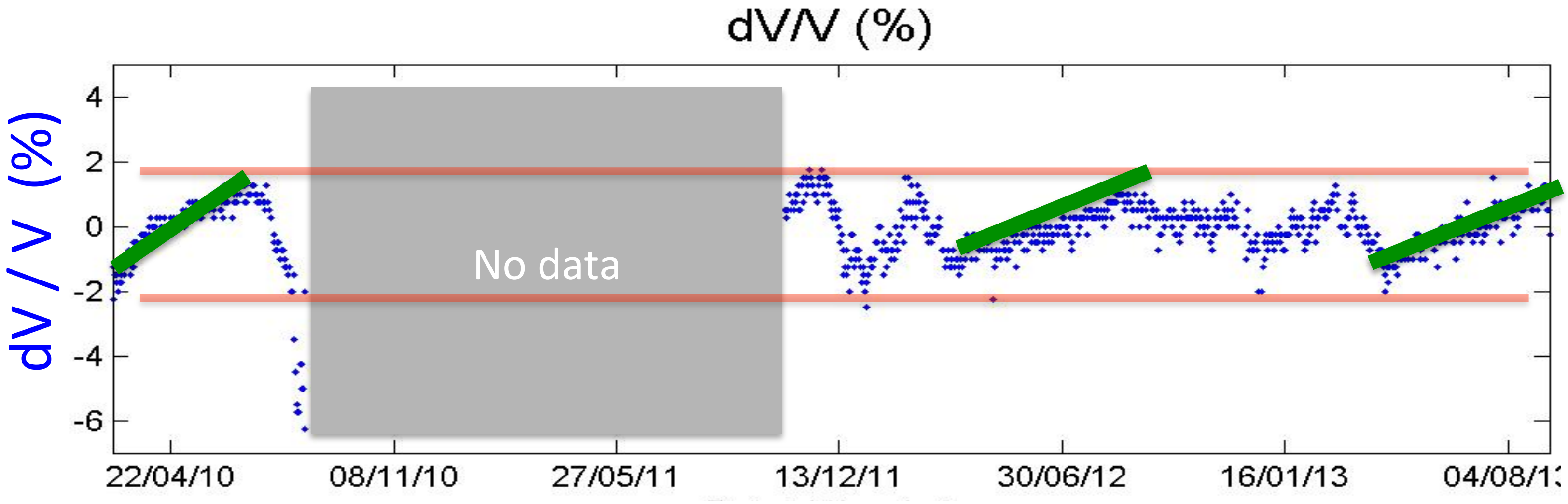


Mainsant et al, JGR (2012)



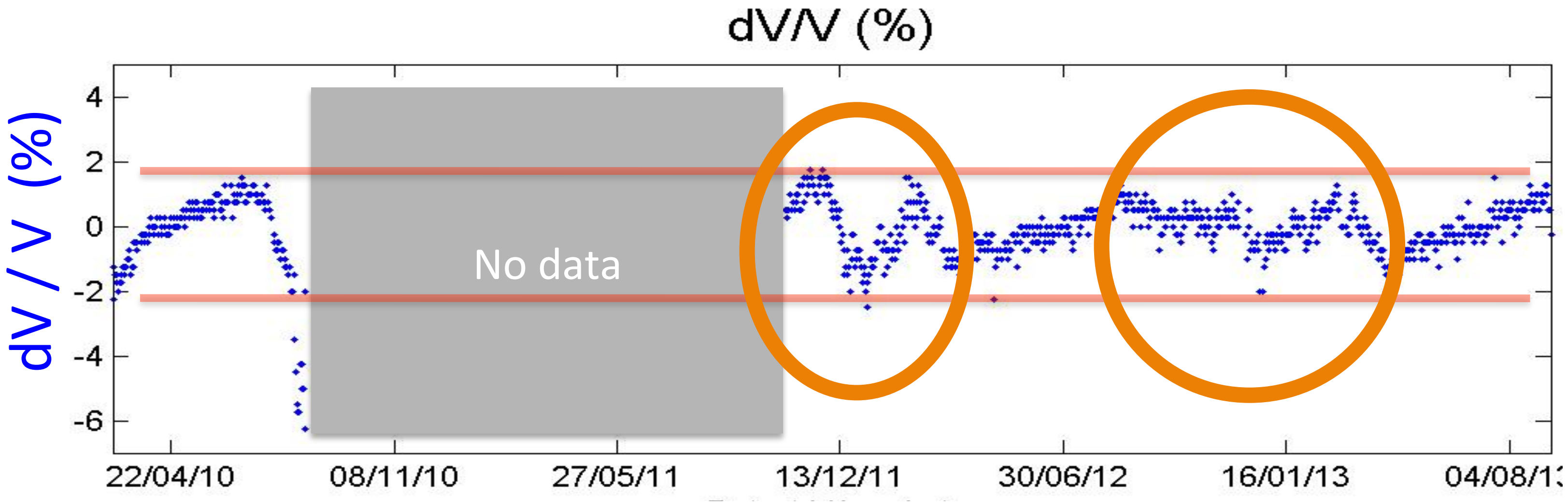
Fluctuations +/- 2%

Mainsant et al, JGR (2012)



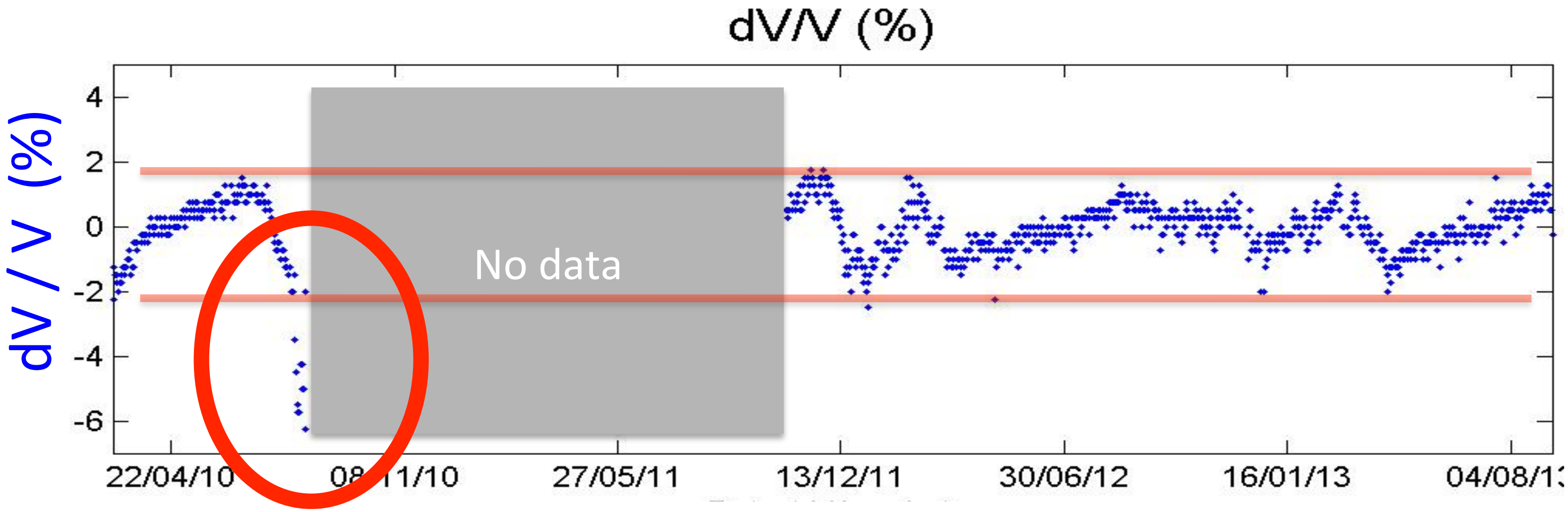
Drying during summer

Mainsant et al, JGR (2012)



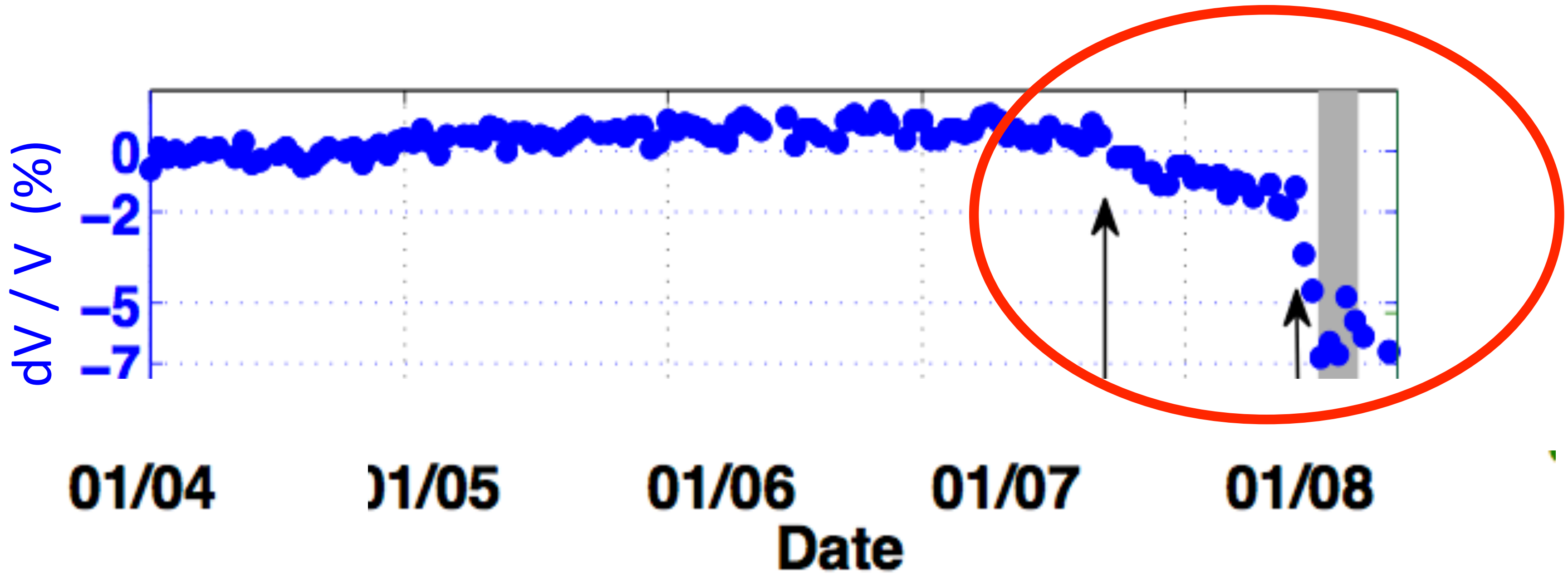
Winter : Moisture / freezing / snow…

Mainsant et al, JGR (2012)



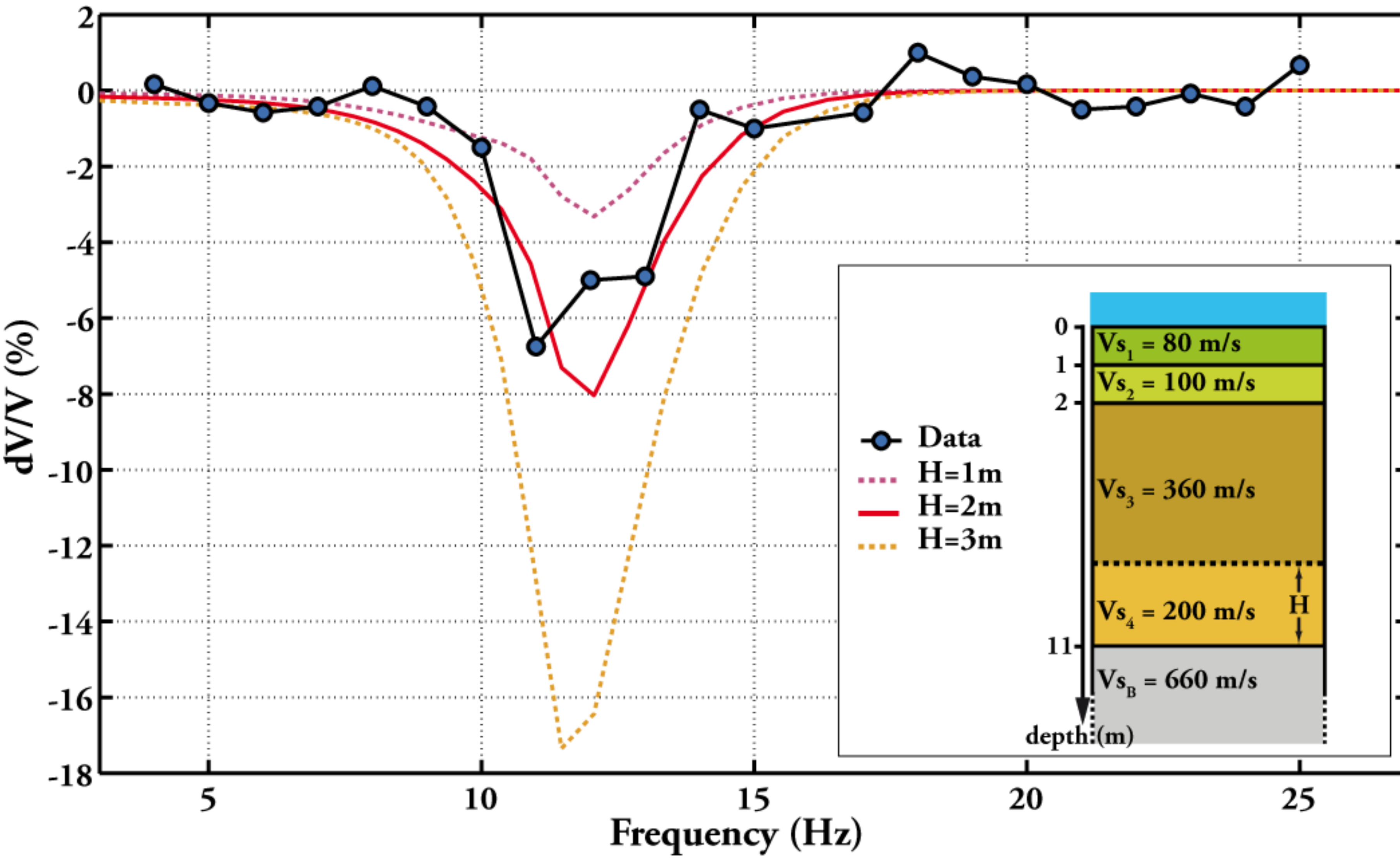
Large decrease => Liquefaction?

Mainsant et al, JGR (2012)



5 days precursory signal

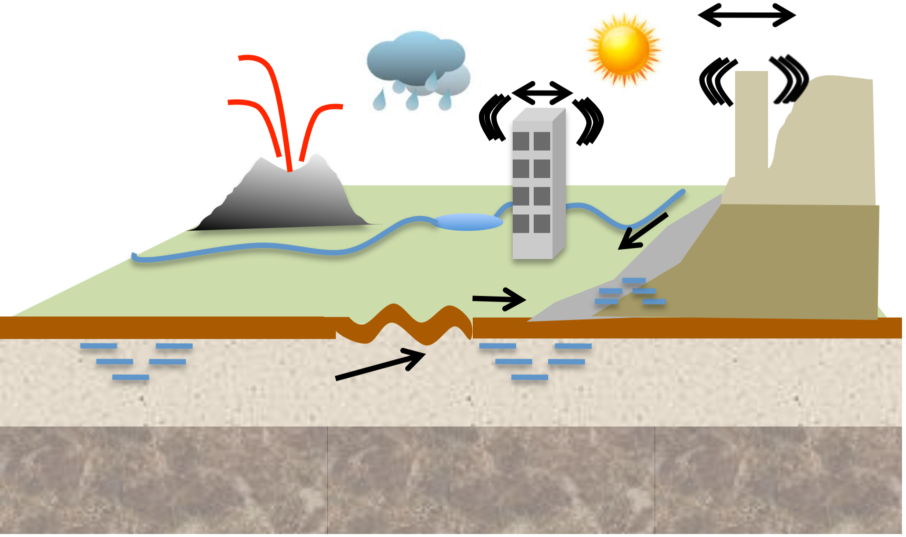
Mainsant et al, JGR (2012)

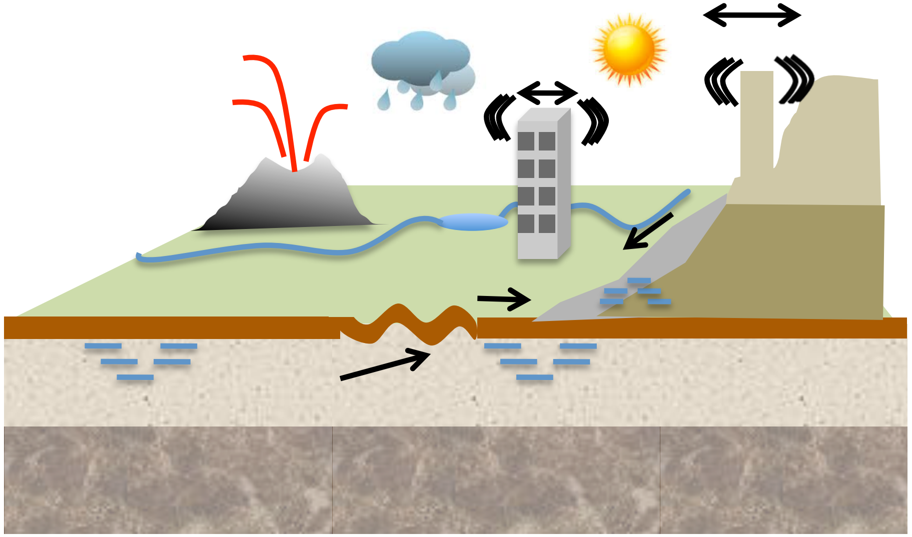


Mainsant et al, JGR (2012)

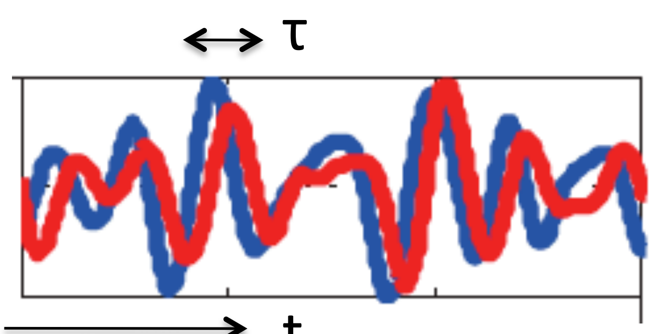
Environmental SEISMOLOGY

Larose et al, J. Appl. Geophys. (2015)





State 1 → State 2

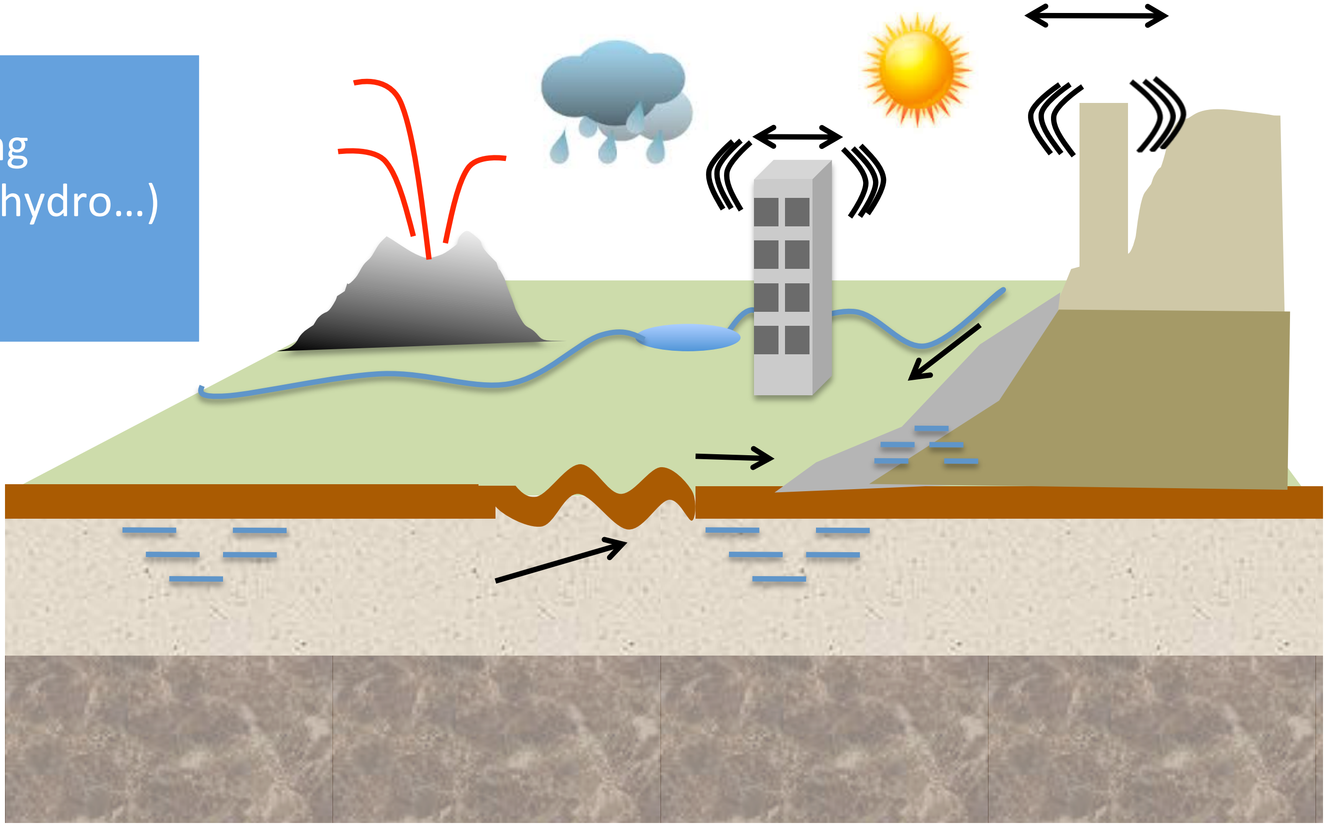


Larose et al, J. Appl. Geophys. (2015)

External forcing
- environemental (T, hydro…)
- human

Urbanised basins
Volcanoes
Unstable slopes

Gravity
Damage
Tectonics
volcanology



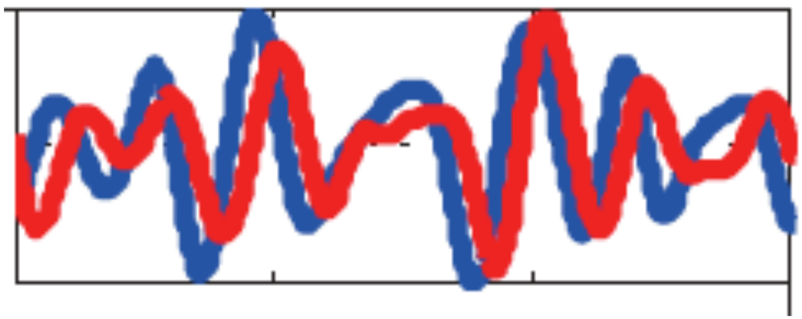
Larose et al, J. Appl. Geophys. (2015)

Change of seismic waveforms

Learn on the environment	Discriminate internal/external forcing	Learn on the susceptibility	Discriminate Reversible/irreversible changes
Hydrology …	Active fault, landslide, volcanology	To humidity, temperature…	Active fault, landslide, volcanology
↓	↓	↓	↓
Water ressources	Natural Hazards	Non-linearities, Damage	Natural Hazards

Larose et al, J. Appl. Geophys. (2015)

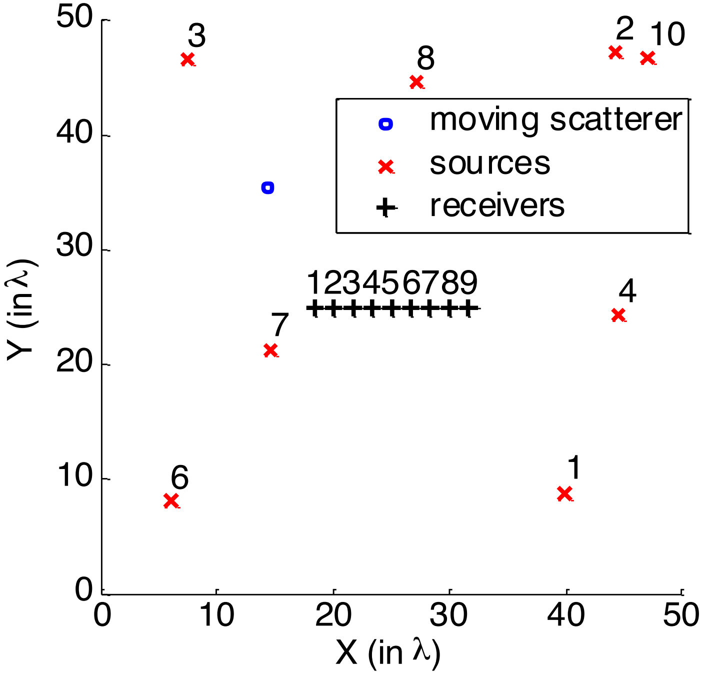
1. Convergence rate
2. Coda Wave Interferometry
3. Coda Wave Decorrelation

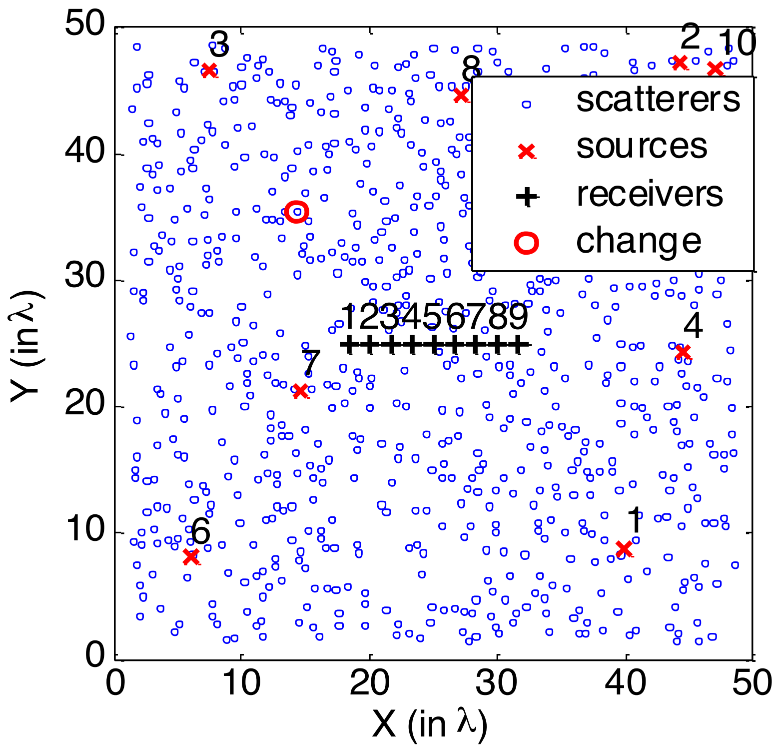


3D CARTOGRAPHIES

→ Damage & cracks [m2/m3]

→ Relative velocity changes[%]

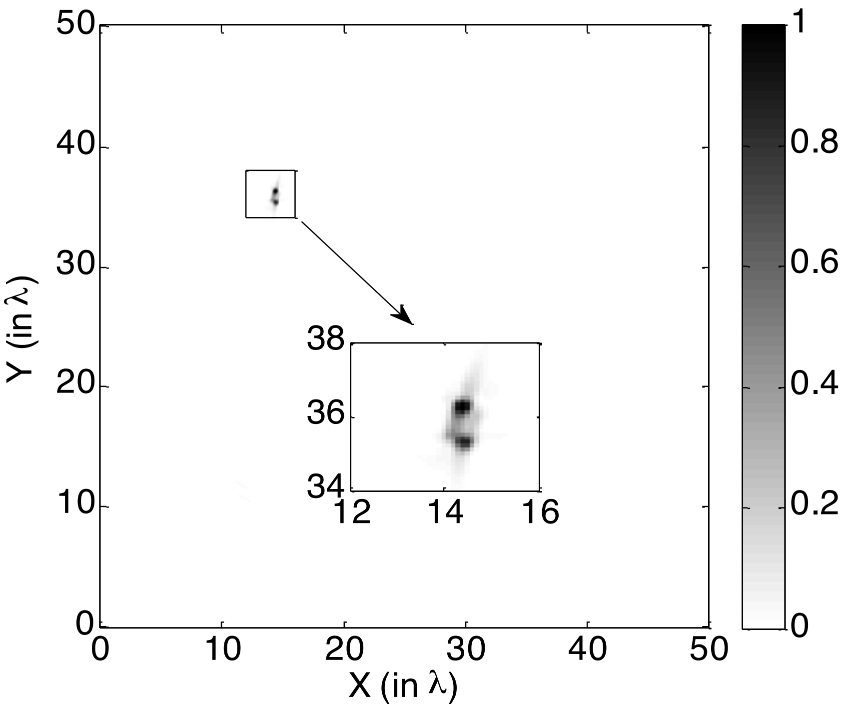




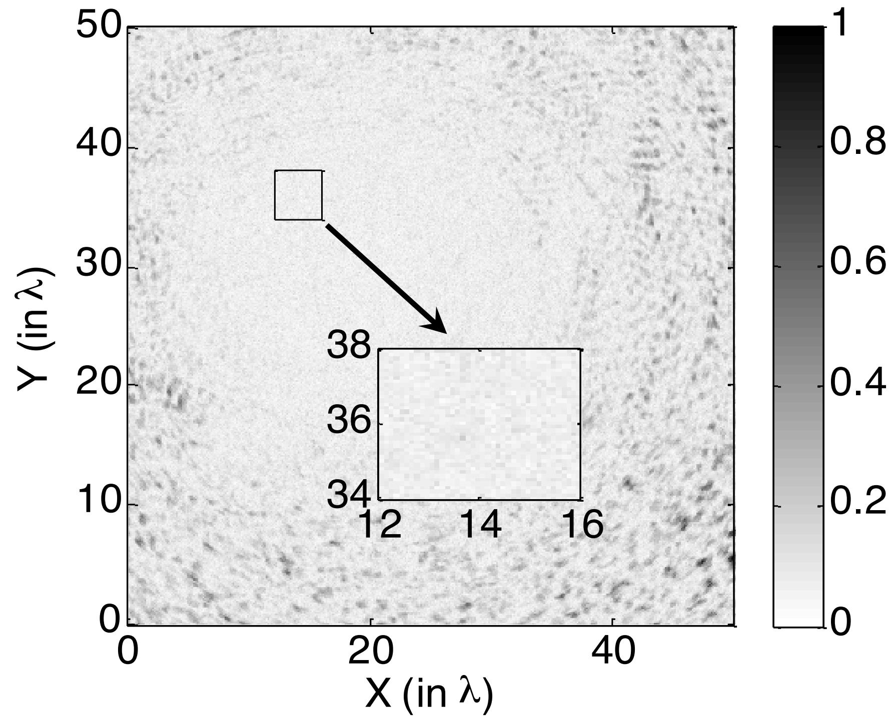
Simple scattering
1 change

Multiple scattering
800 scatterers+ 1 change

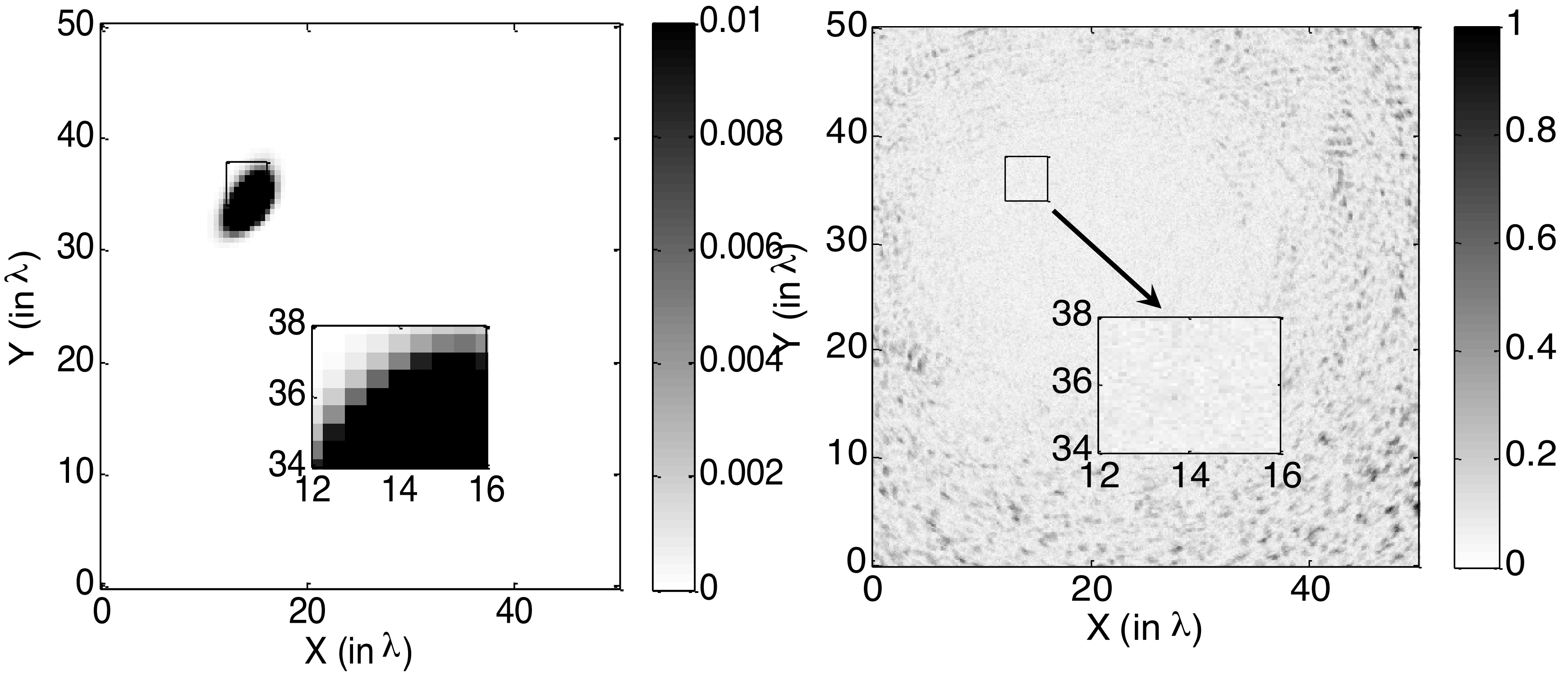
classical imaging



Simple scattering
1 change



Multiple scattering
800 scatterers+ 1 change



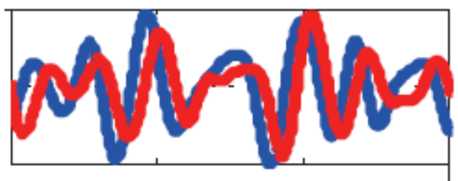
Locadiff (2010) // classical imaging

Locadiff :

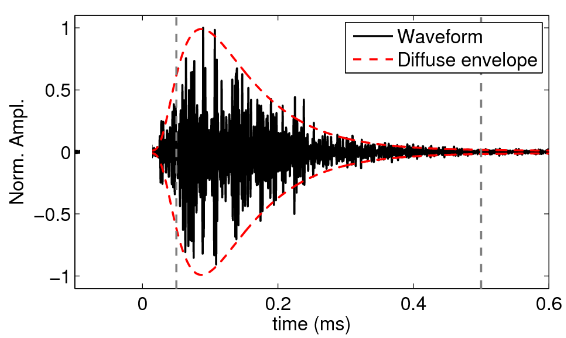
Larose et al, Appl. Phys. Lett. (2010)
Rossetto et al, J. Appl. Phys. (2011)
Planes et al, 2013, 2014, 2015… Obermann et al, 2013, 2014, 2015

Mesoscopic waves

Waveform → Detect



Intensity → Locate

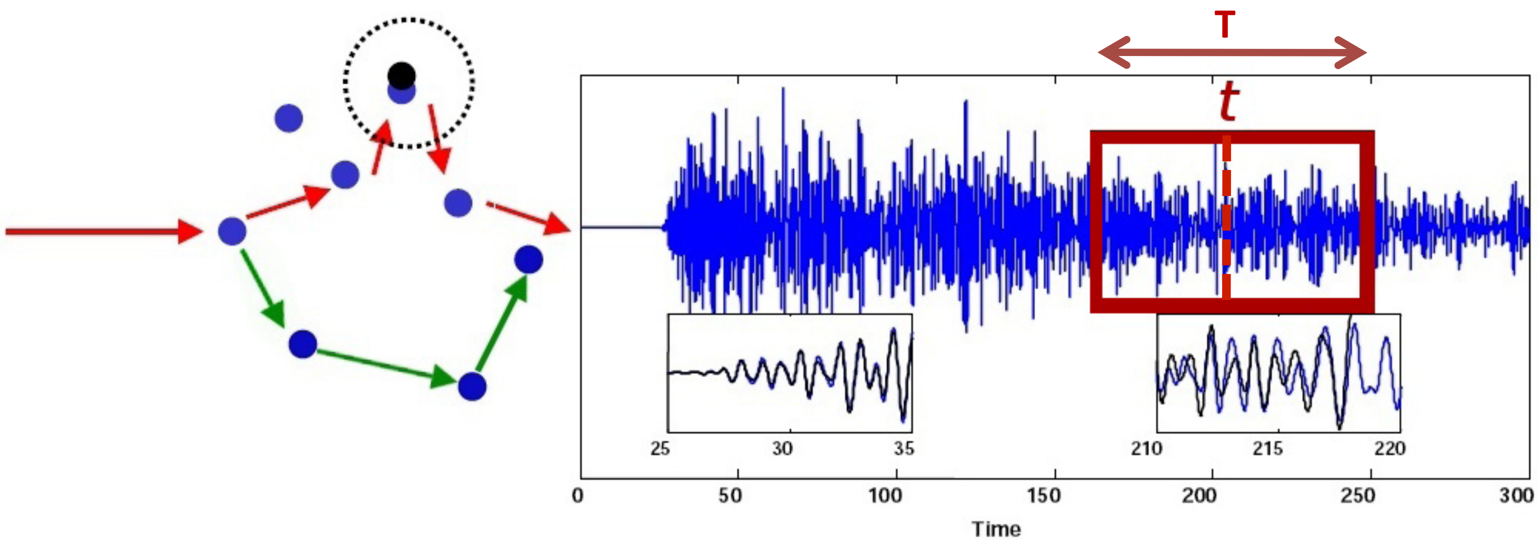


3D CARTOGRAPHIES

→ Damage & cracks [m2/m3]

→ Relative velocity changes[%]

Signature of a change in the coda

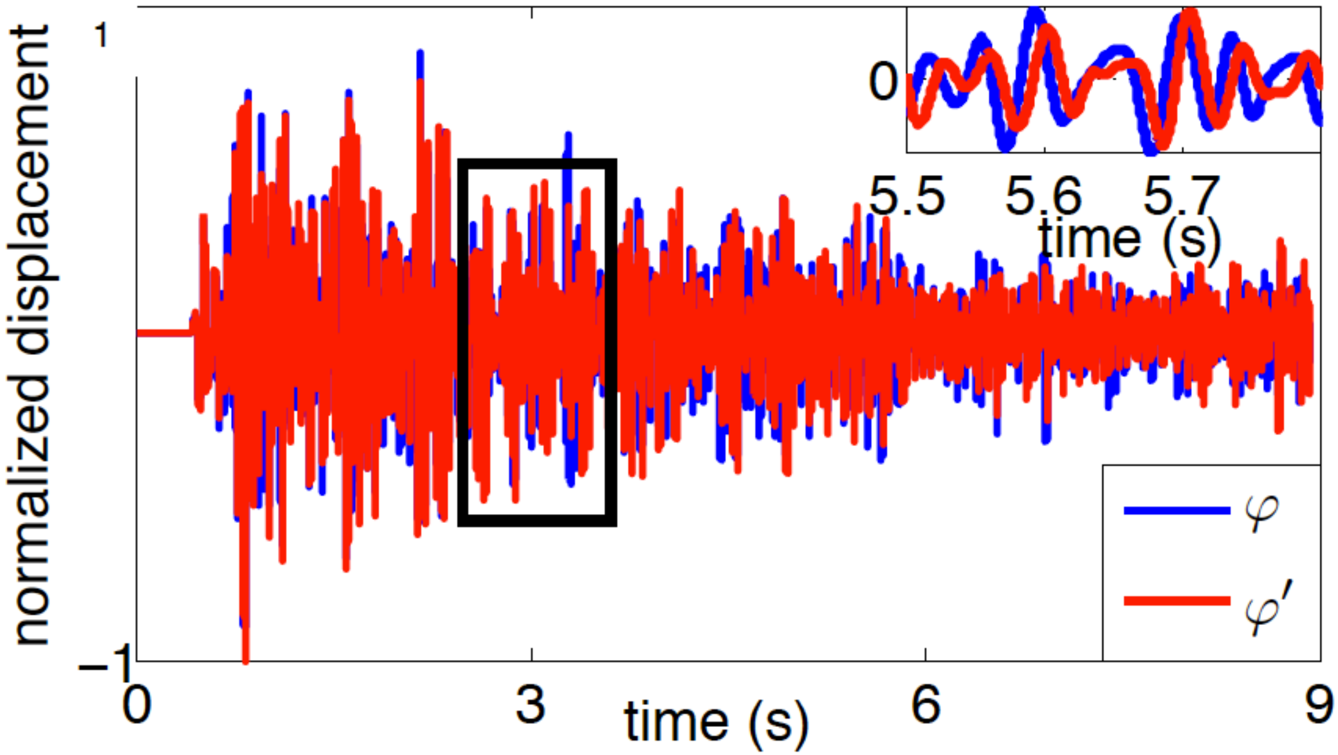


Very sensitive to weak changes

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

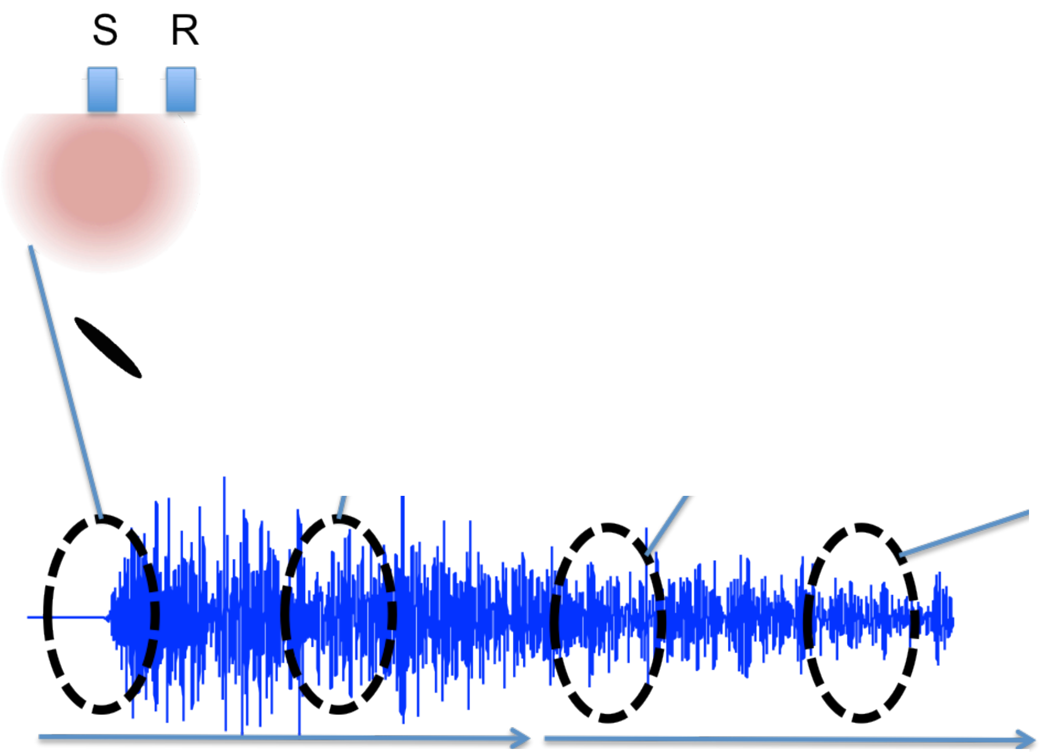
Stretching factor : $\epsilon(t) = \epsilon$ that maximises $\langle \phi_0(t).\phi_1(t(1-\epsilon)) \rangle_T$

Signature of a change in the coda



$$CC(\varepsilon) = \frac{\int_{t_1}^{t_2} \varphi'\left[t(1-\varepsilon)\right] \varphi\left[t\right] dt}{\sqrt{\int_{t_1}^{t_2} \varphi'^2\left[t(1-\varepsilon)\right] dt \int_{t_1}^{t_2} \varphi^2\left[t\right] dt}},$$

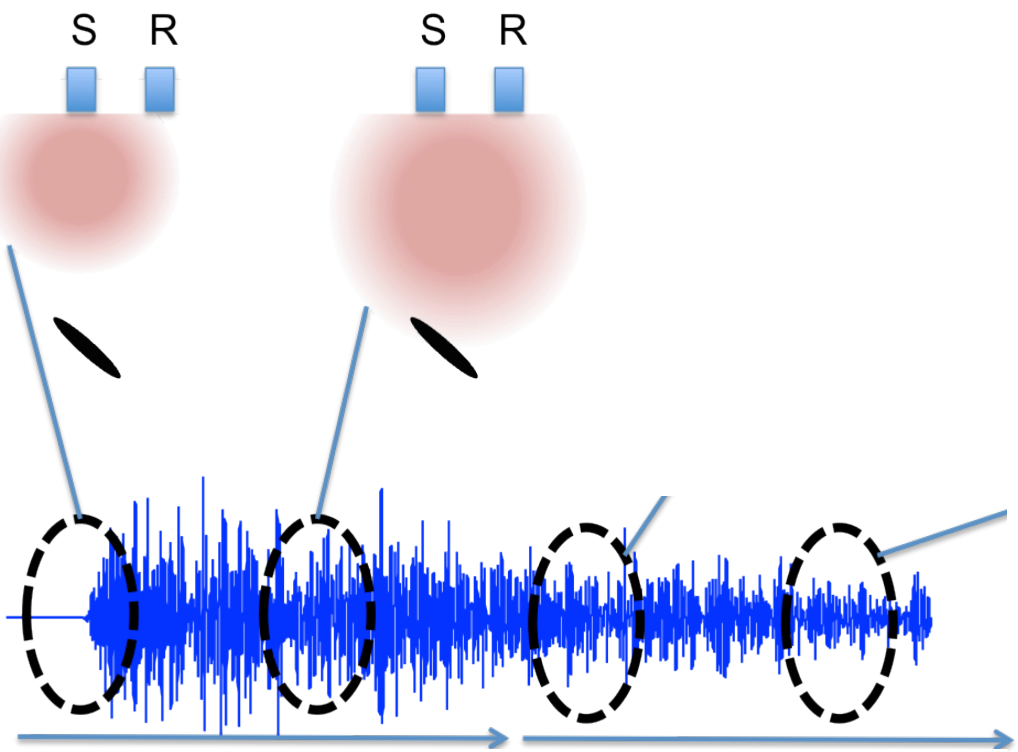
Signature of a change in the coda



No decorrelation
No velocity change

Decorrelation
Velocity change

Signature of a change in the coda



No decorrelation
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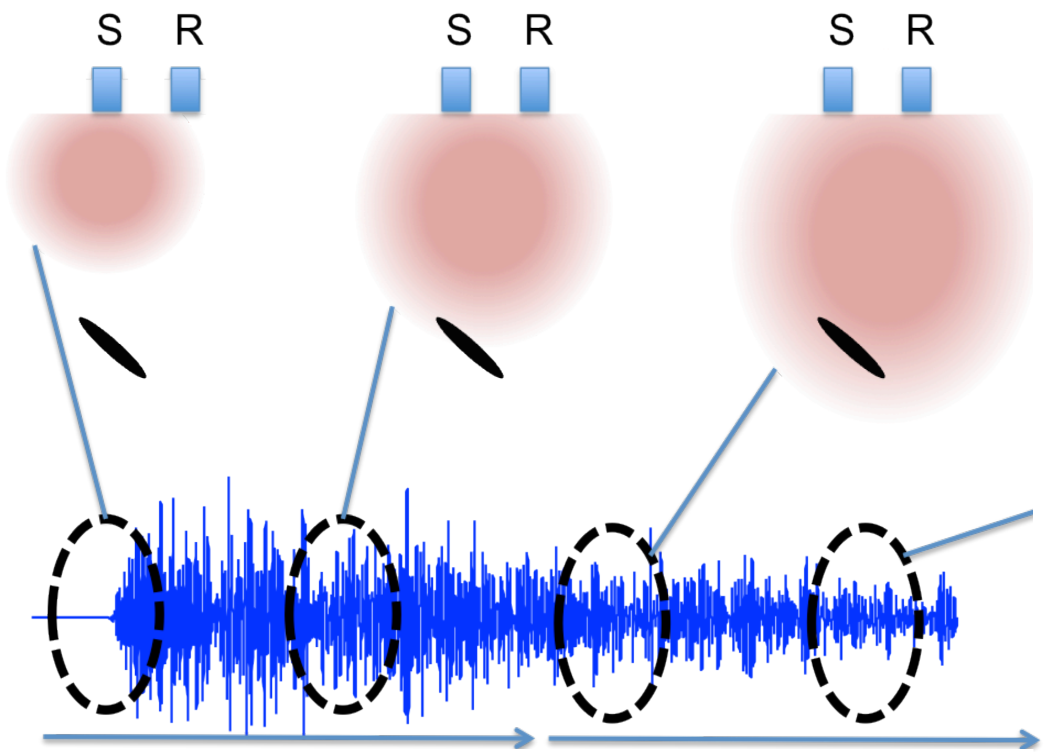
Decorrelation
Velocity change

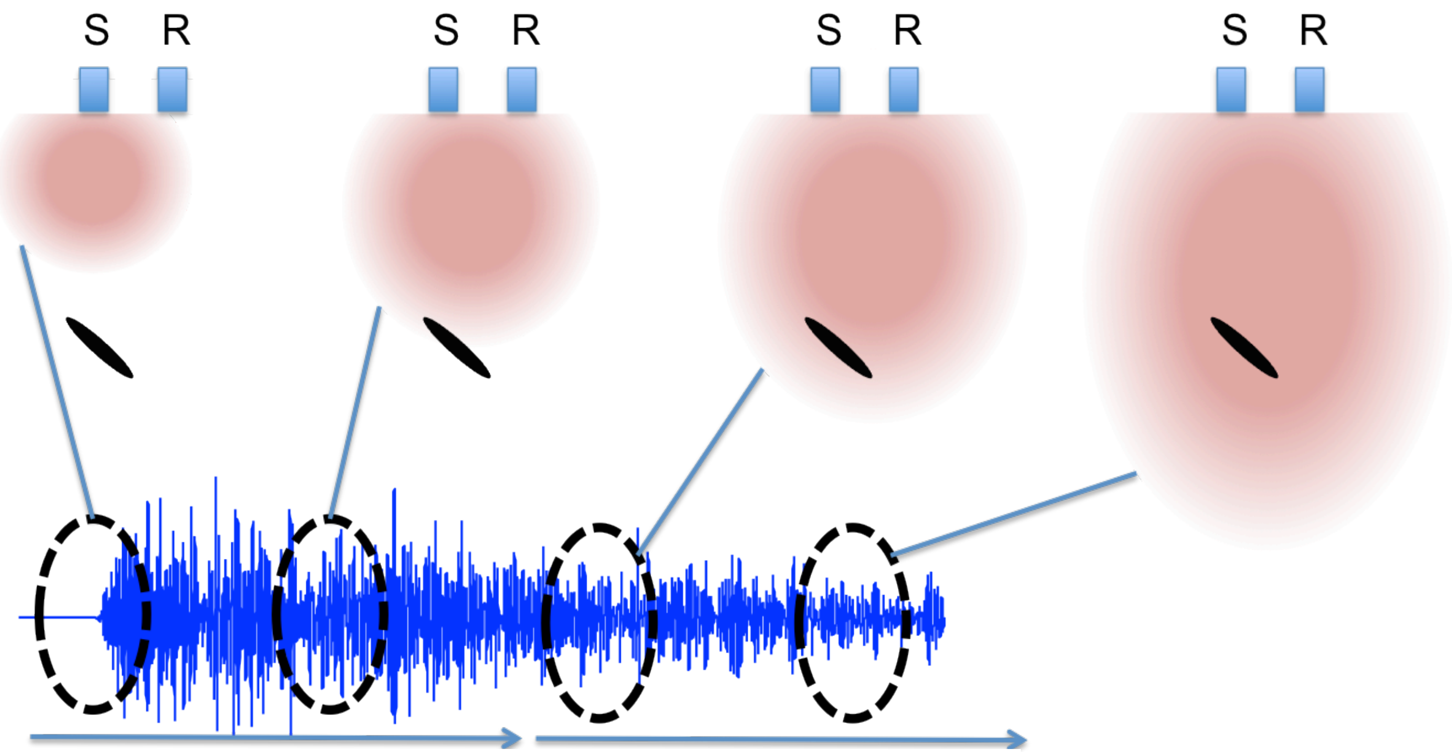
Signature of a change in the coda



No decorrelation
No velocity change

Decorrelation
Velocity change

Signature of a change in the coda



No decorrelation
No velocity change

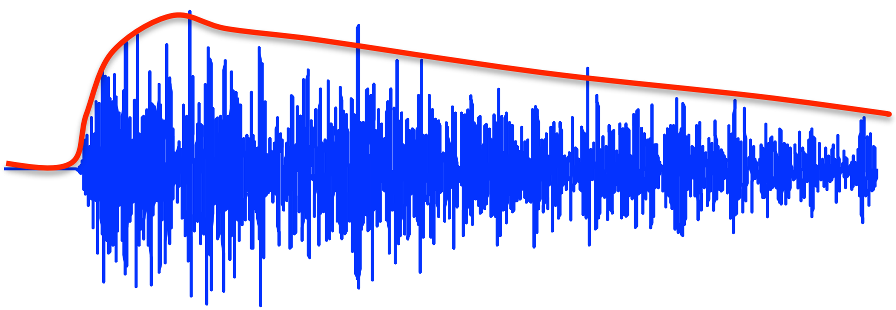
Decorrelation
Velocity change

THE INTENSITY

=

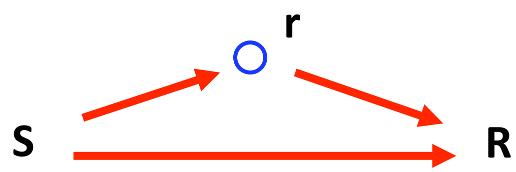
PROBABILITY OF TRANSPORT

I(S,R,t)



Diffusion (heat)

Decorrelation induced by an extra scatterer : Theoretical model



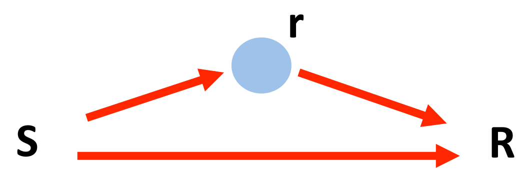
Theoretical decorrelation

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

Rossetto et al. [J. Appl. Phys. 2011]

I : Intensity propagator (Diffusion solution, Radiative Transfer)
σ : Scattering cross section of the new defect

Local relative velocity change dV/V : Theoretical model



Pacheco & Snieder [2005]

Theoretical relative velocity change

$$\varepsilon^{\text{app}}(S,R,r,t) = \frac{dv}{v}\frac{\Delta \mathrm{V}}{t}\frac{\int_0^t I(S,r,u)I(r,R,t-u)du}{I(S,R,t)}$$

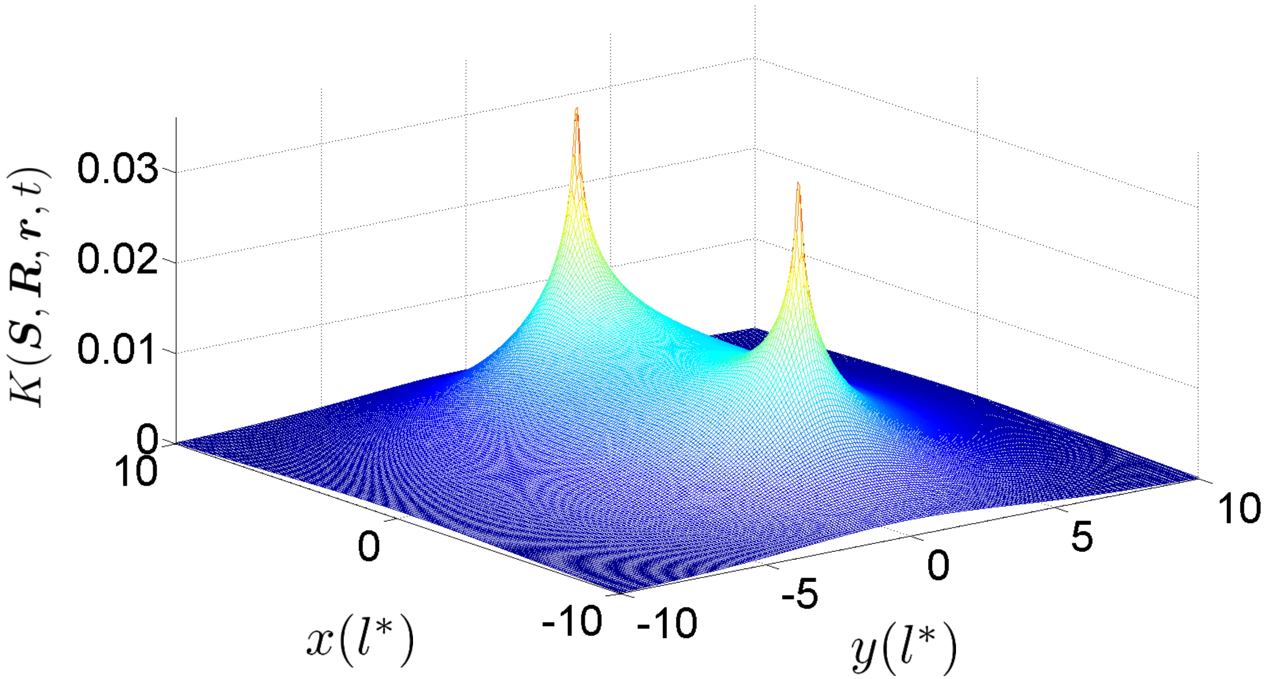
I : Intensity propagator (Diffusion solution, Radiative Transfer)
dv/v : Scattering cross section of the new defect

Sensitivity kernel

decorrelation

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

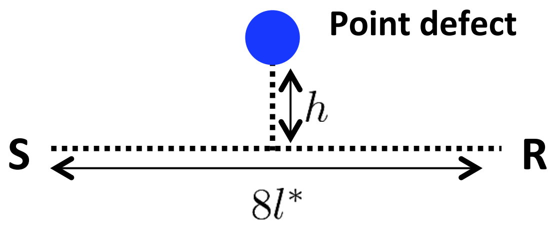
$$K(\boldsymbol{S},\boldsymbol{R},\boldsymbol{r},t) = \frac{\int_0^t I(\boldsymbol{S},\boldsymbol{r},u) I(\boldsymbol{r},\boldsymbol{R},t-u)du}{I(\boldsymbol{S},\boldsymbol{R},t)}$$



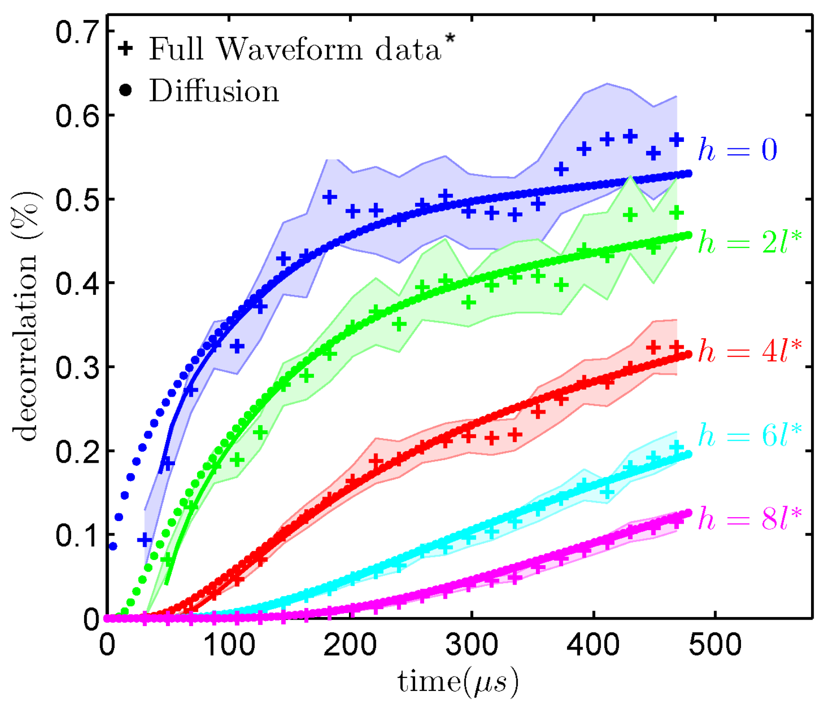
$$I(\boldsymbol{S},\boldsymbol{R},t) = \text{Diffusion solution}$$

Forward problem validation

Far field



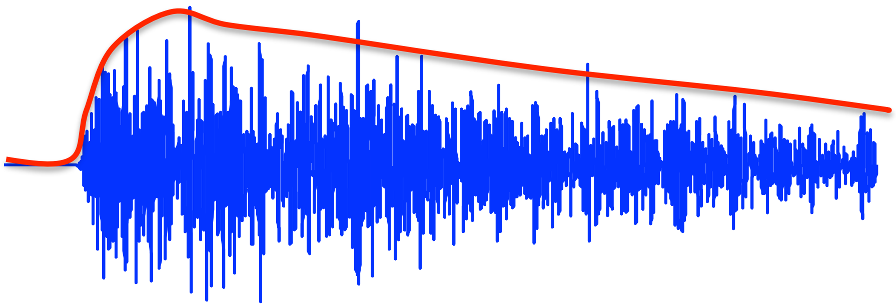
$$DC^{th}(\boldsymbol{S},\boldsymbol{R},\boldsymbol{r},t) = \frac{c\sigma}{2}\frac{\int_0^t I(\boldsymbol{S},\boldsymbol{r},u)I(\boldsymbol{r},\boldsymbol{R},t-u)du}{I(\boldsymbol{S},\boldsymbol{R},t)}$$



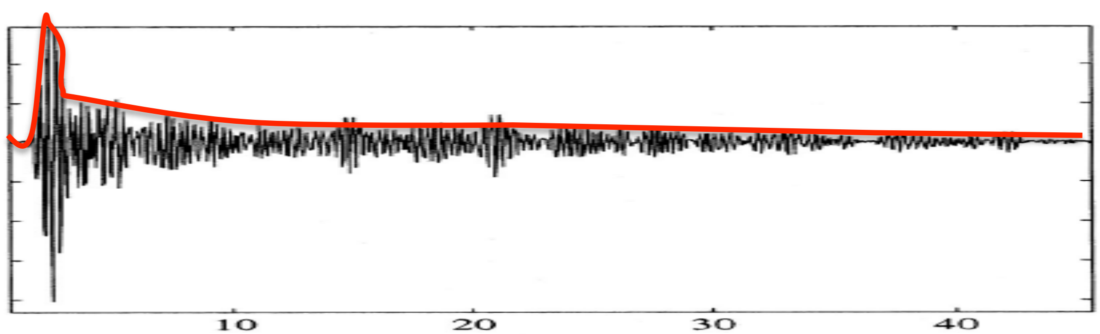
$$I(\boldsymbol{s},\boldsymbol{r},t) = \frac{I_0}{(4\pi Dt)}e^{\frac{\|\boldsymbol{s}-\boldsymbol{r}\|^2}{4Dt}}$$

T. Planes et al, 2014 & 2015

Sensitivity Kernels NEED:
Predict the TRANSPORT OF THE INTENSITY *I(S,R,t)*



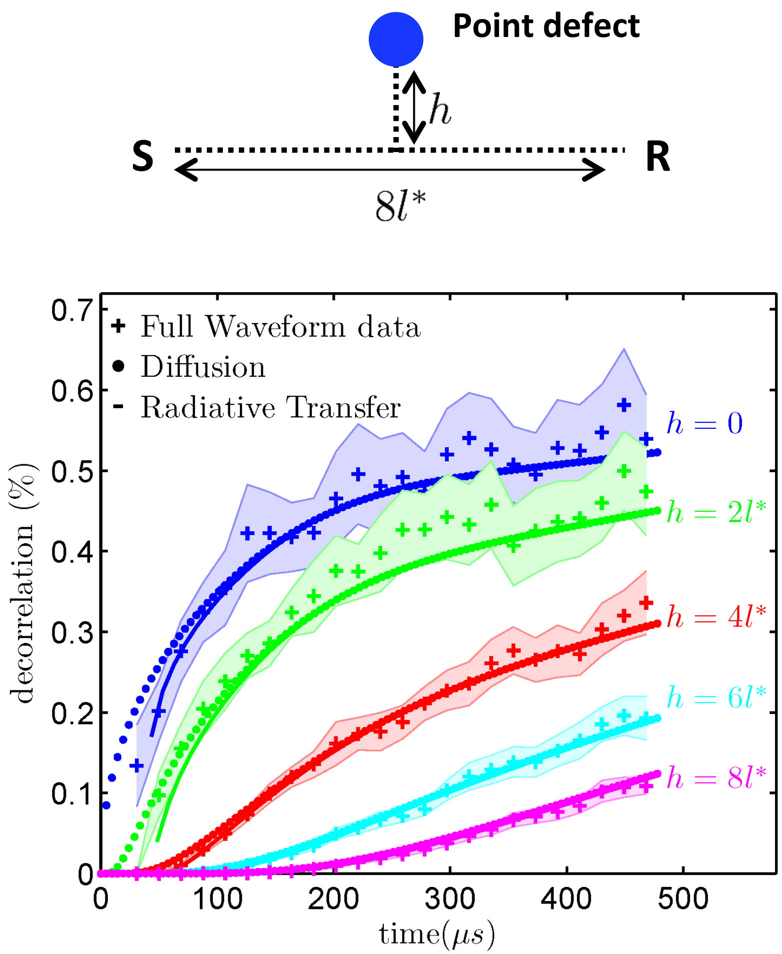
Diffusion (heat)



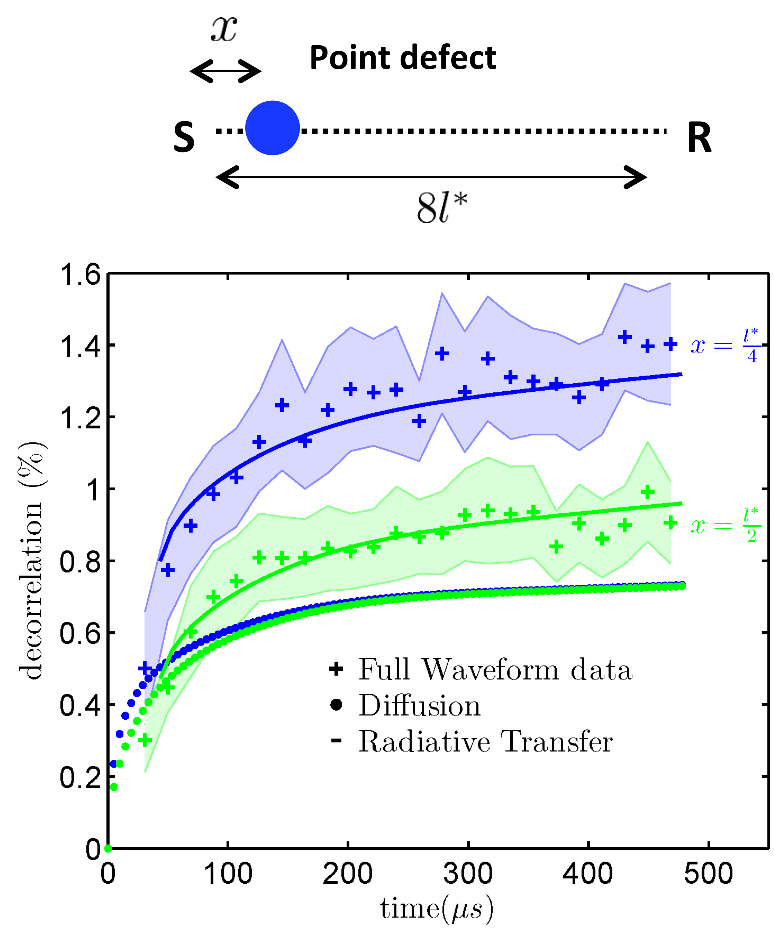
Radiative Transfert
Sato 1993,
Passchens 1997…

T. Planes et al, 2014 & 2015

Far field



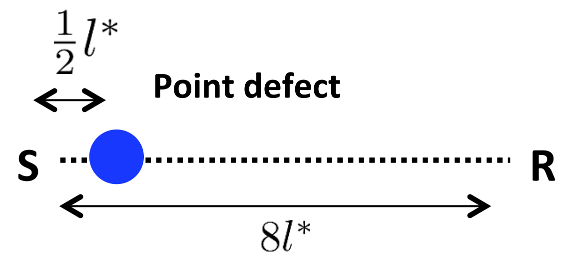
Near field



T. Planes et al, 2014 & 2015

Forward problem validation

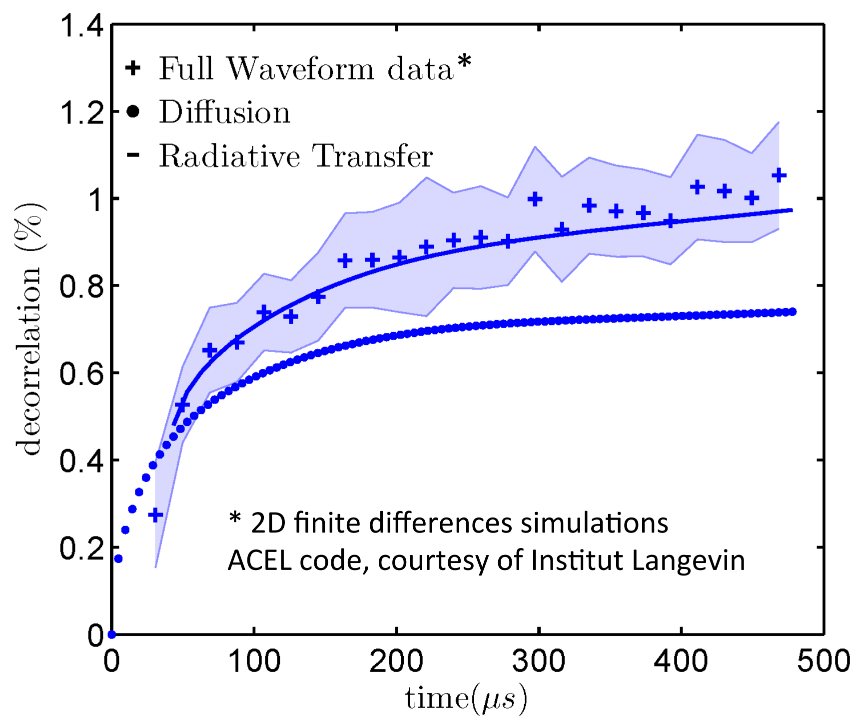
Near field



2D Radiative Transfer Solution
[Paasschens PRE 1997] :

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

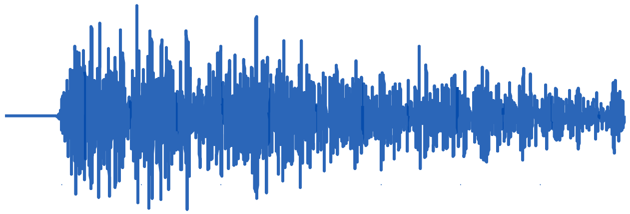
$$\underbrace{+\frac{1}{2\pi l c t}\left(1-\frac{r^2}{c^2t^2}\right)^{-\frac{1}{2}} e^{[l^{-1}(\sqrt{c^2t^2-r^2}-ct]}\Theta(ct-r)}_{\text{incohérent}}$$



T. Planes et al, 2014 & 2015

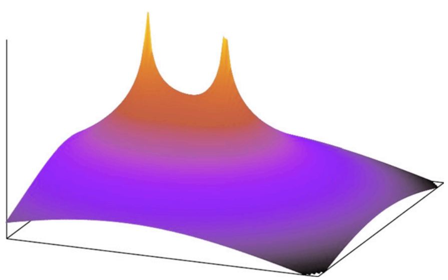
Application to ACTIVE data

Workflow



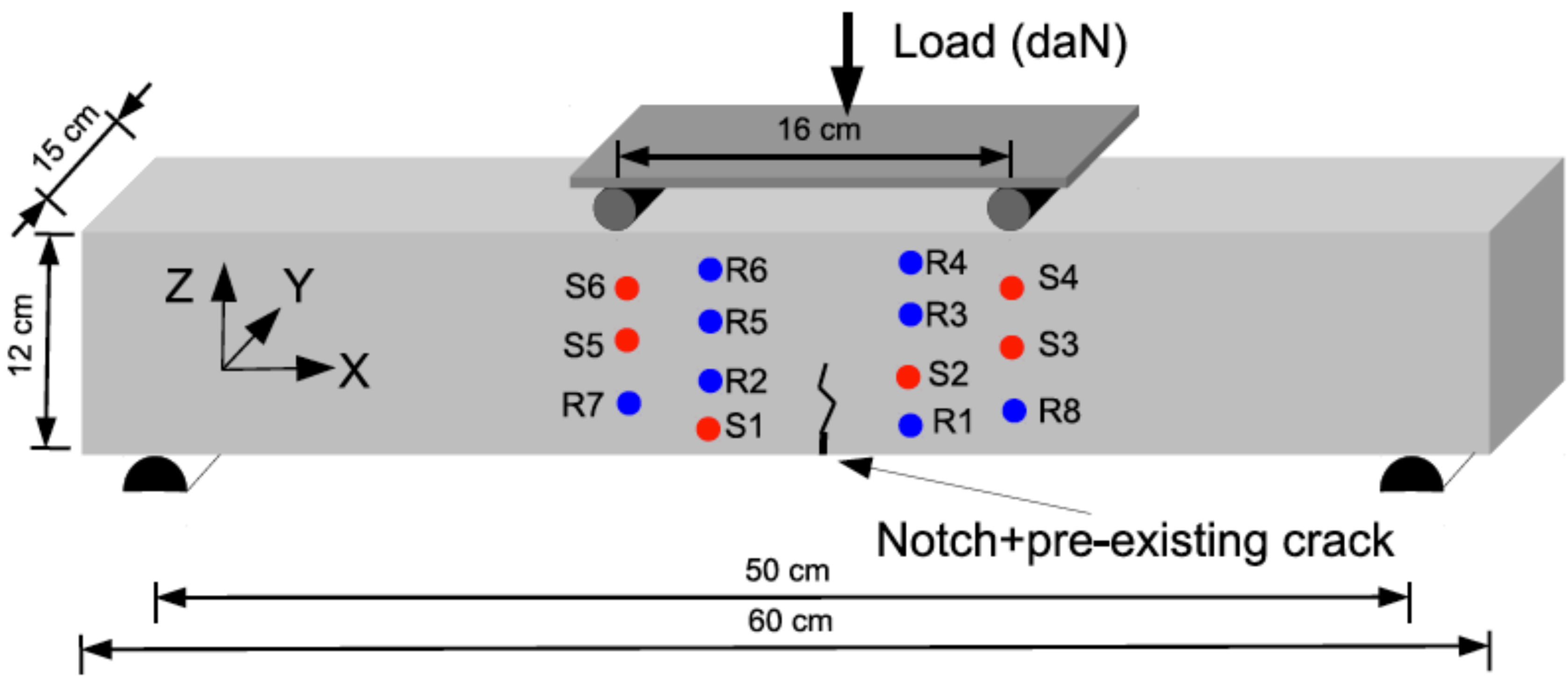
Active records

Measure dV/V and DC

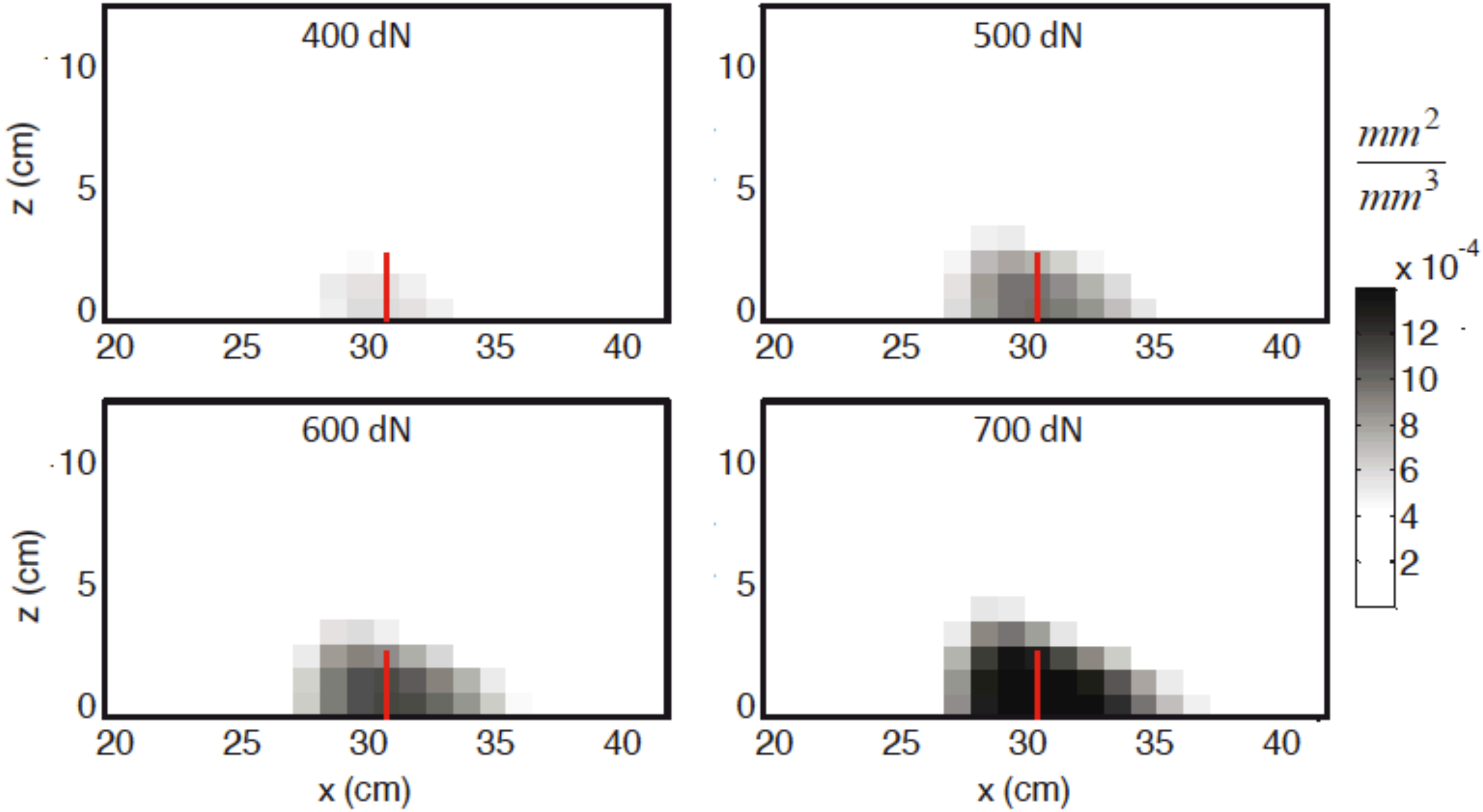


Evaluate sensitivity kernels

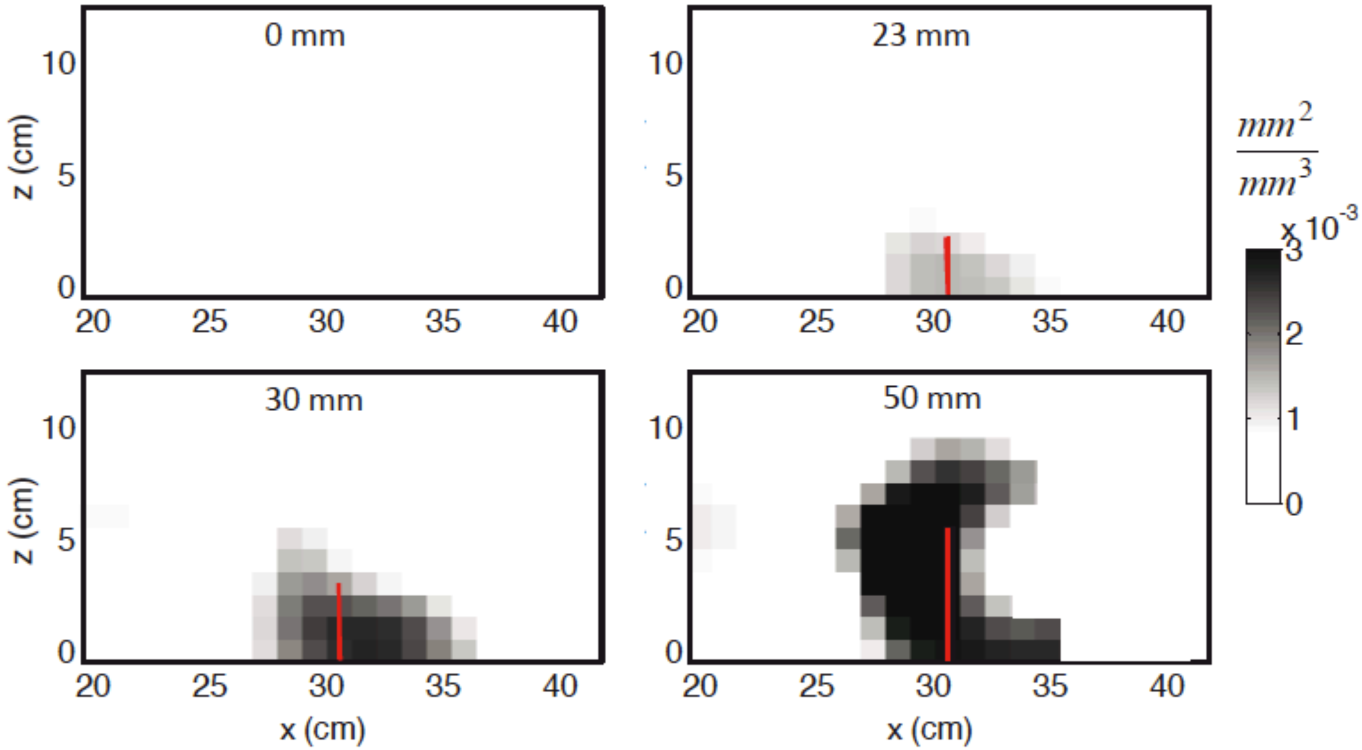
LOCATE
the changes



Larose et al, J. Acoust. Soc. Am. (2015)



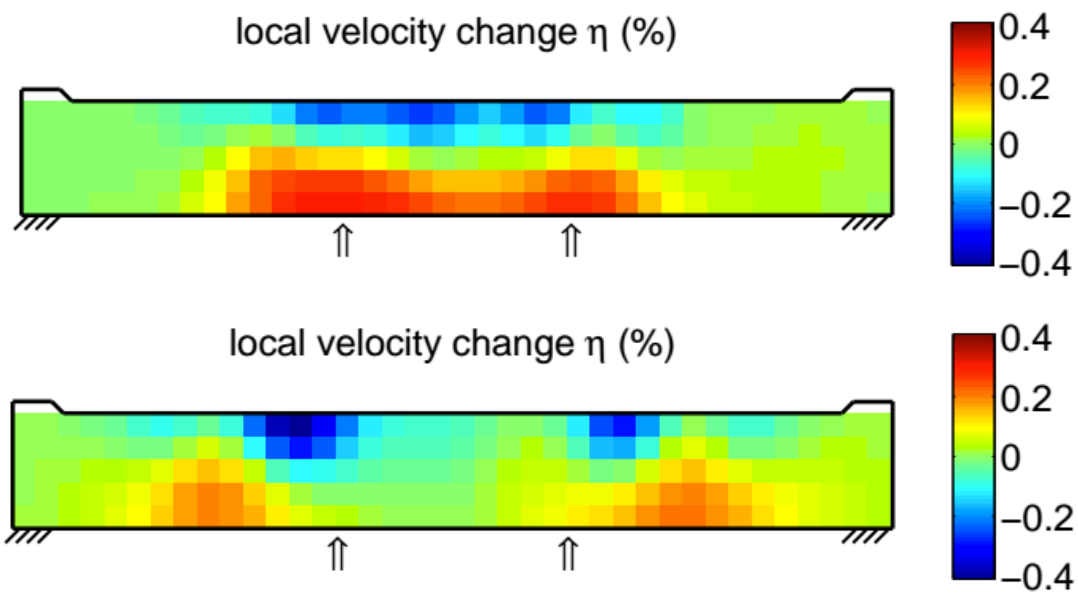
Larose et al, J. Acoust. Soc. Am. (2015)



Larose et al, J. Acoust. Soc. Am. (2015)

Stress map (3D)
In Situ & non-destructive

600 kPa



(3D)

800 kPa

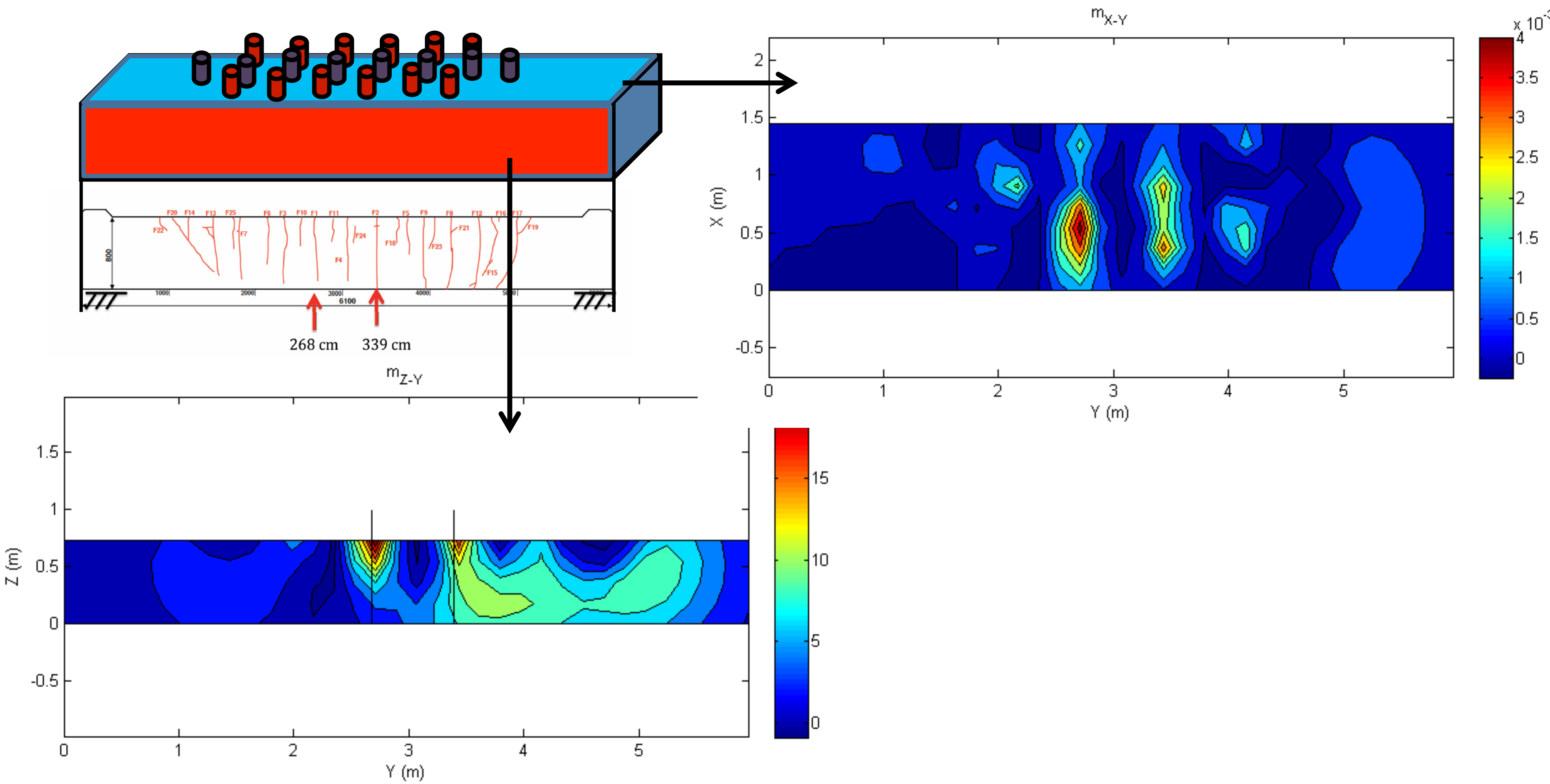
(3D)

CEOS

Zhang et al (2015)

Comportement et Evaluation des Ouvrages Spéciaux vis-à-vis de la fissuration et du retrait

Damage/crack localisation



Zhang et al (2015)

CEOS

Comportement et Evaluation des Ouvrages Spéciaux vis-à-vis de la fissuration et du retrait

Application to PASSIVE data

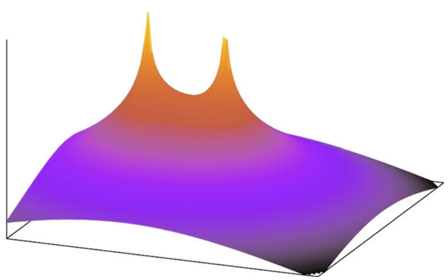
Workflow

Ambient noise → Daily cross-correlation

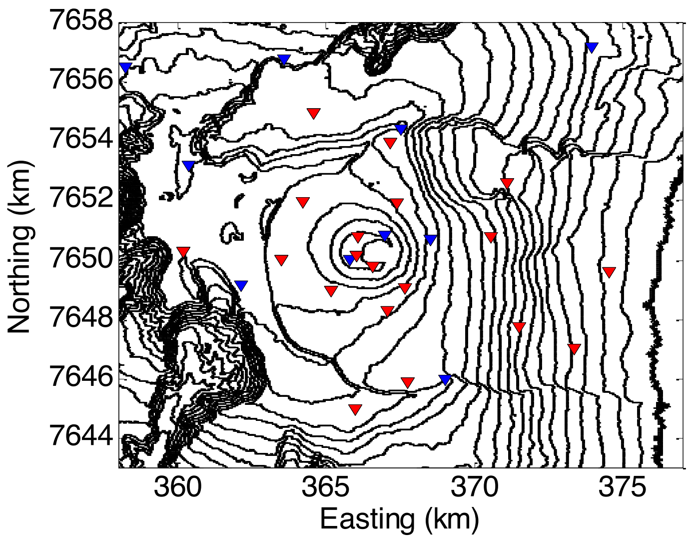
↓

Measure dV/V and Kd

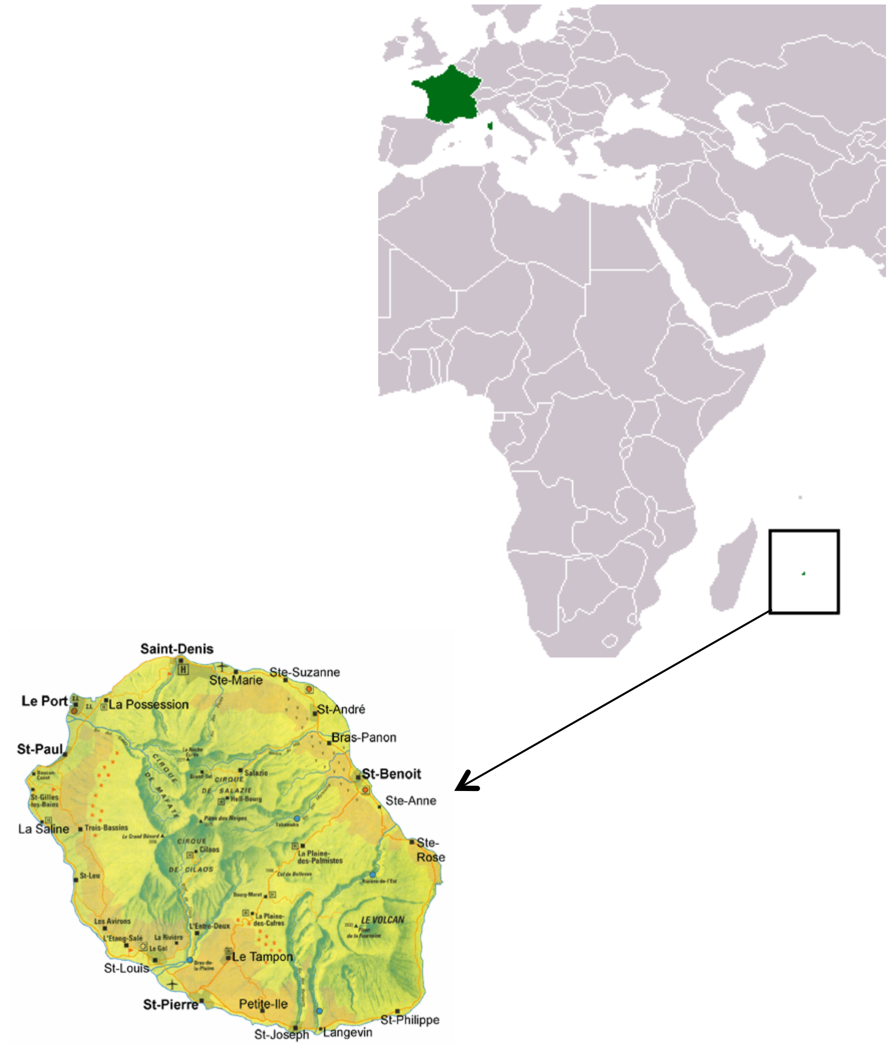
↓

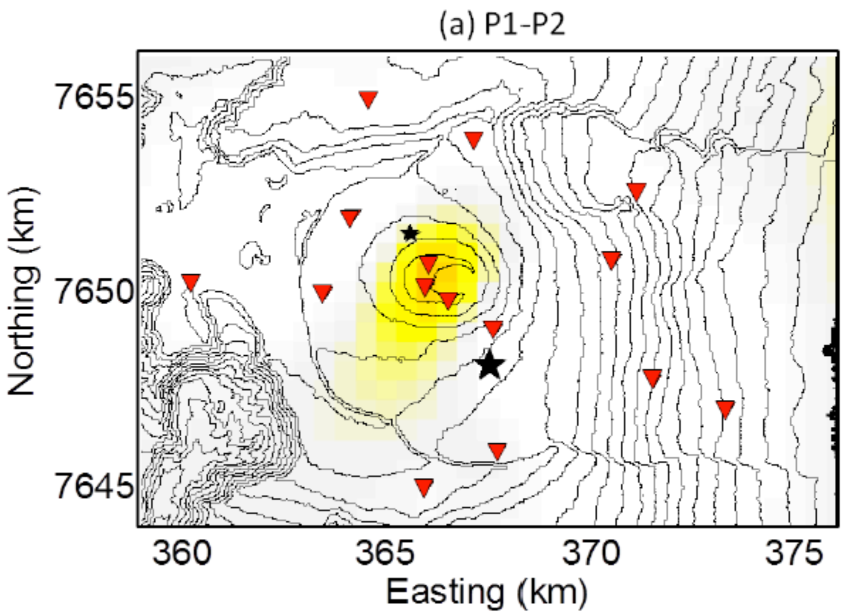


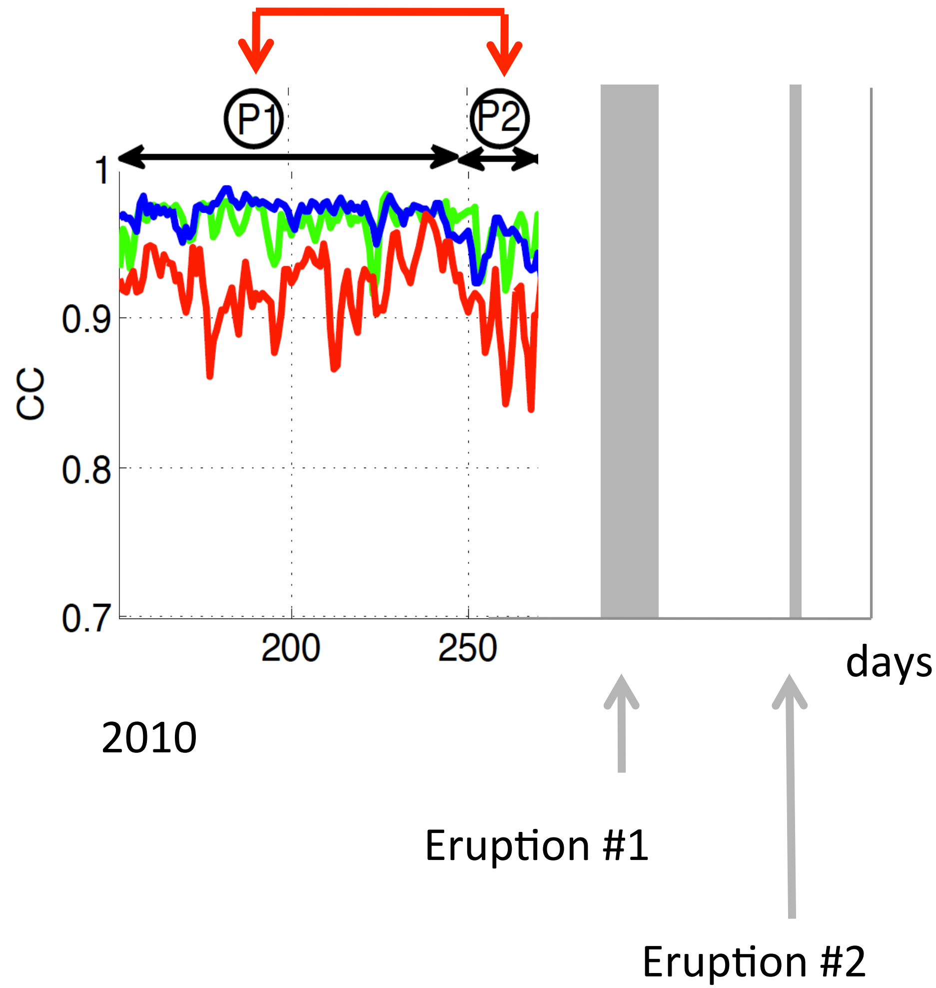
Evaluate sensitivity kernels → LOCATE the changes


7658
7656
7654
7652
7650
7648
7646
7644
Northing (km)
360
365
370
375
Easting (km)

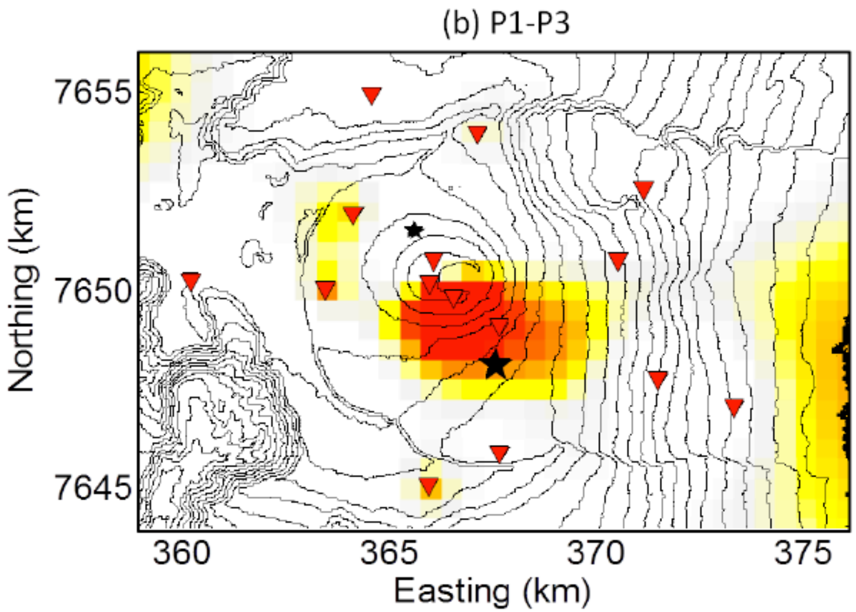
UnderVolc

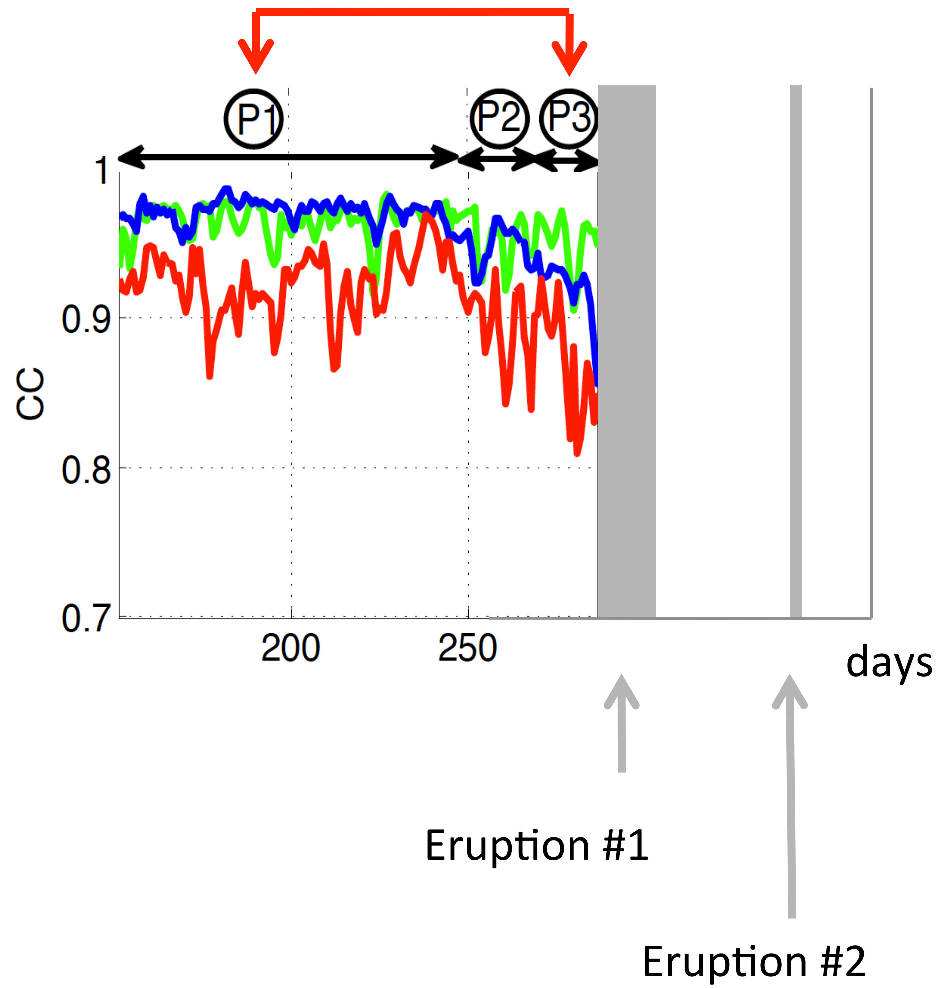

Saint-Denis
Ste-Suzanne
Ste-Marie
Le Port
La Possession
St-André
Bras-Panon
St-Paul
St-Benoit
Ste-Anne
La Saline
Ste-Rose
LE VOLCAN
Le Tampon
St-Louis
St-Pierre
Petite-Ile
St-Joseph
Langevin
St-Philippe



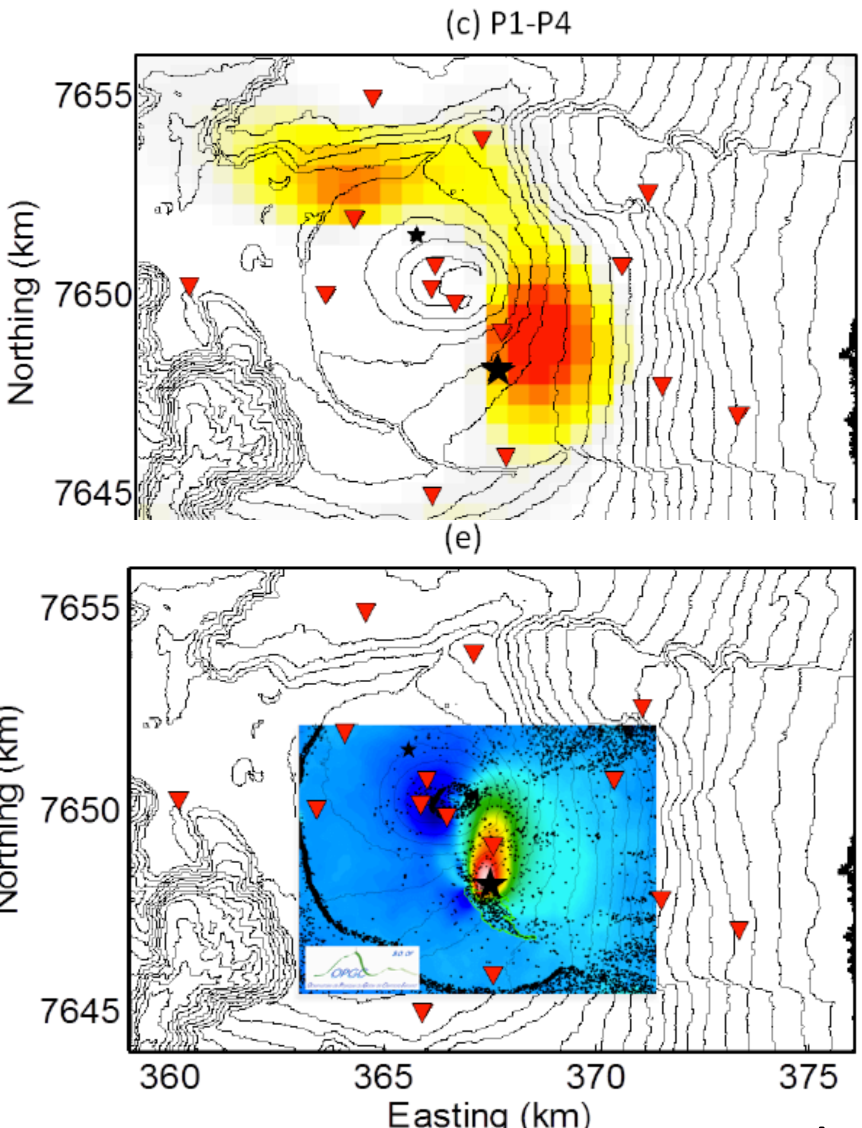


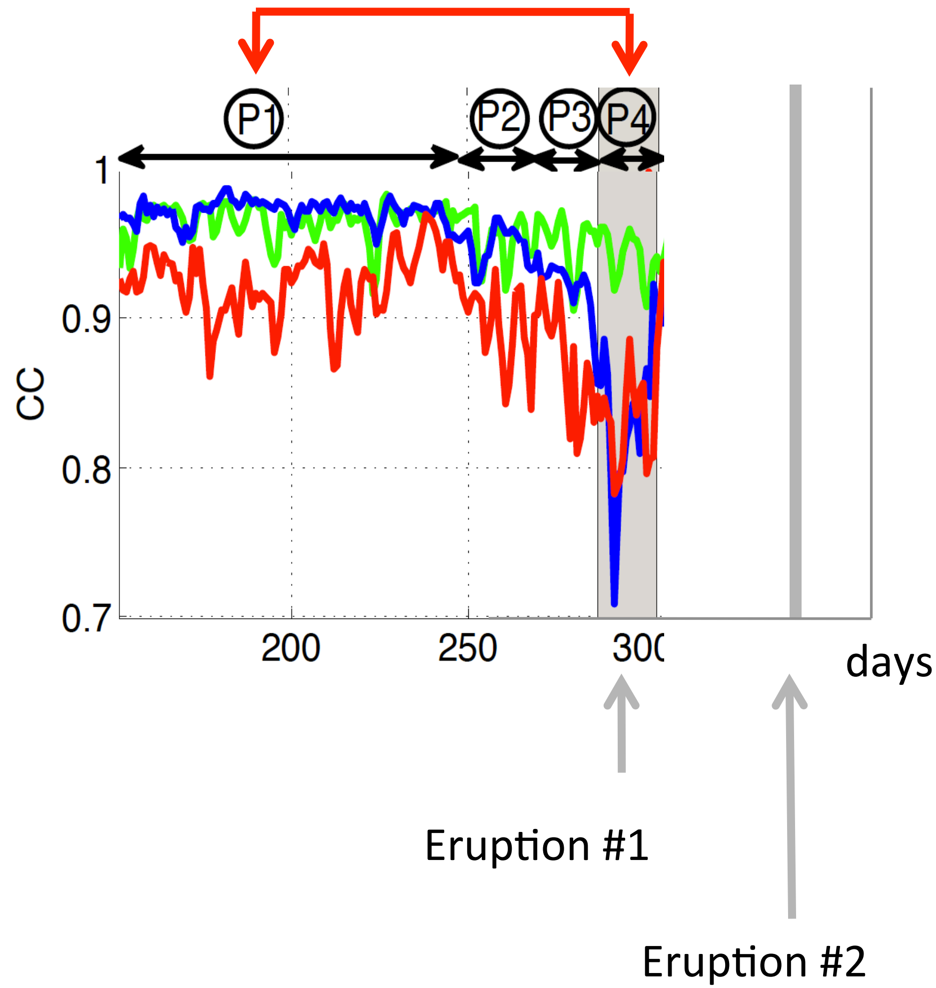
A. Obermann et al. J. Geophys. Res. (2013)



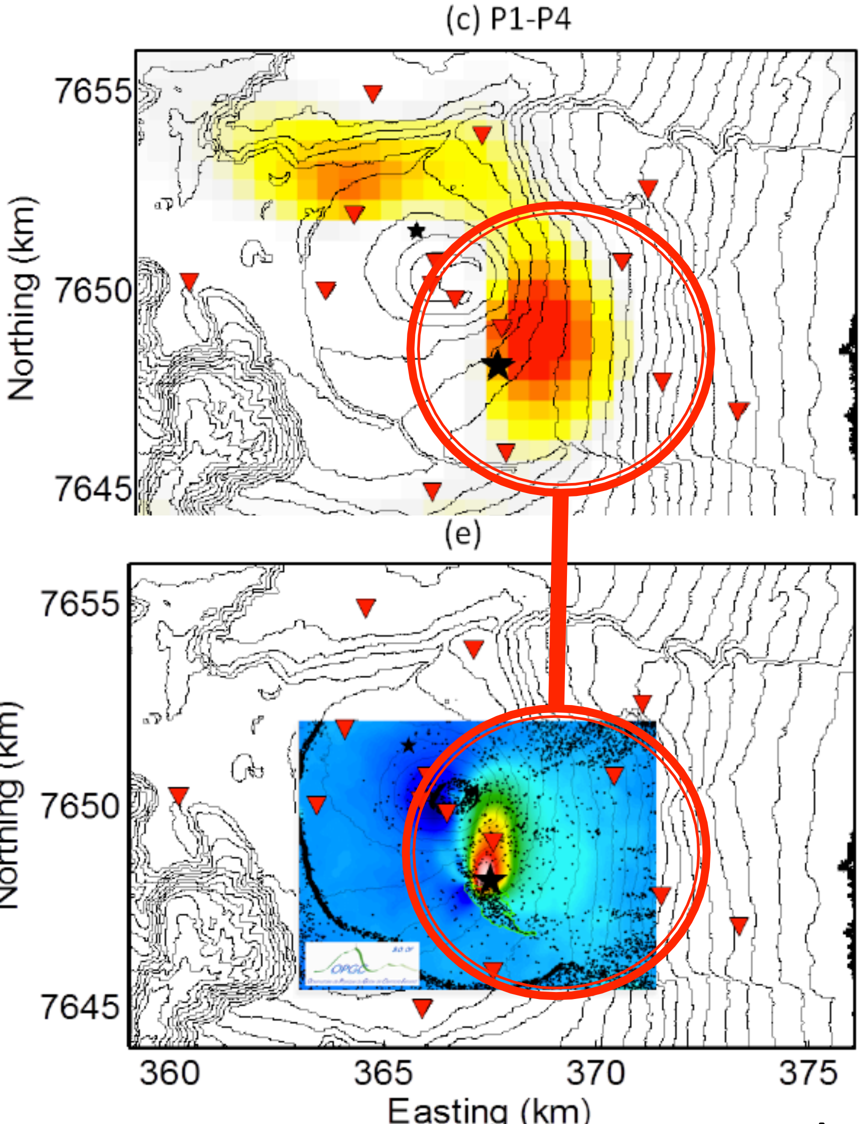


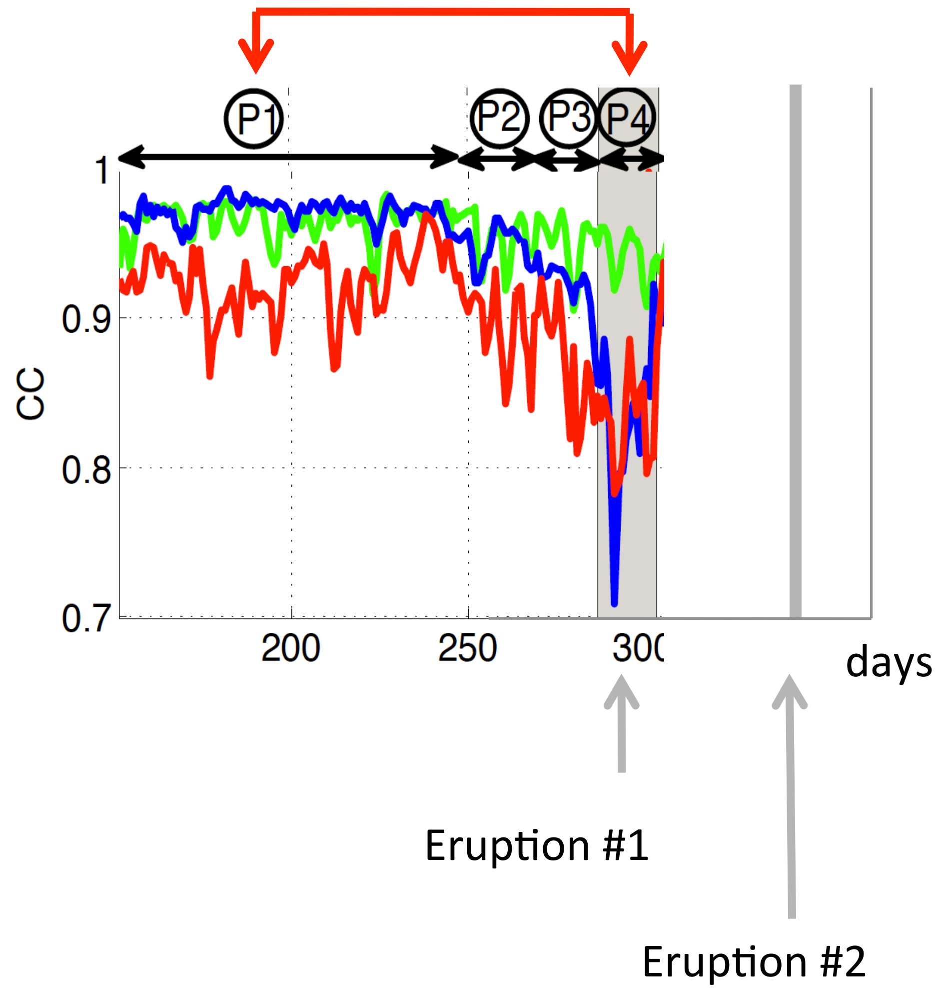
A. Obermann et al. J. Geophys. Res. (2013)



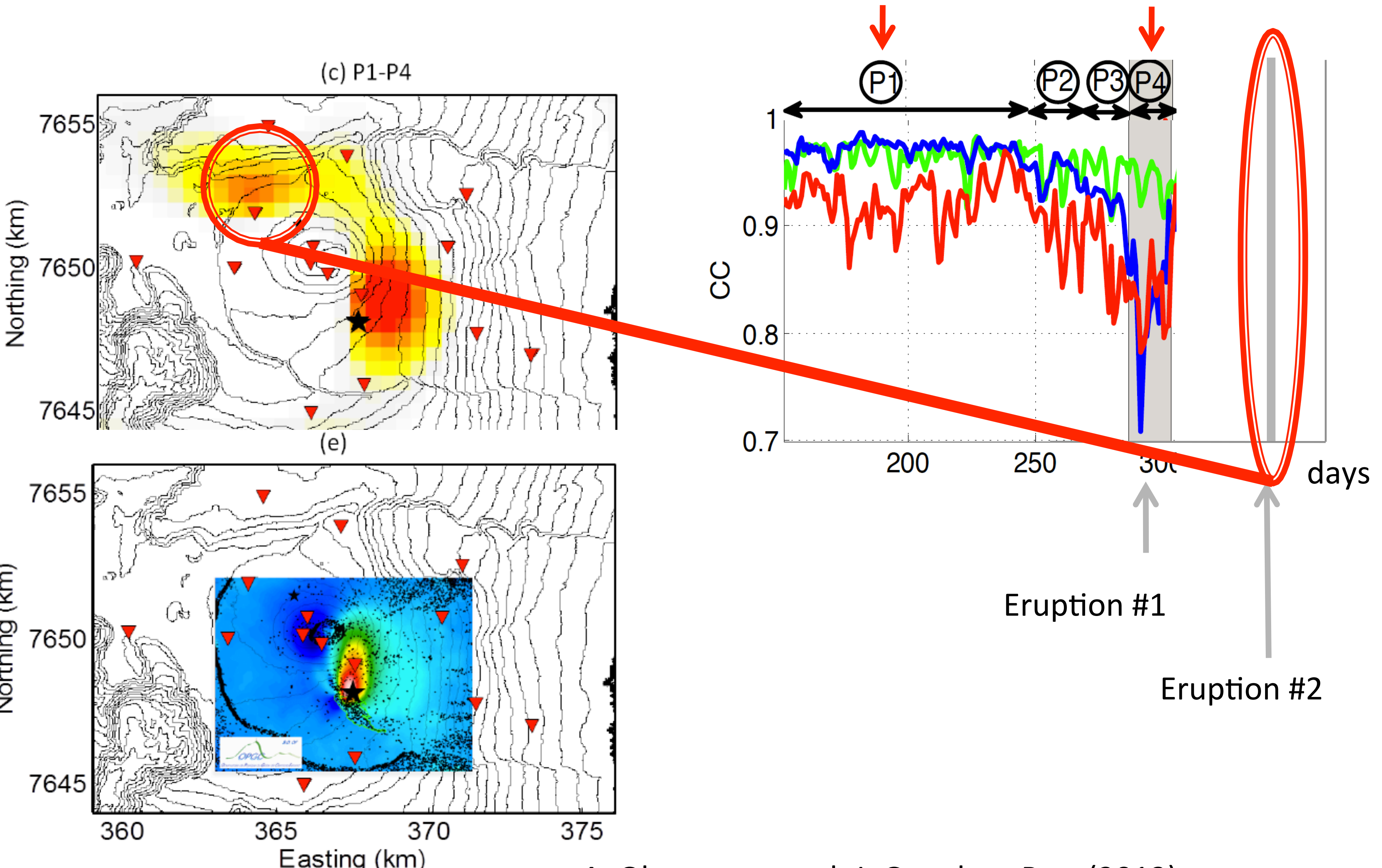


A. Obermann et al. J. Geophys. Res. (2013)

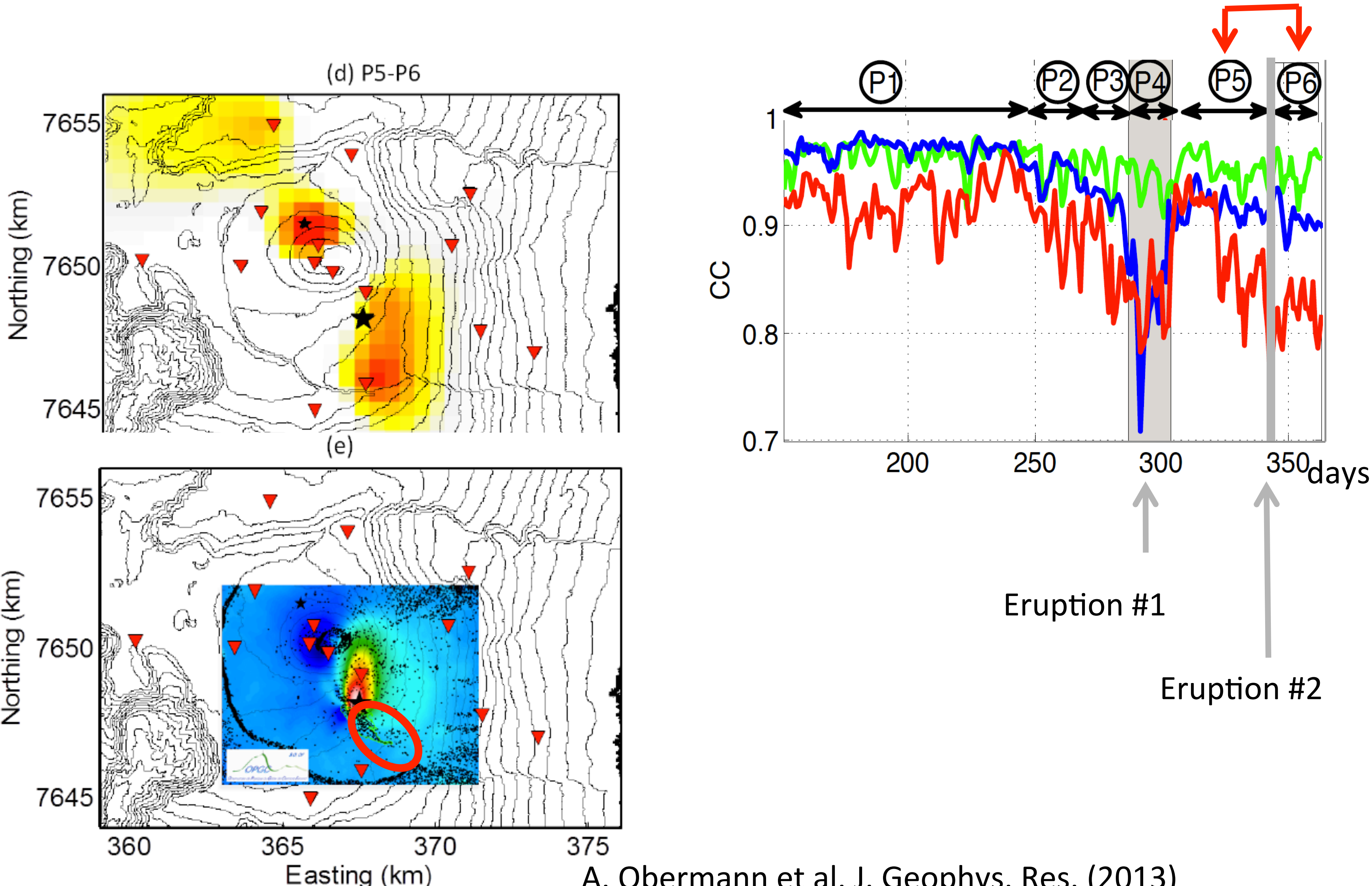




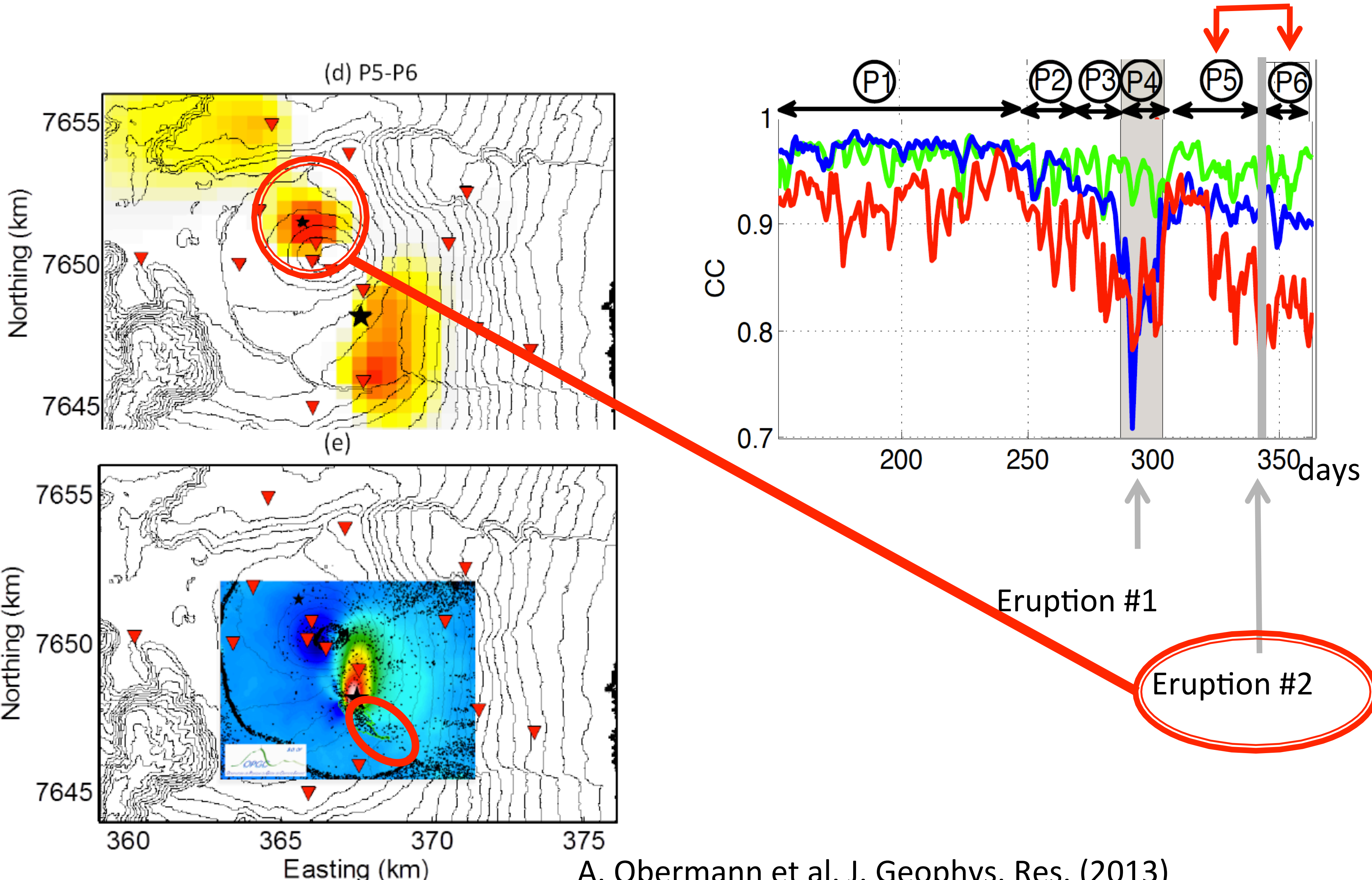
A. Obermann et al. J. Geophys. Res. (2013)



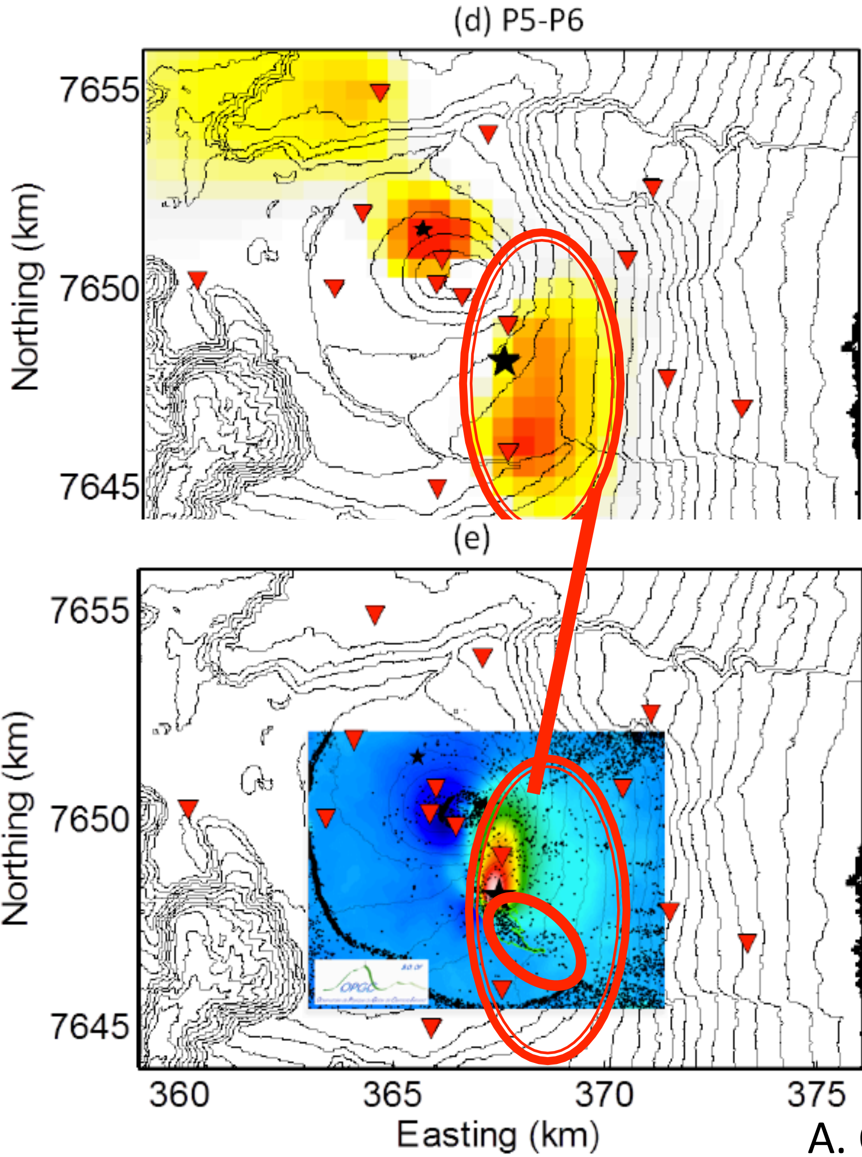
A. Obermann et al. J. Geophys. Res. (2013)

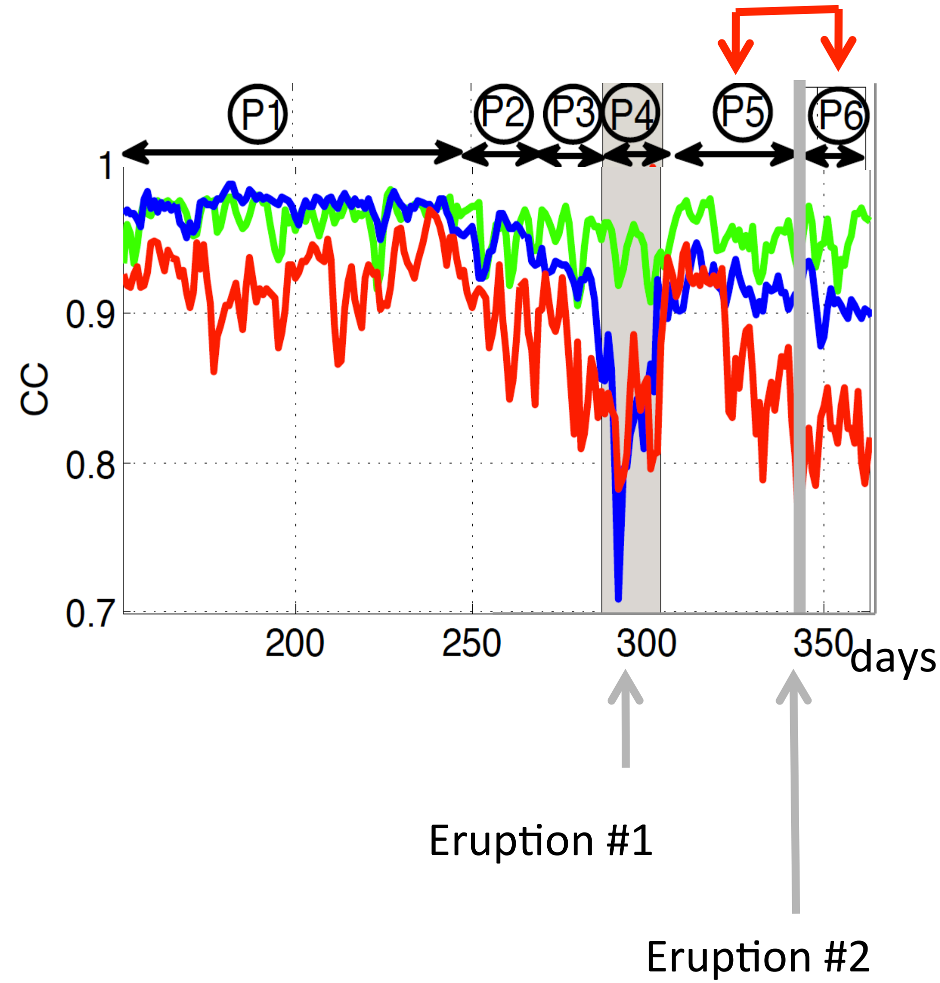


A. Obermann et al. J. Geophys. Res. (2013)

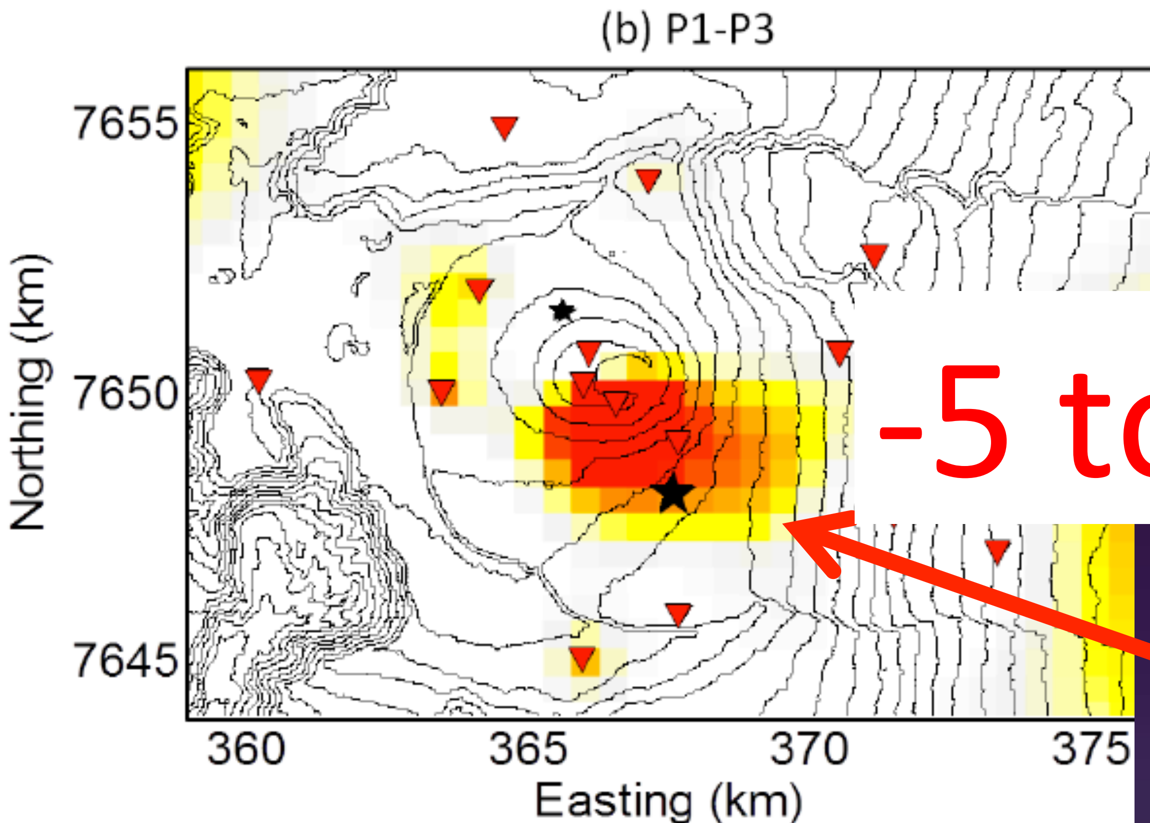


A. Obermann et al. J. Geophys. Res. (2013)





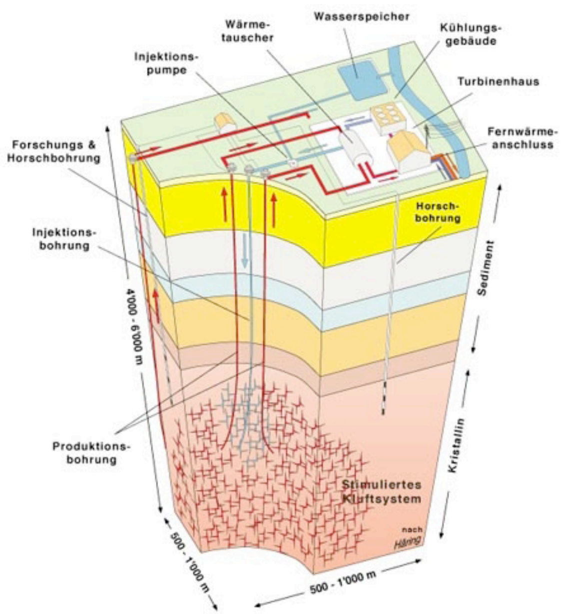
A. Obermann et al. J. Geophys. Res. (2013)

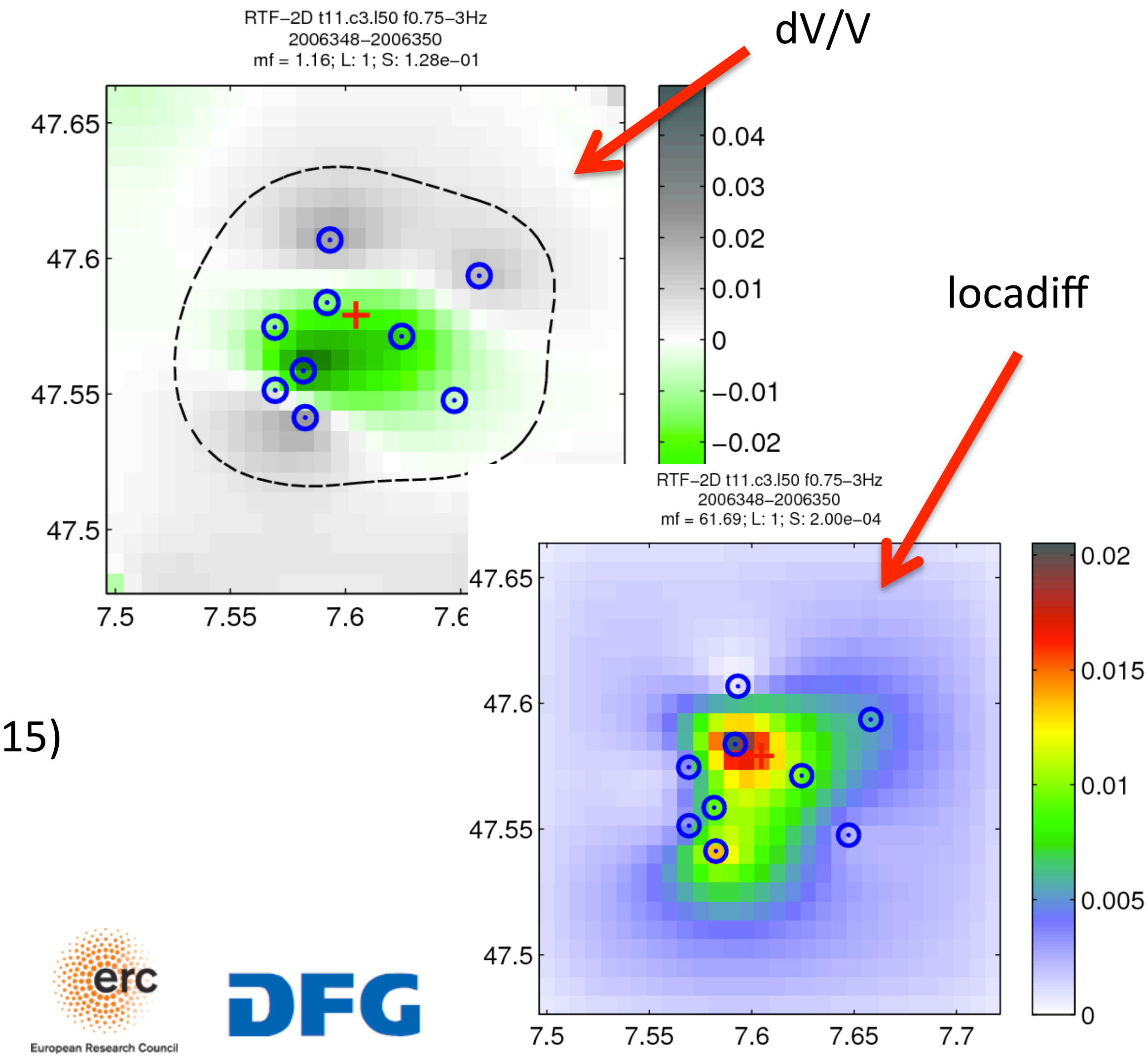


-5 to -10 days

A. Obermann et al. J. Geophys. Res. (2013)

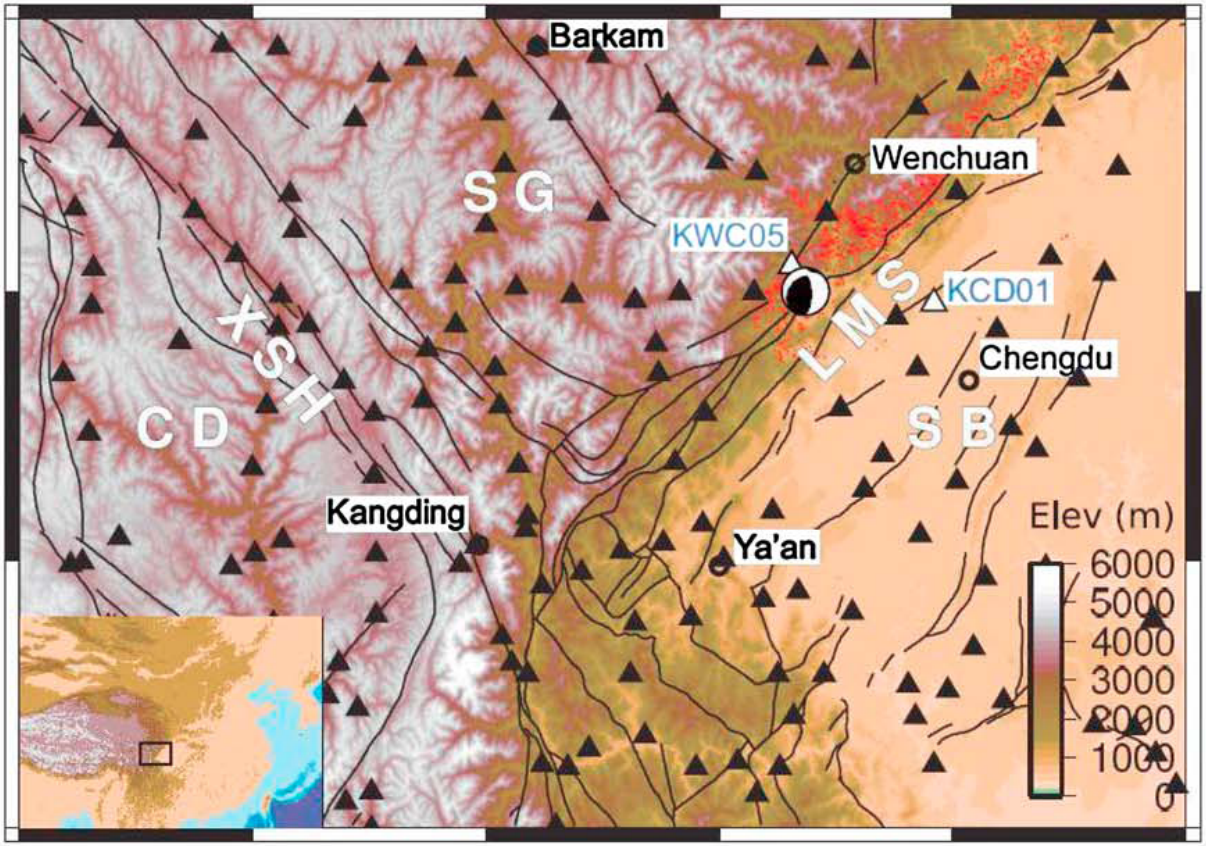
2006 Basel geothermal injection experiment

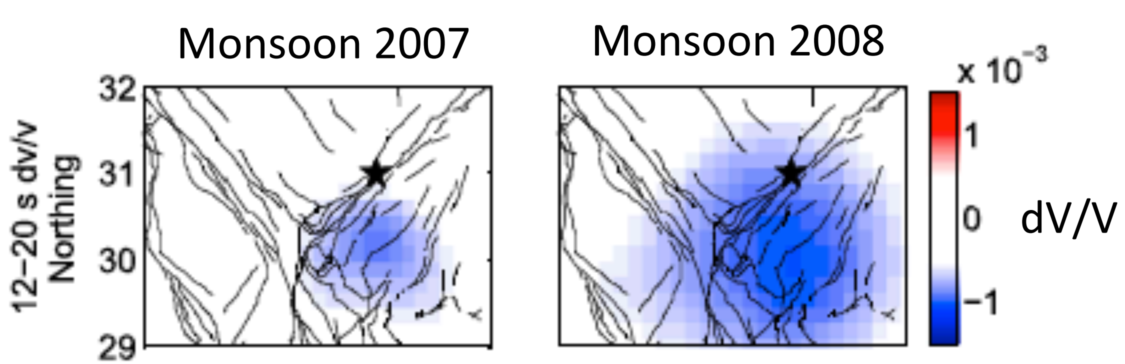




G. Hillers et al… Geophysics (2015)

At large scale :

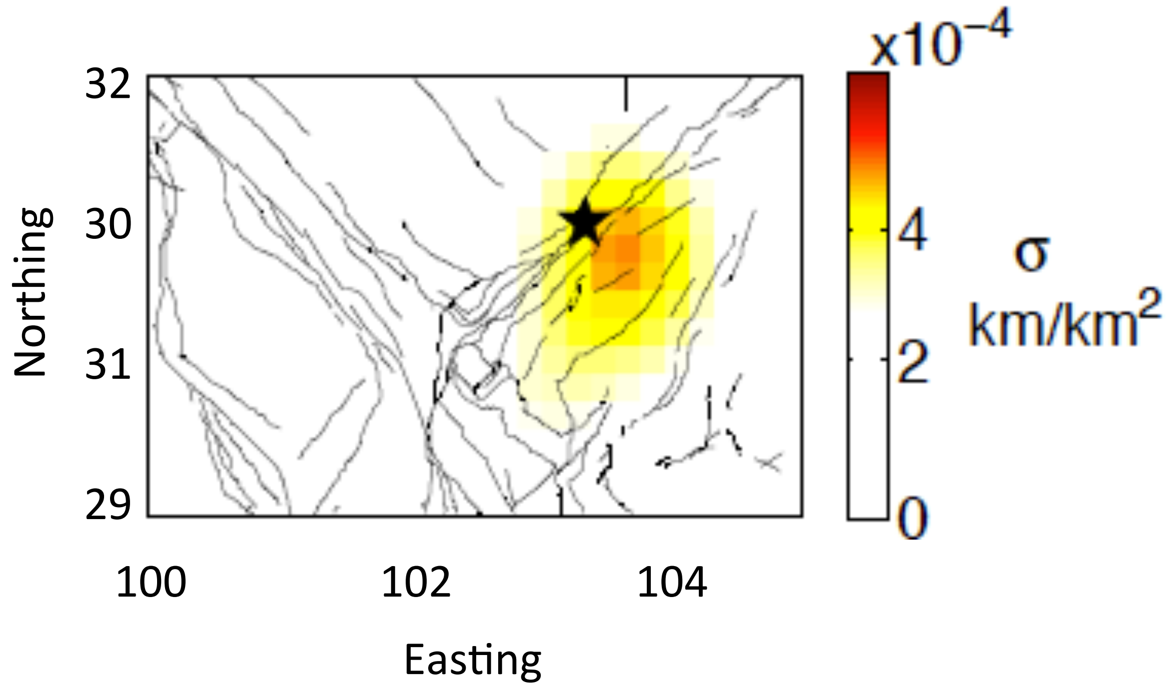




Obermann et al, 2014

Wenchuan Earthquake @ 1-3 s

50 days Before // 50 days after



Obermann et al, 2014