IRSN
INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

Faire avancer la sûreté nucléaire

Interest of noise-based approaches in operational seismic hazard applications: ***focus on site effect estimation***

Bérénice Froment

C. Gélis, F. Tchawe-Nziaha (PhD stud.), M. Cushing...

IRSN: *Institut de Radioprotection et de Sûreté Nucléaire*

→ French public service expert in nuclear and radiation risks

➔ **Research** **and** **public service missions**

Technical and operational support and assistance to public authorities regarding nuclear and radiation risks

IRSN defines and conducts research programs aimed at maintaining and developing the skills necessary for expert assessments in its specializations

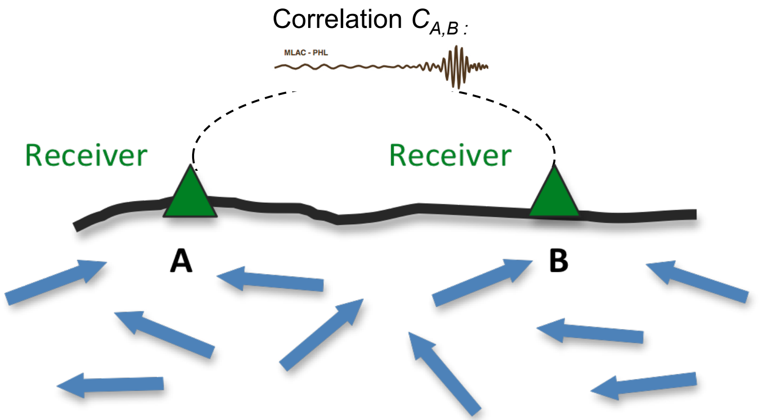
→ Its activities cover all the related scientific and technical issues

➔ physicists, biologists, chemists, physicians, veterinary surgeons, etc…

… geologists & seismologists ➔ seismic hazard

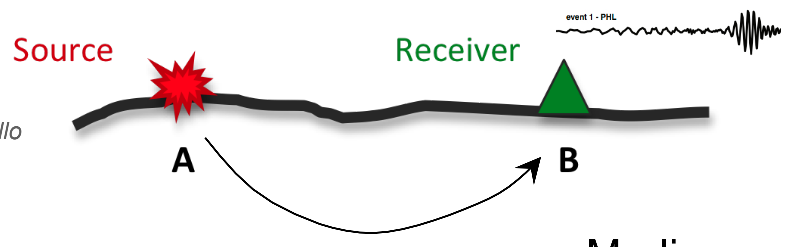
Idea of the presentation:

A methodology



« noise » = permanent vibrations of the Earth surface

Shapiro and Campillo (2004)



Medium characterization

Interest: independent of the occurrence of earthquakes

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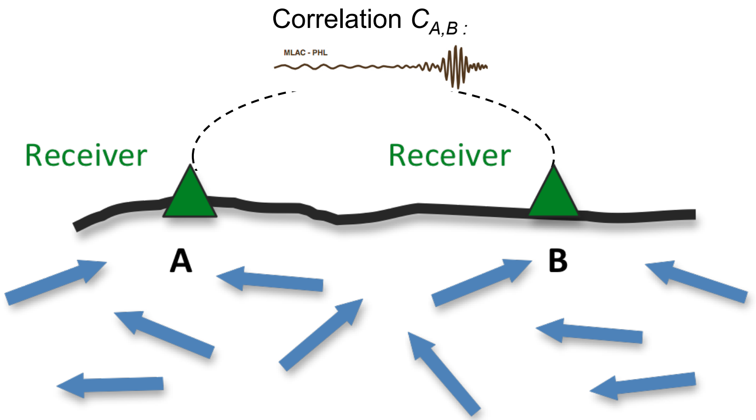

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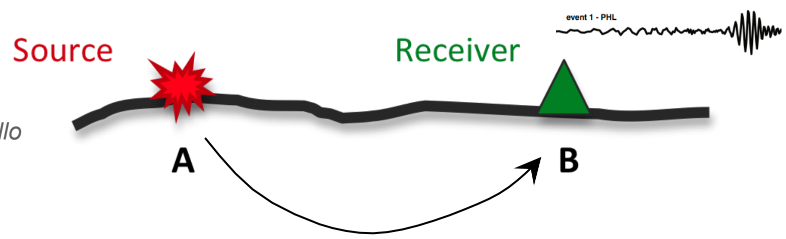

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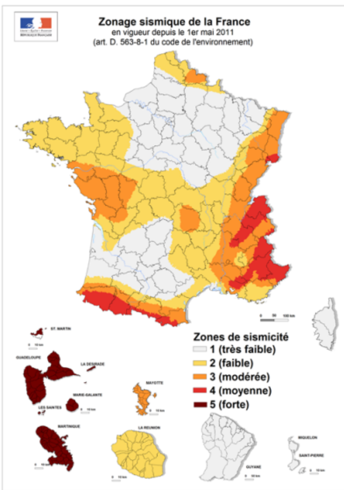
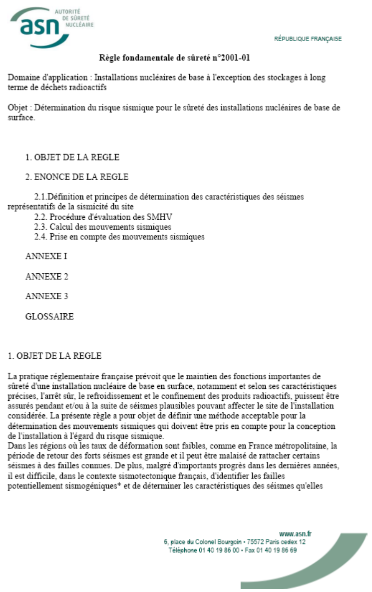




AUTORITÉ DE SÛRETÉ NUCLÉAIRE

RÉPUBLIQUE FRANÇAISE

Règle fondamentale de sûreté n°2001-01

Domaine d'application : Installations nucléaires de base à l'exception des stockages à long terme de déchets radioactifs

Objet : Détermination du risque sismique pour le sûreté des installations nucléaires de base de surface.

1. OBJET DE LA REGLE
2. ENONCE DE LA REGLE
   2.1. Définition et principes de détermination des caractéristiques des séismes représentatifs de la sismicité du site
   2.2. Procédure d'évaluation des SMHV
   2.3. Calcul des mouvements sismiques
   2.4. Prise en compte des mouvements sismiques

ANNEXE I

ANNEXE 2

ANNEXE 3

GLOSSAIRE

1. OBJET DE LA REGLE

La pratique réglementaire française prévoit que le maintien des fonctions importantes de sûreté d'une installation nucléaire de base en surface, notamment et selon ses caractéristiques précises, l'arrêt sûr, le refroidissement et le confinement des produits radioactifs, puissent être assurés pendant et/ou à la suite de séismes plausibles pouvant affecter le site de l'installation considérée. La présente règle a pour objet de définir une méthode acceptable pour la détermination des mouvements sismiques qui doivent être pris en compte pour la conception de l'installation à l'égard du risque sismique.
Dans les régions où les taux de déformation sont faibles, comme en France métropolitaine, la période de retour des forts séismes est grande et il peut être malaisé de rattacher certains séismes à des failles connues. De plus, malgré d'importants progrès dans les dernières années, il est difficile, dans le contexte sismotectonique français, d'identifier les failles potentiellement sismogéniques* et de déterminer les caractéristiques des séismes qu'elles

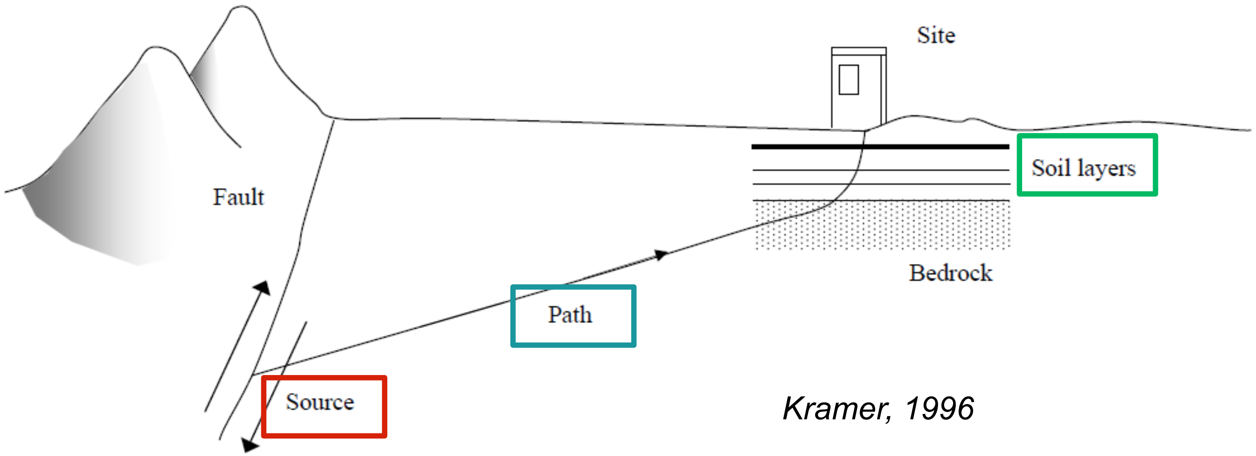
www.asn.fr
6, place du Colonel Bourgoin • 75572 Paris cedex 12
Téléphone 01 40 19 86 00 • Fax 01 40 19 86 69

Research studies...

...=> Seismic Hazard Assessment (SHA) for **French** nuclear facilities guided by a **regulation**

Seismic motion: « from physics to SHA »

The seismic motion recorded at the surface come from the seismic waves that are generated by a seismic source. These are modified during the propagation from the source to the site and by the local site configuration.



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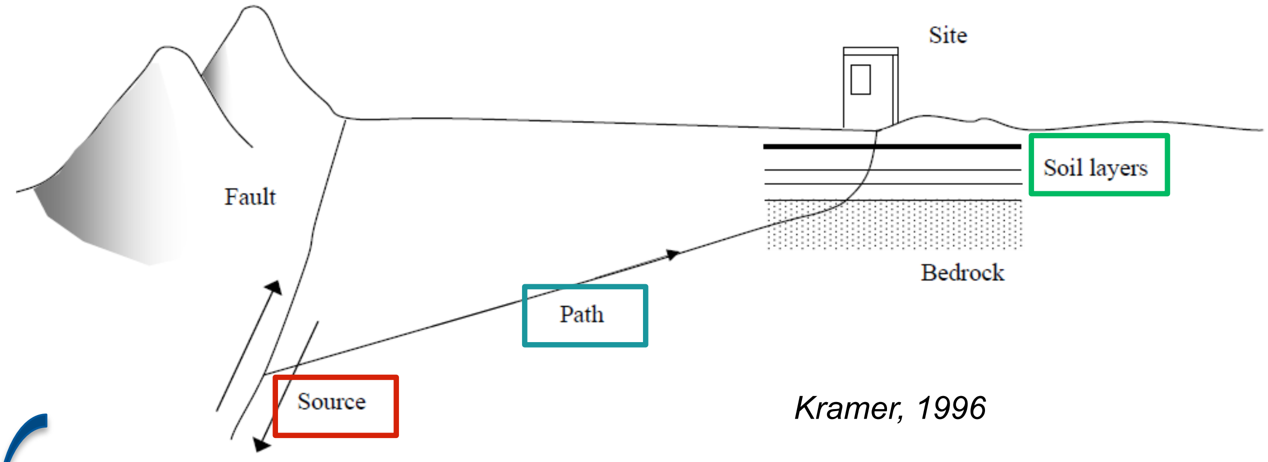

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In practice (SHA) → use of Ground Motion Prediction Equations (GMPEs):

$$GM = f_{source}(M, \text{mechanism},\ldots) + f_{path}(R,\ldots) + f_{site}$$

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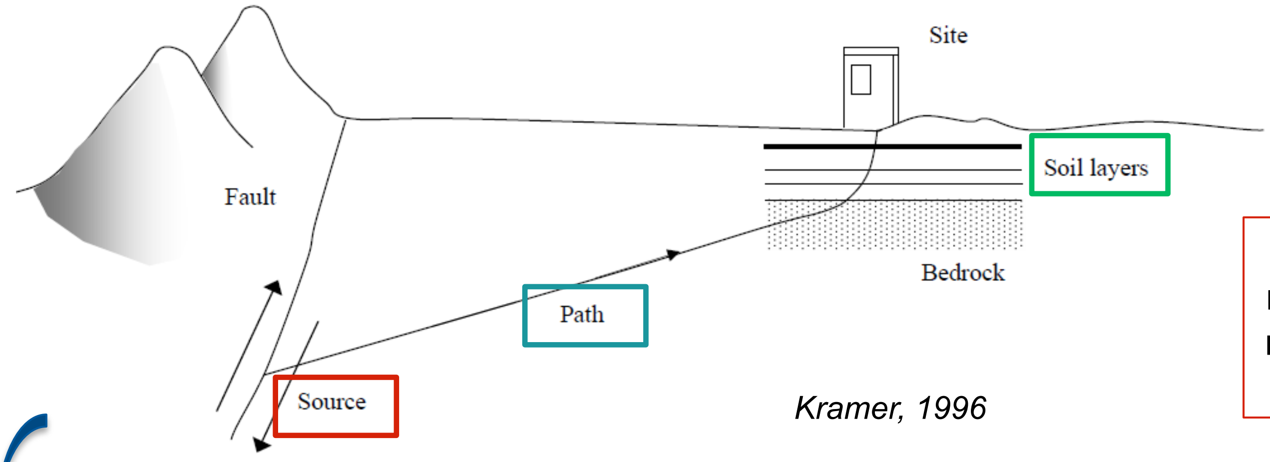

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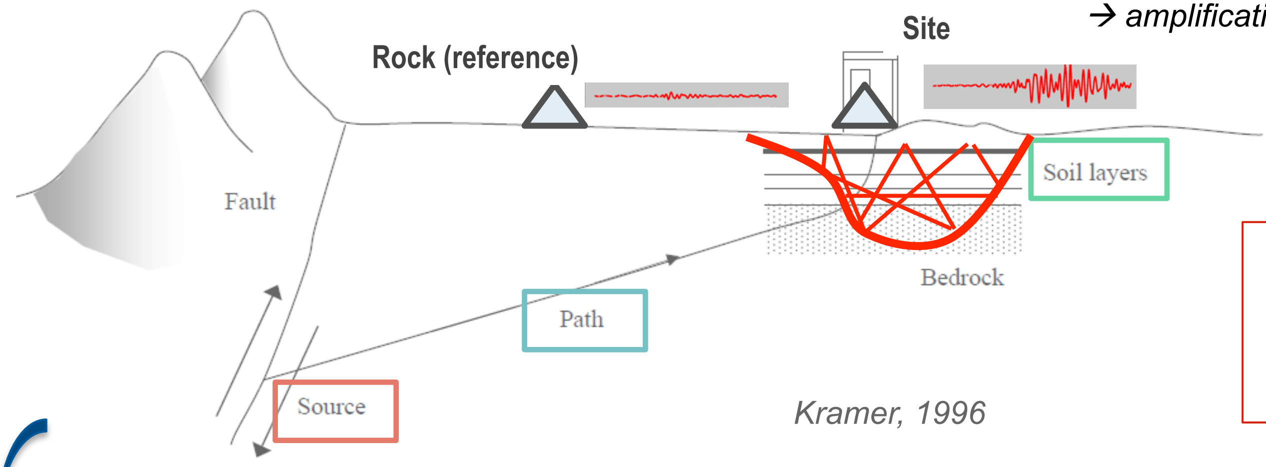
Sedimentary basin => trapping → amplification ; increase of signal duration ; spatial variability



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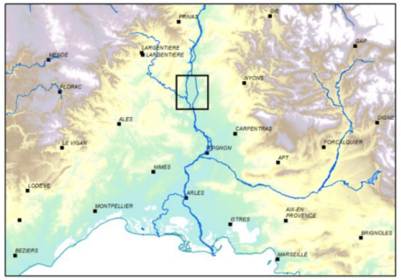

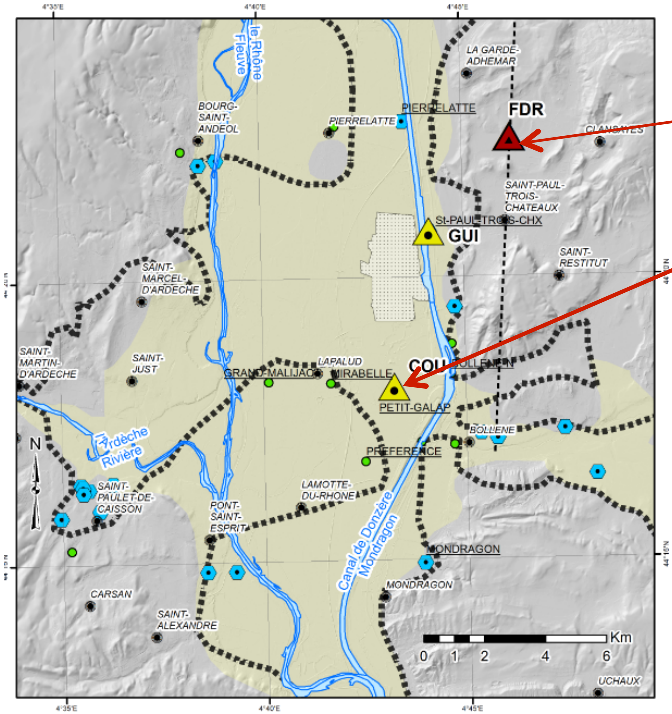

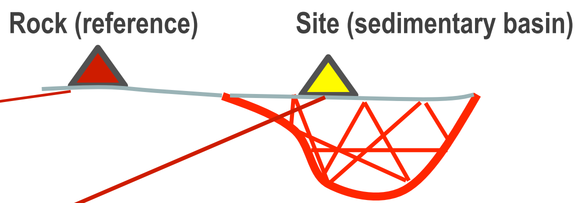

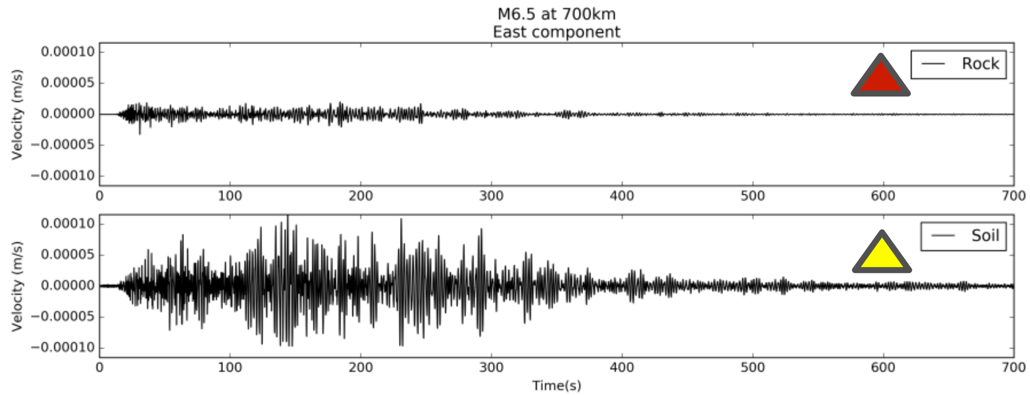

Norcia earthquake (filtered between 0.4 and 10 Hz)

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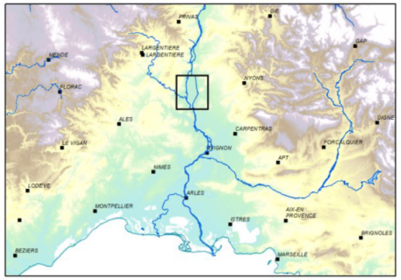

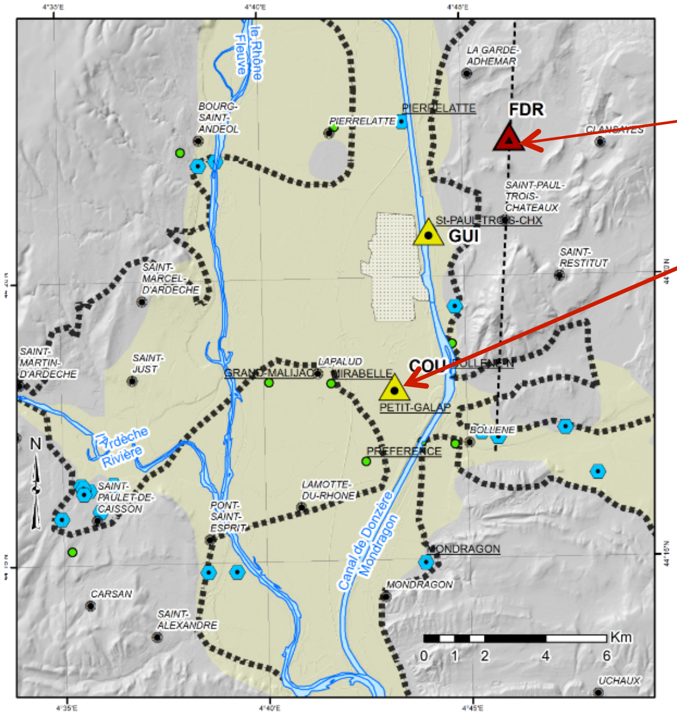

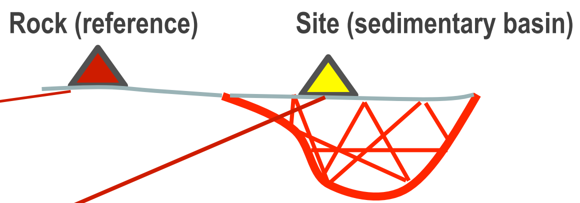

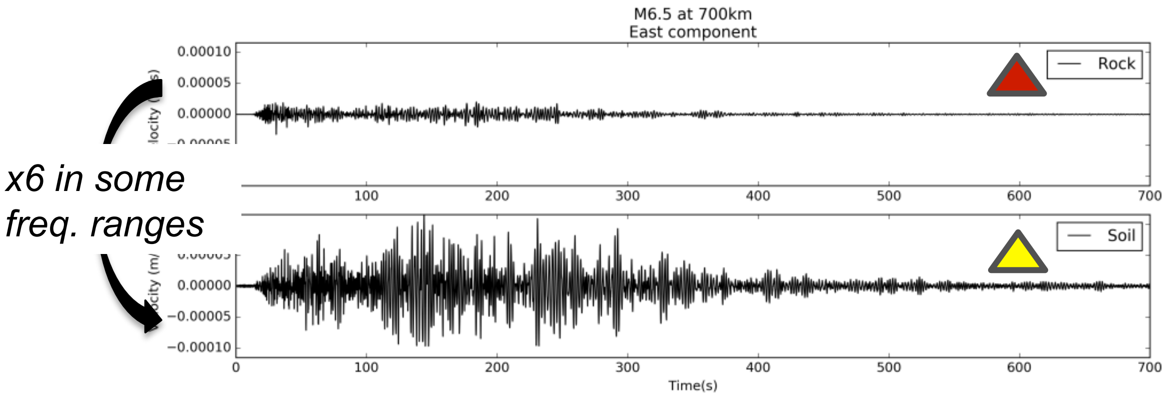

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How to take into account site effects in seismic hazard studies?

Proxy-based Approach

Soil parameters used in Ground Motion Prediction Equations:

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Specific Approach

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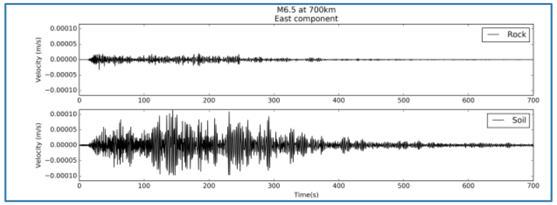
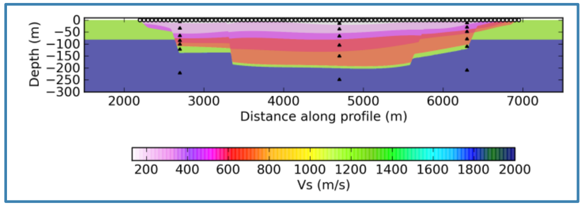
Empirical estimation of the ground response

Seismic recordings on site

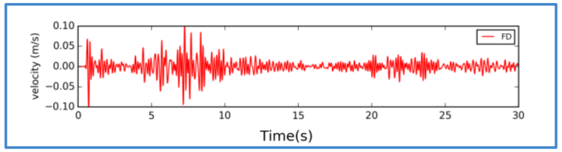


Modelisation of the ground response

Soil model for the numerical simulation
=> Medium characterization



Simulation tool
=> Verification and validation



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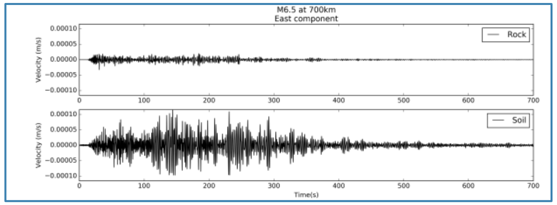

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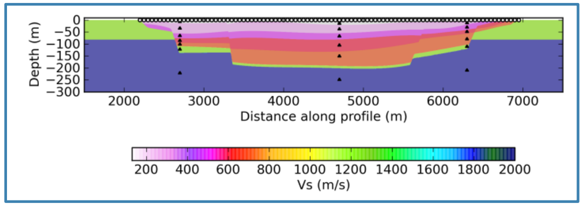

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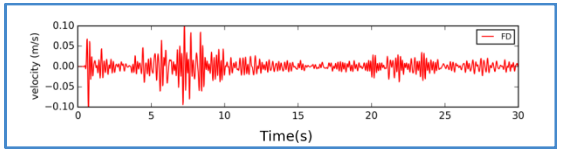

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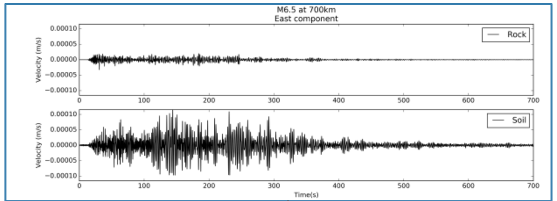

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GJI Seismology

Can broad-band earthquake site responses be predicted by the ambient noise spectral ratio? Insight from observations at two sedimentary basins

Vincent Perron,[1,2,3,*] Céline Gélis,[2] Bérénice Froment,[2] Fabrice Hollender,[1,3] Pierre-Yves Bard,[3] Giovanna Cultrera[4] and Edward Marc Cushing[2]

[1] CEA, DEN, F-13108 Saint-Paul-lez-Durance, France. E-mail: vincent.perron.mail@gmail.com
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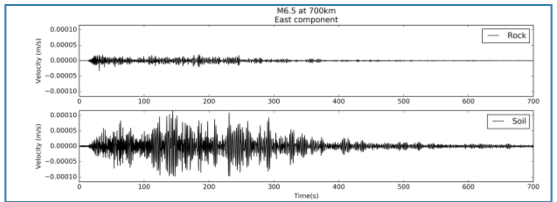

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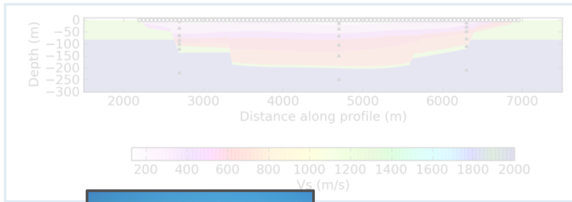

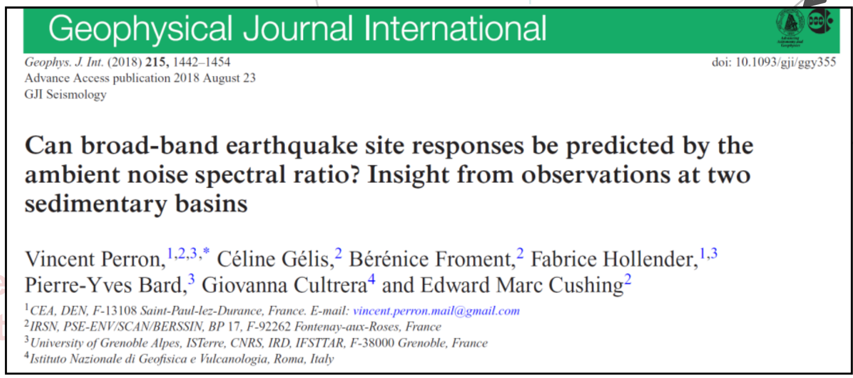

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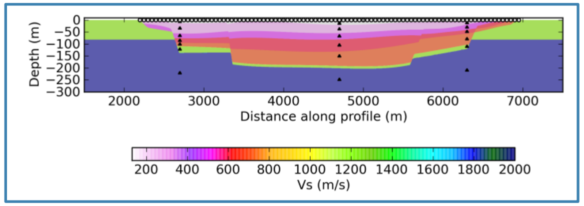

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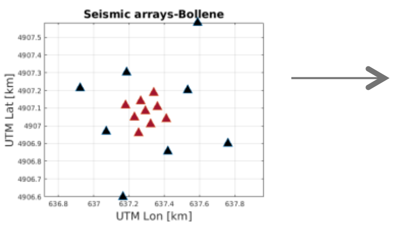

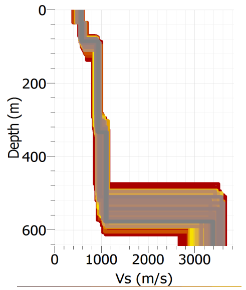

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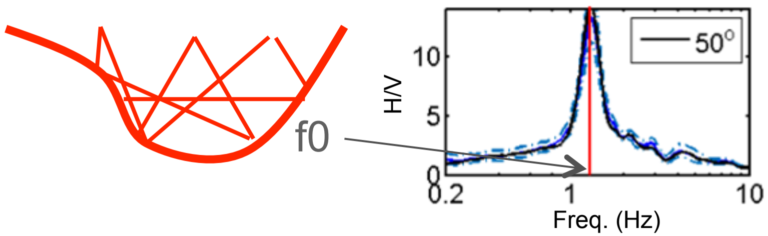

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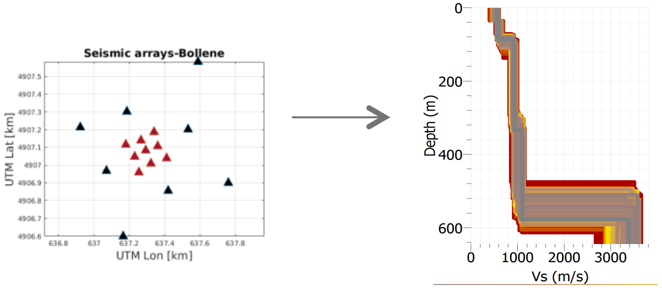

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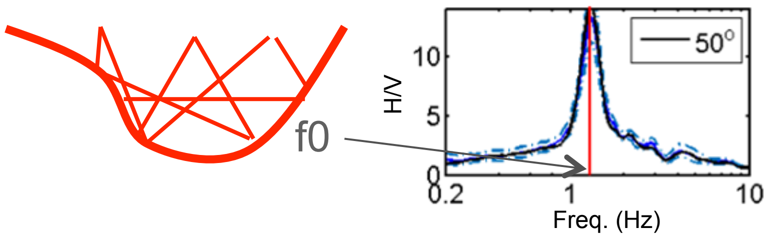

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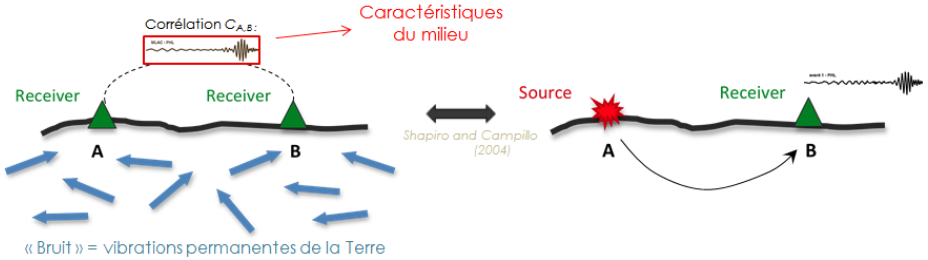
- The GF reconstruction through noise correlations ➔ Extract the coherent information from the ambient noise to retrieve the deterministic information about the propagation between 2 stations



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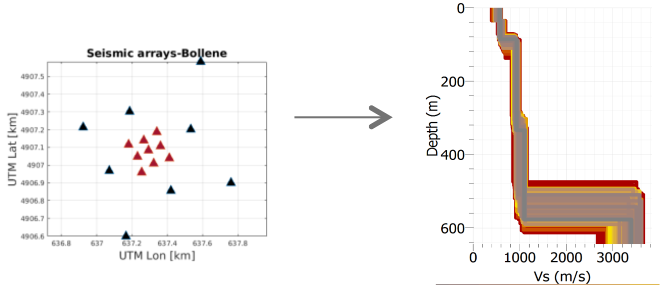

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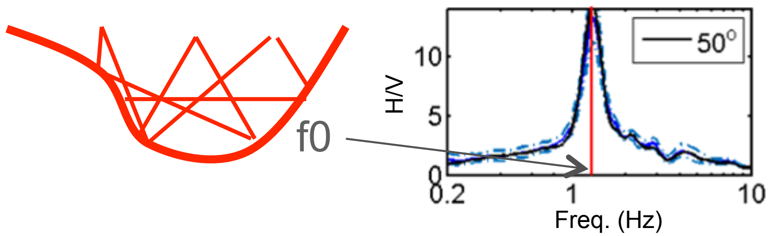

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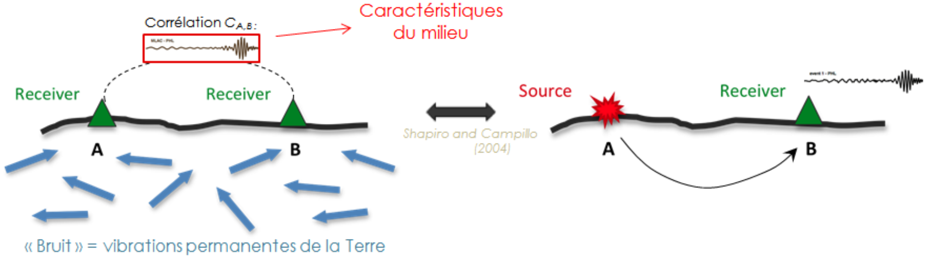


Example of application:

On the use of the coda of noise autocorrelations to compute H/V spectral ratios

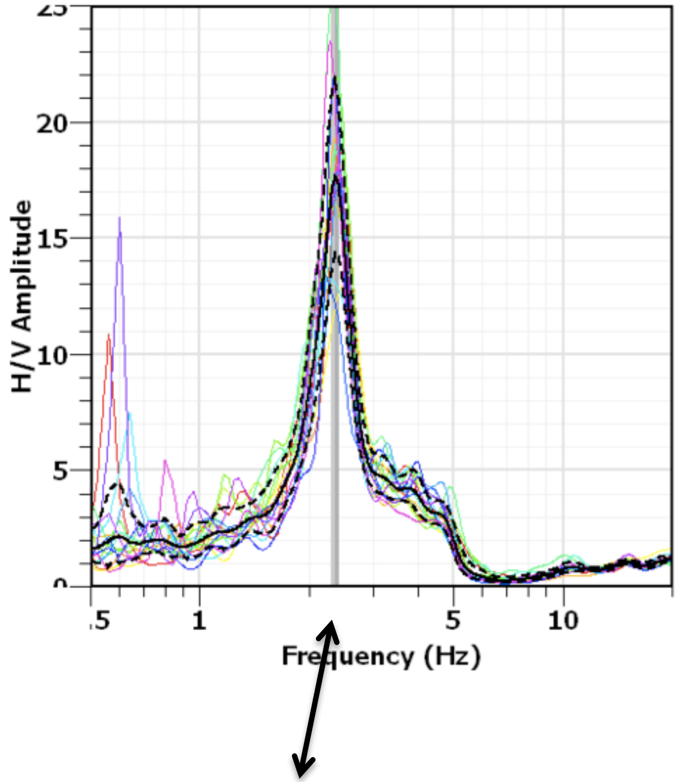
Flomin Tchawe-Nziaha, Bérénice Froment, Michel Campillo & Ludovic Margerin

In review at GJI

H/V method

- Definition: ratio between the Fourier amplitude spectra of the horizontal (H) to vertical (V) components of ambient noise vibrations recorded at one single station

$$\frac{H}{V}(\omega) = \frac{Horizontal\ comp.\ spectrum}{Vertical\ comp.\ spectrum}\ ^{*}$$



f_0 : fundamental resonance frequency of the site

Advantage :

- Simple method to estimate the fundamental frequency of local stratigraphy using seismic ambient vibrations

➔ widely used in an operational context

Limitations :

- Provides only reliable information on the soil's fundamental frequency
- Controversy regarding the physical interpretation (Body-wave vs Surface wave based interpretations)

Idea :
Can we extract more information from this kind of measurement?

*Usually in the form of: $\frac{H}{V} = \frac{\sqrt{(E^2+N^2)/2}}{Z}$

Physical interpretations

- **Interpretation 1**: Transfer function of vertically incident S-waves (e.g. Nakamura et al., 1989 & 2000)

  → *« body-wave based theories »*

- **Interpretation 2**: Rayleigh waves ellipticity or Airy phase of Love (e.g. Nogoshi & Igarashi, 1971 ; Kono & Ohmachi, 1989)

  → *« surface-wave based theories »*

⇒ *Propose an explanation of the possible origin of the H/V lower-frequency peak , but do not insert this explanation in a theory of the seismic noise wavefield => no information about the overall shape*

→ *« full-wavefield based theories »*

. Numerical simulations (e.g. Lanchet & Bard, 1994, 1995 ; Fäh et al., 2001 ; Bonnefoy-Claudet et al., 2006):

noise = wavefield resulting from a multitude of « random » sources

. **Diffuse Field Assumption** (e.g. Margerin et al., 2009 ; Sanchez-Sesma et al., 2011)

Diffuse, equipartitioned wavefield

Diffuse Field Assumption

→ Studies by Margerin (2009), Margerin et al. (2009)

→ Sanchez-Sesma et al. (2011) :

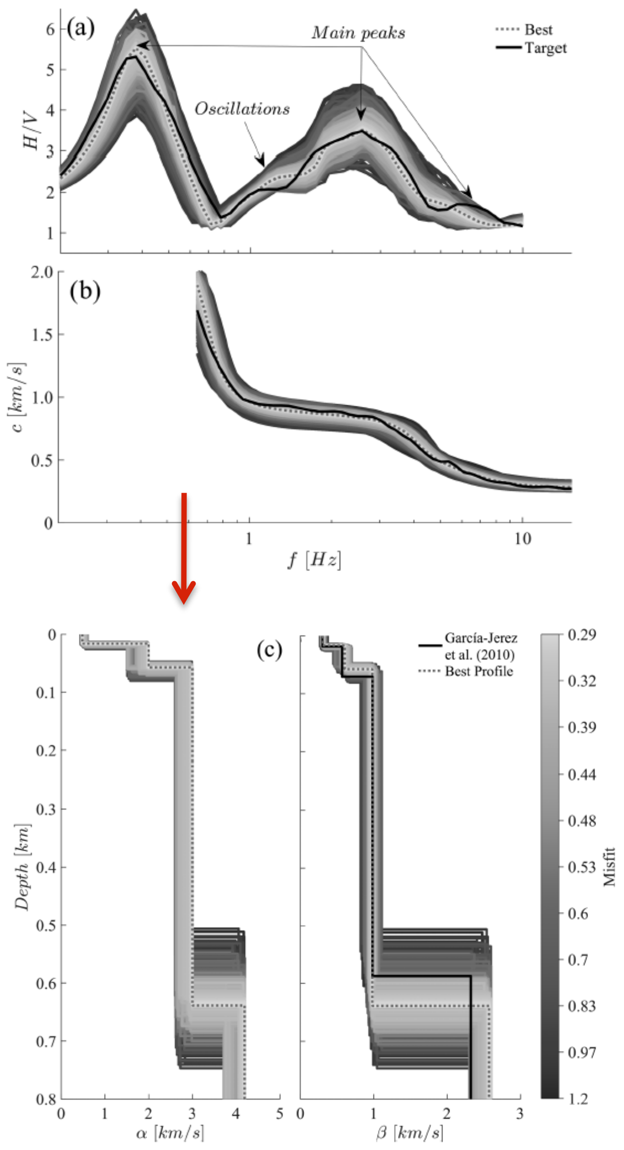
. Assumption : Seismic noise is diffuse

$$E_i(\mathbf{x},\omega) = \rho\omega^2 \langle u_i(\mathbf{x},\omega)\, u_i^*(\mathbf{x},\omega)\rangle \propto Im[G_{ii}(\mathbf{x},\mathbf{x},\omega)]$$

$$HVSR(\omega) = \sqrt{\frac{E_1(\mathbf{x},\omega) + E_2(\mathbf{x},\omega)}{E_3(\mathbf{x},\omega)}}$$

⇒ $$HVSR(\omega) = \sqrt{\frac{Im[G_{11}(\mathbf{x},\mathbf{x},\omega)] + Im[G_{22}(\mathbf{x},\mathbf{x},\omega)]}{Im[G_{33}(\mathbf{x},\mathbf{x},\omega)]}}$$

*« This theory links average energy densities with the GF in 3-D and considers the H/V ratio as an intrinsic property of the medium. Therefore our approach naturally **allows for the inversion of H/V […] including the contributions of Rayleigh, Love and body waves**. »*



Piña-Flores et al., 2017

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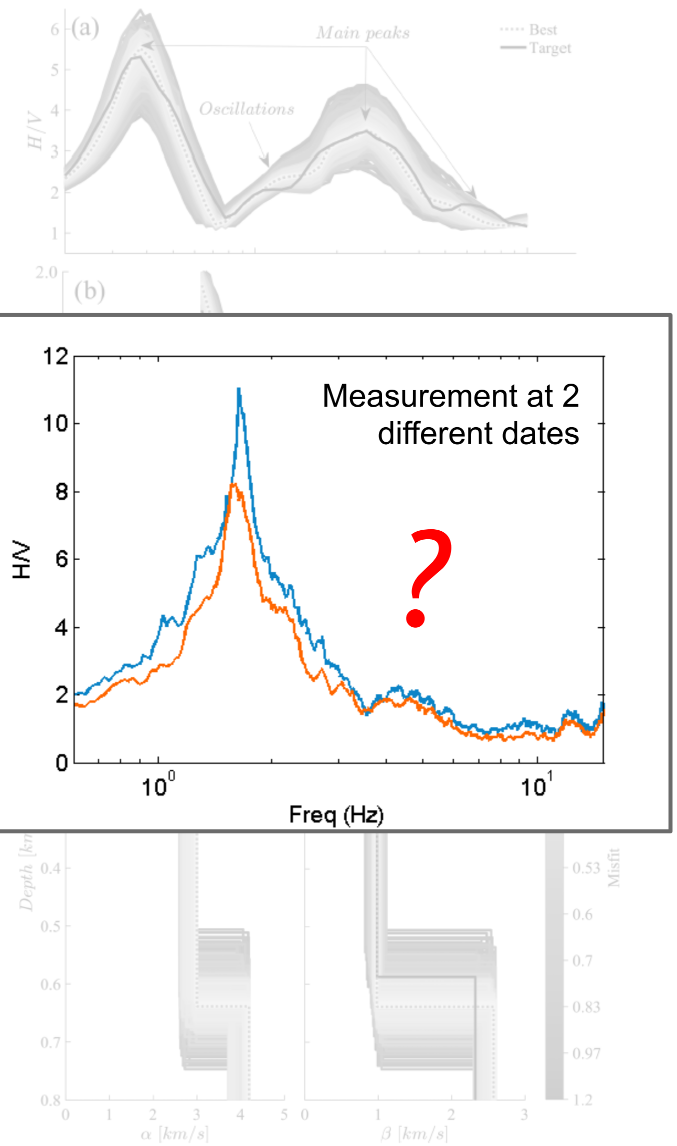
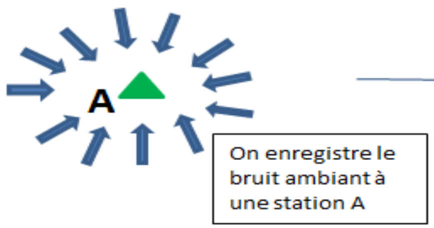


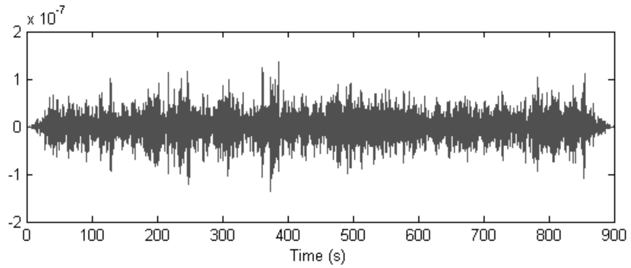
Piña-Flores et al., 2017

Our Approach: using the coda of noise autocorrelation

Idea : use the advantages of both seismic noise (easy to implement, readily recordable) and the coda waves (diffuse character)

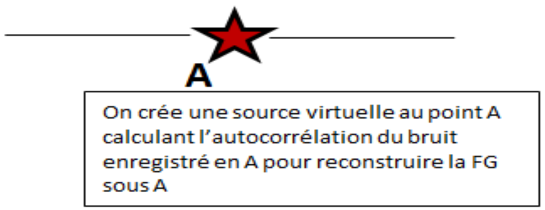
a) Bruit brut : mélange incohérent d'ondes sismiques

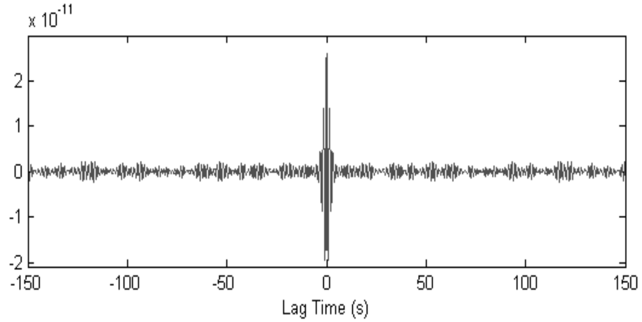




On ne distingue pas les phases de propagation dans le signal du bruit

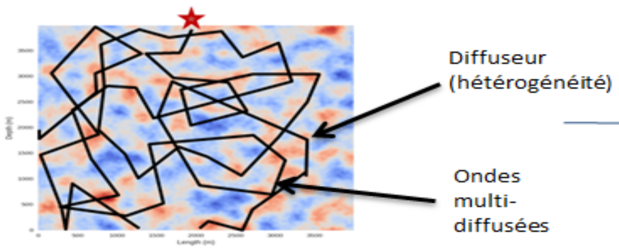
b) On calcule l'autocorrélation du signal en A pour extraire la partie déterministe

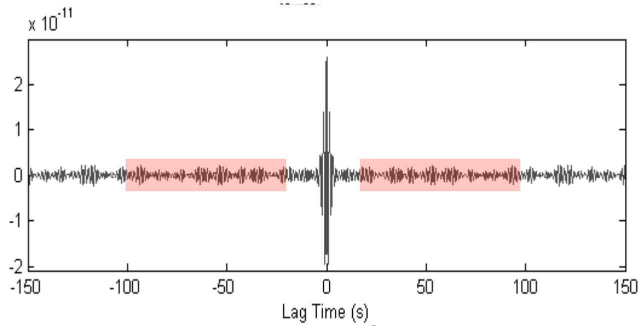




Le centre correspond au temps zéro dû à la symétrie de l'autocorrélation

c) Sur le signal déterministe, on sélectionne les arrivées tardives (coda) qui correspondent aux ondes multiplement diffusées





Coda en rouge. On va calculer le rapport H/V sur cette partie du signal.

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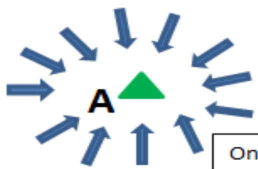
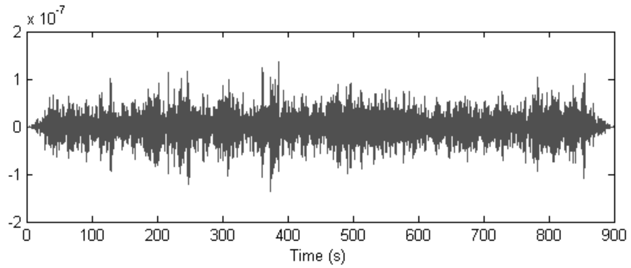


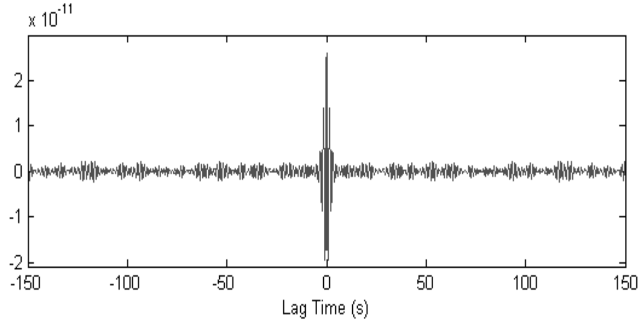
On enregistre le bruit ambiant à une station A



On ne distingue pas les phases de propagation dans le signal du bruit

b) On calcule l'autocorrélation du signal en A pour extraire la partie déterministe

On crée une source virtuelle au point A calculant l'autocorrélation du bruit enregistré en A pour reconstruire la FG sous A



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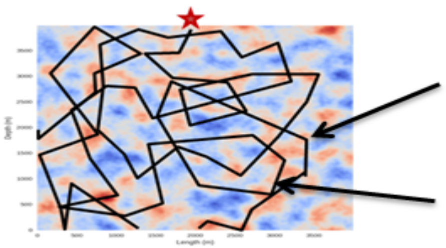
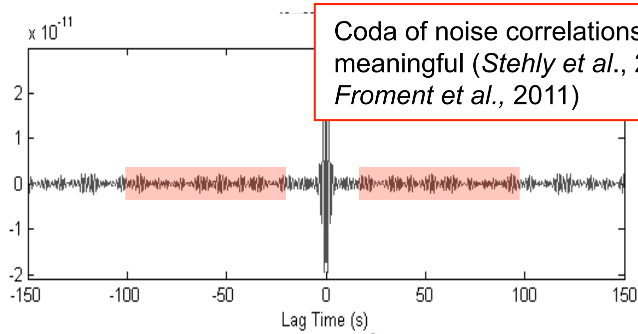


Diffuseur (hétérogénéité)

Ondes multi-diffusées



Coda of noise correlations is meaningful (*Stehly et al.*, 2008 ; *Froment et al.*, 2011)

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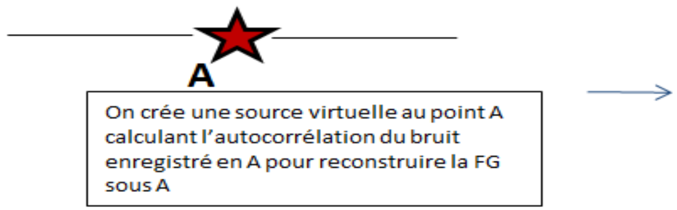
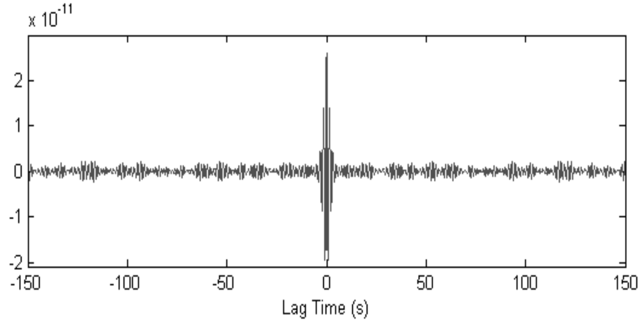


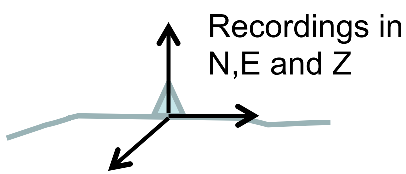


Le centre correspond au temps zéro dû à la symétrie de l'autocorrélation

Noise correlation tensor:

$$\begin{pmatrix} ZZ & ZE & ZN \\ EZ & EE & EN \\ NZ & NE & NN \end{pmatrix}$$

→ Vertical virtual source (Z) => record on Z, N and E



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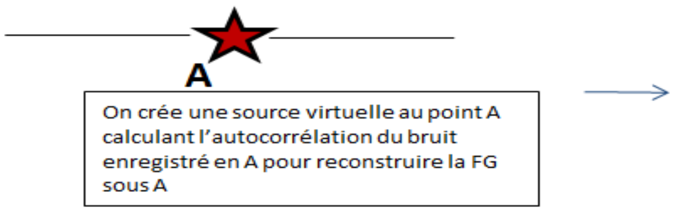

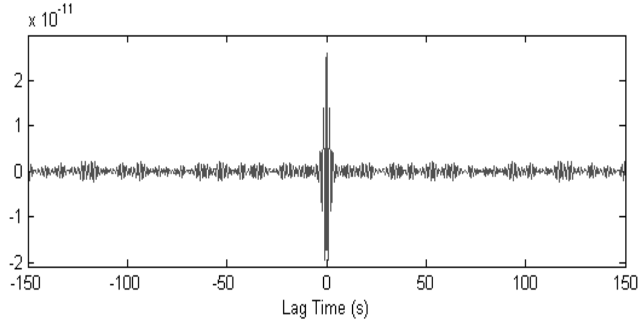

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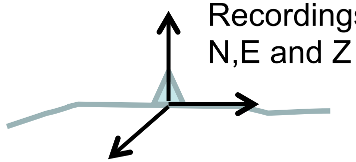

Recordings in N,E and Z

$$\Rightarrow H/V_{C_Z} = \frac{ZE + ZN}{ZZ}$$

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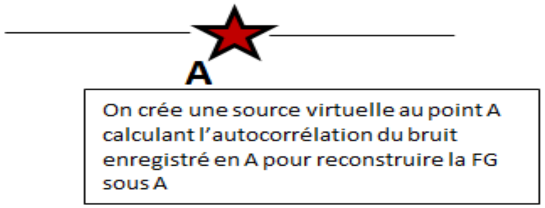

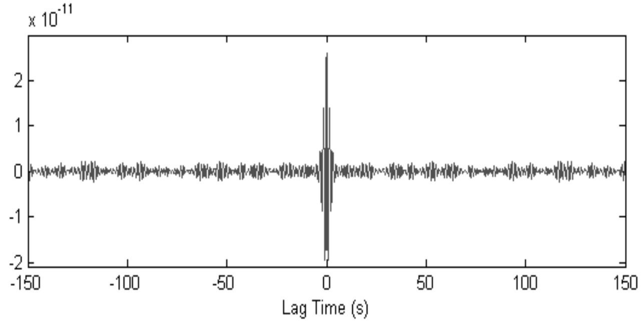

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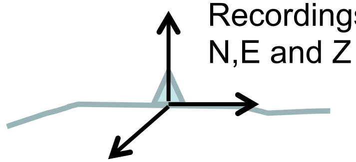

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$$\Rightarrow \; H/V_{C_Z}$$

$$H/V_{C_E}$$

$$H/V_{C_N}$$

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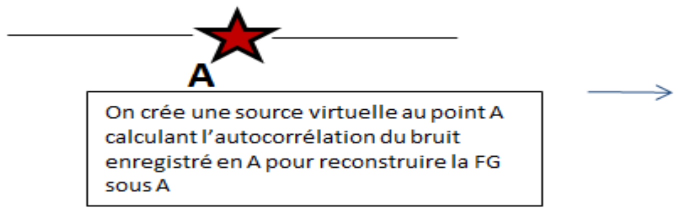

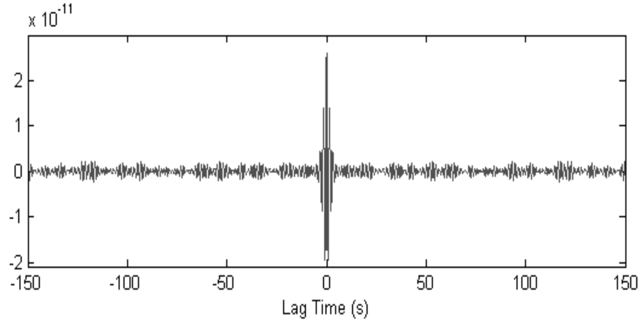

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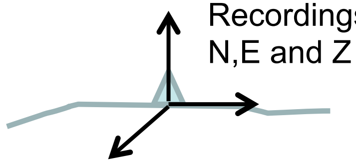

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$$\Rightarrow H/V_{C_Z} = \frac{ZE + ZN}{ZZ}$$

$$\Rightarrow H/V_{C_Z}$$

$$H/V_{C_E}$$

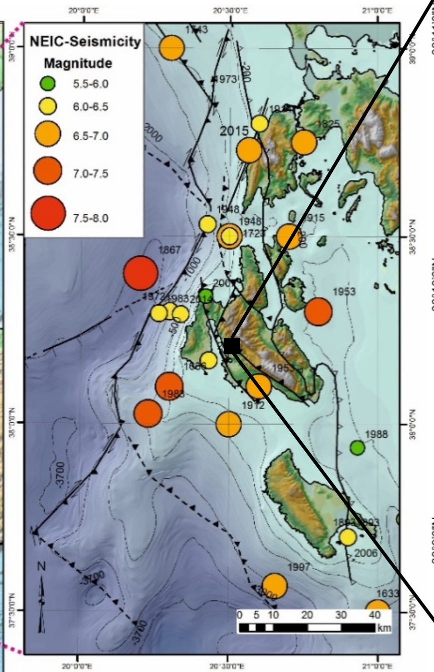
$$H/V_{C_N}$$

→ Expected to produce a « more complete » wavefield

$$\Rightarrow H/V_c = \frac{H/V_{C_E} + H/V_{C_N}}{2}$$

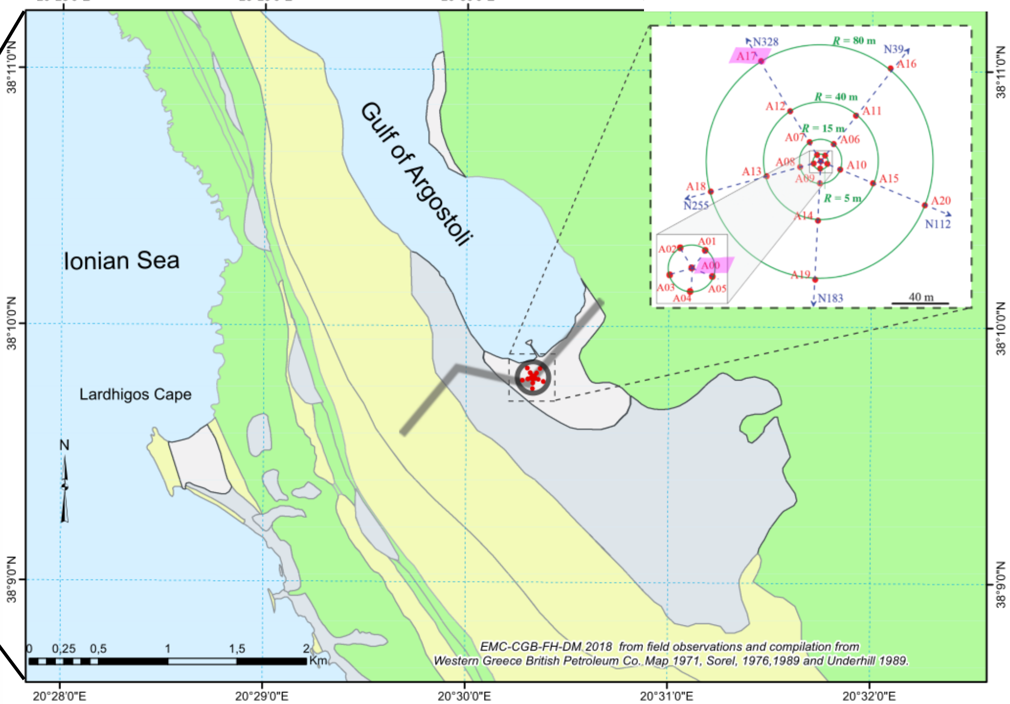
Region / Data

. Plio-quaternary Argostoli basin in Greece (Cephalonia), about 60-to-100-m deep and 2-km wide
. Widely studied: NERA project (6 months recording on 62 acquisition stations) + PIA SINAPS@
. Array A: Station of interest : central station A00
. Data: 1st January - 17 April 2012 => no selection



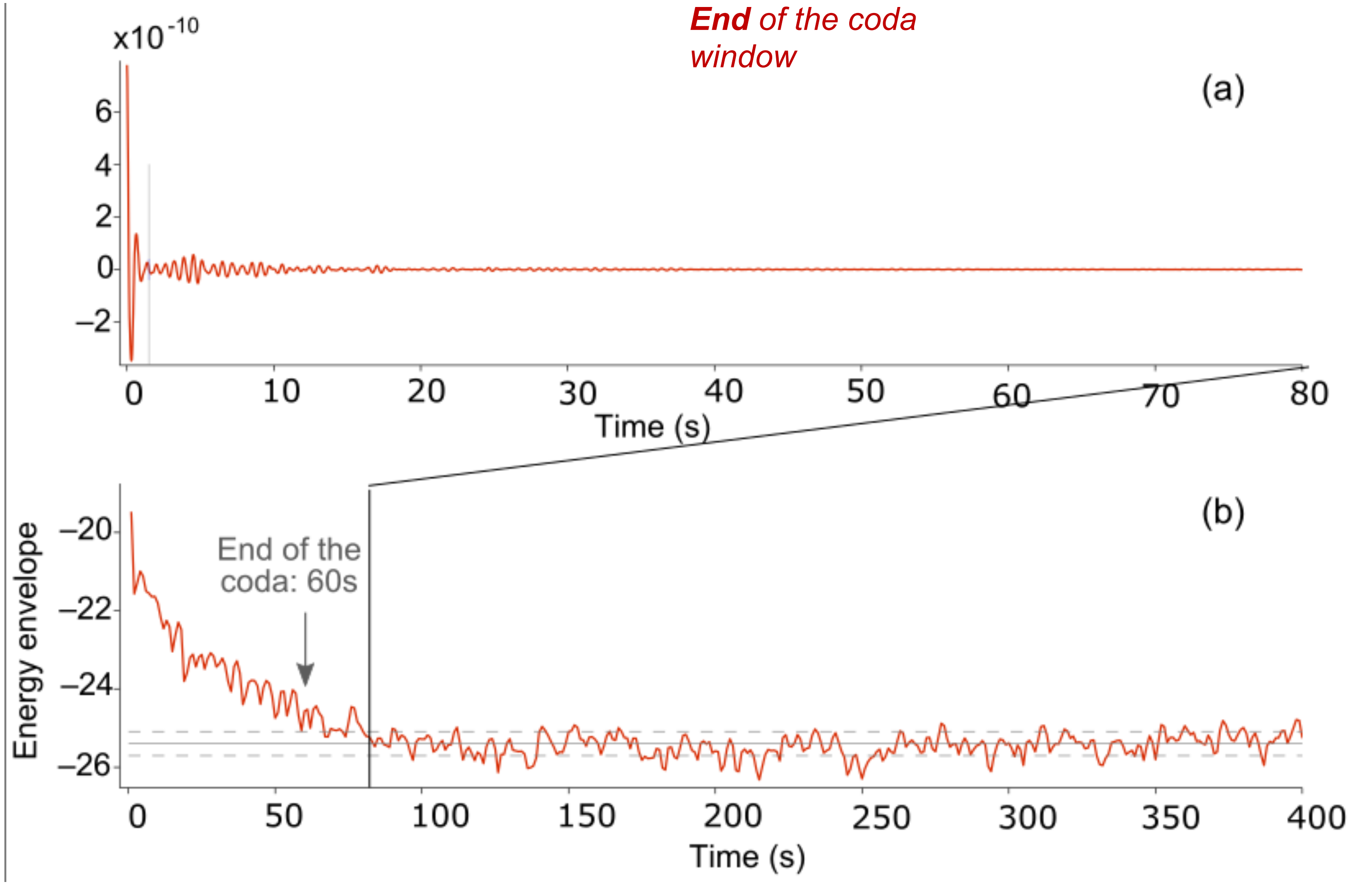
From Cushing et al., 2016

Layout of the array from Imtiaz et al., 2018



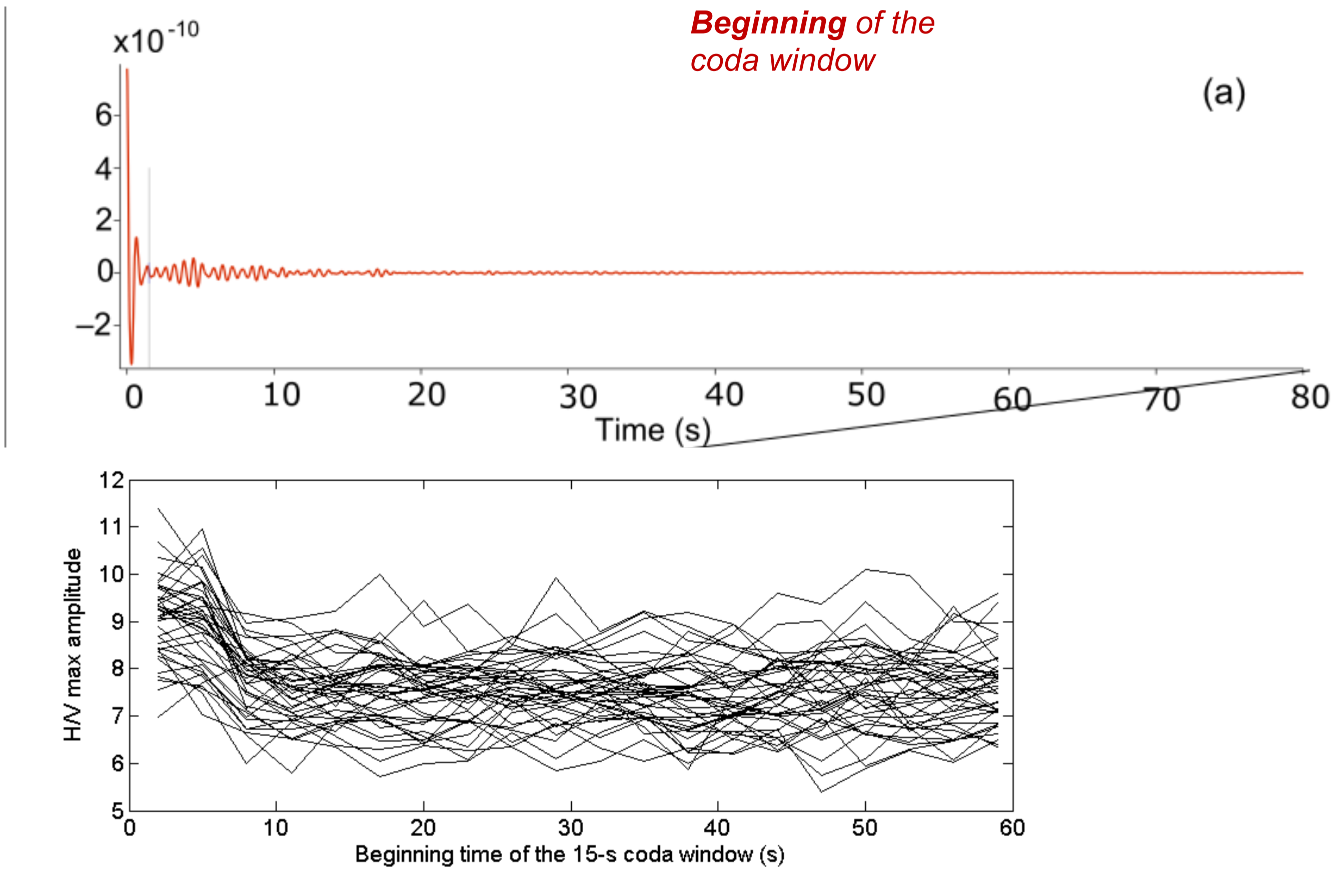
Simplified geological map from Cushing et al., 2019

Coda window



End of the coda window
x10^-10
(a)
6
4
2
0
–2
0
10
20
30
40
50
60
70
80
Time (s)
(b)
Energy envelope
–20
–22
–24
–26
End of the coda: 60s
0
50
100
150
200
250
300
350
400
Time (s)

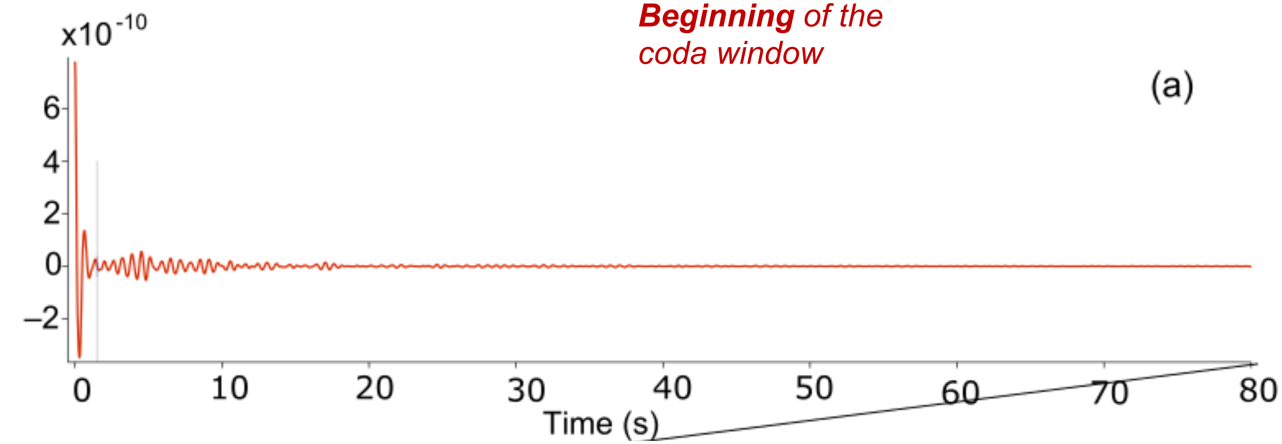
Coda window

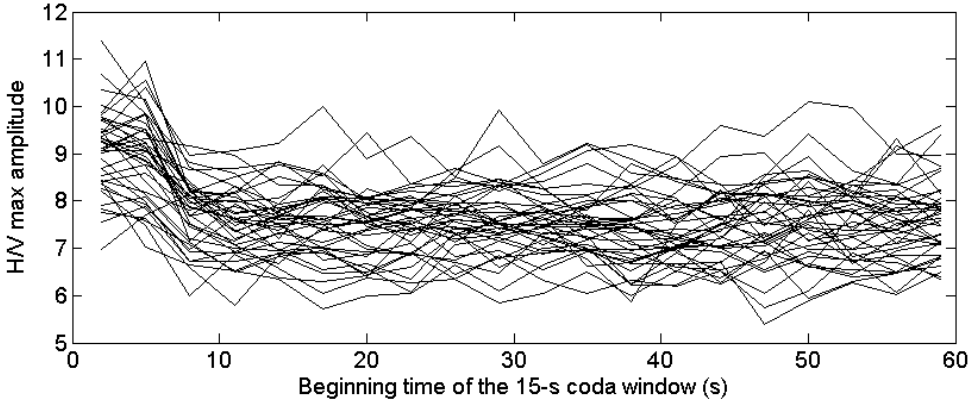


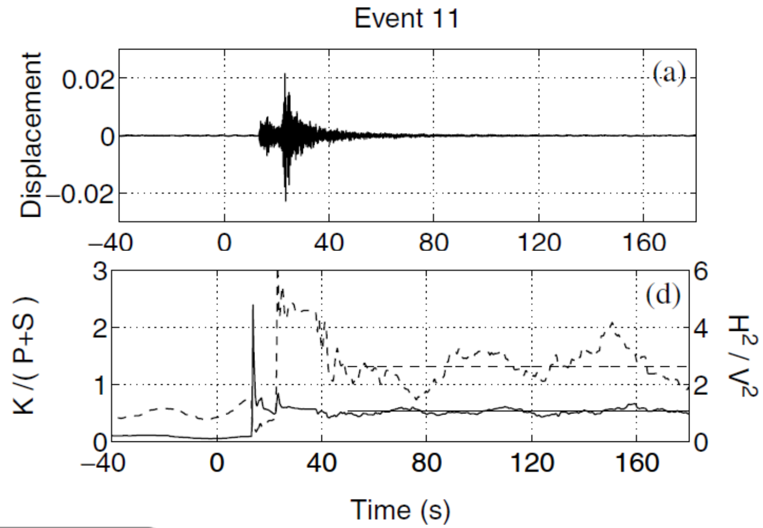
Beginning *of the*
coda window
(a)
x10^-10
Time (s)
H/V max amplitude
Beginning time of the 15-s coda window (s)

Coda window

***Beginning** of the coda window*



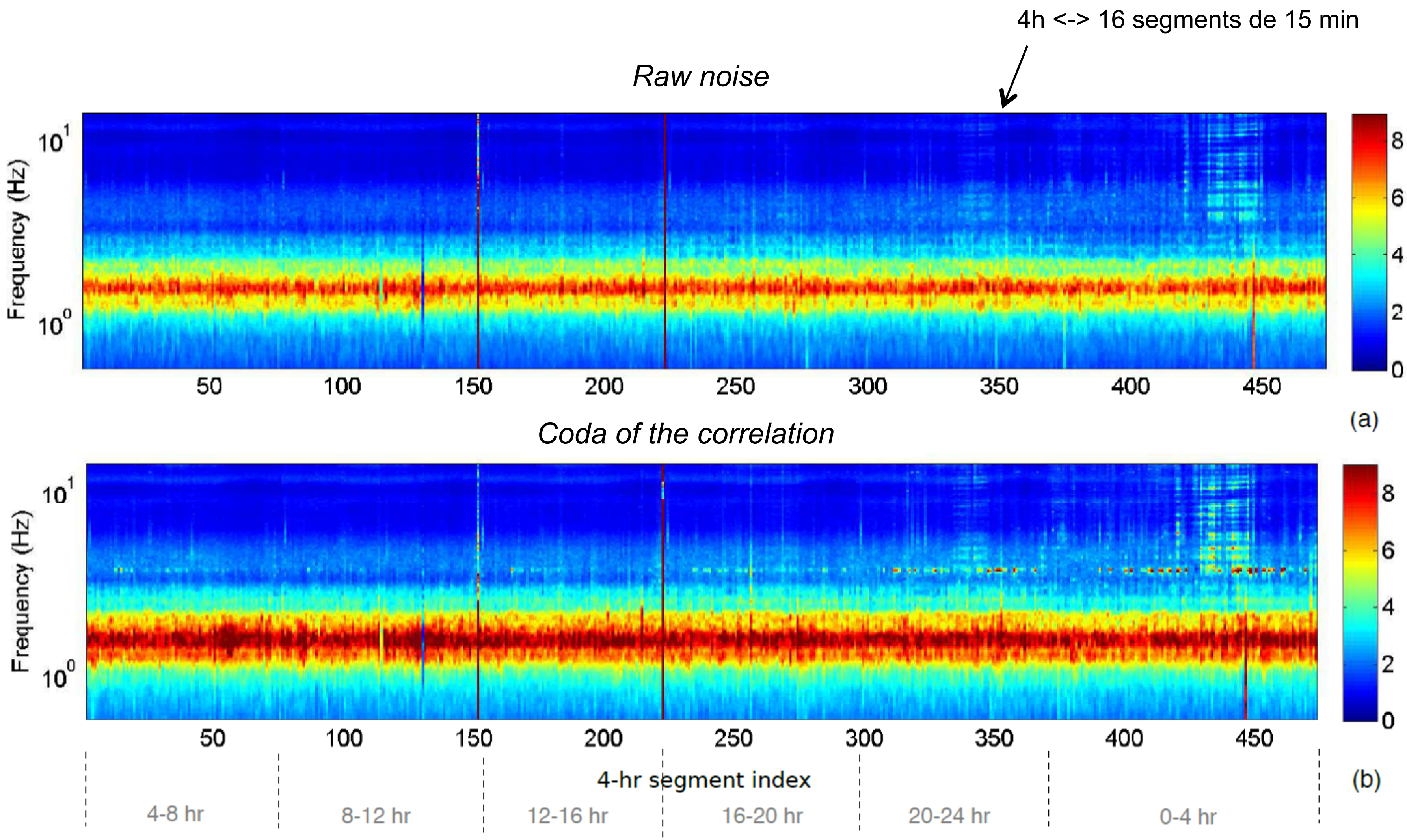




Hennino et al., 2001

(see also, examples shown by L. Margerin at PFO, in Pyrénées, on Mars...)

Results: variations over 3.5 months



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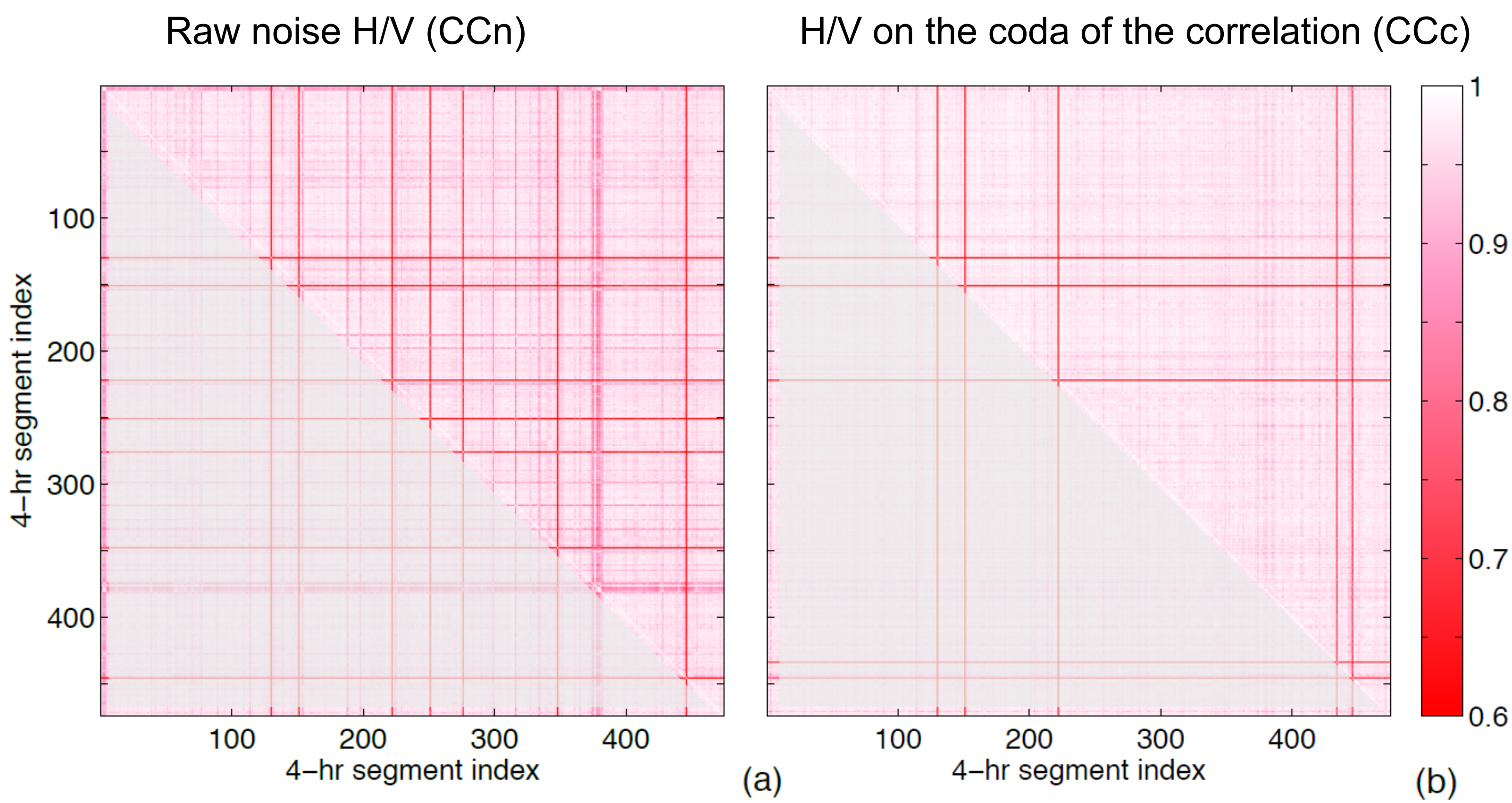

Impact of our approach: CCc-CCn (Improvement ⇔ CCc-CCn >0)

Results: variations over 3.5 months

CCc-CCn

CCn

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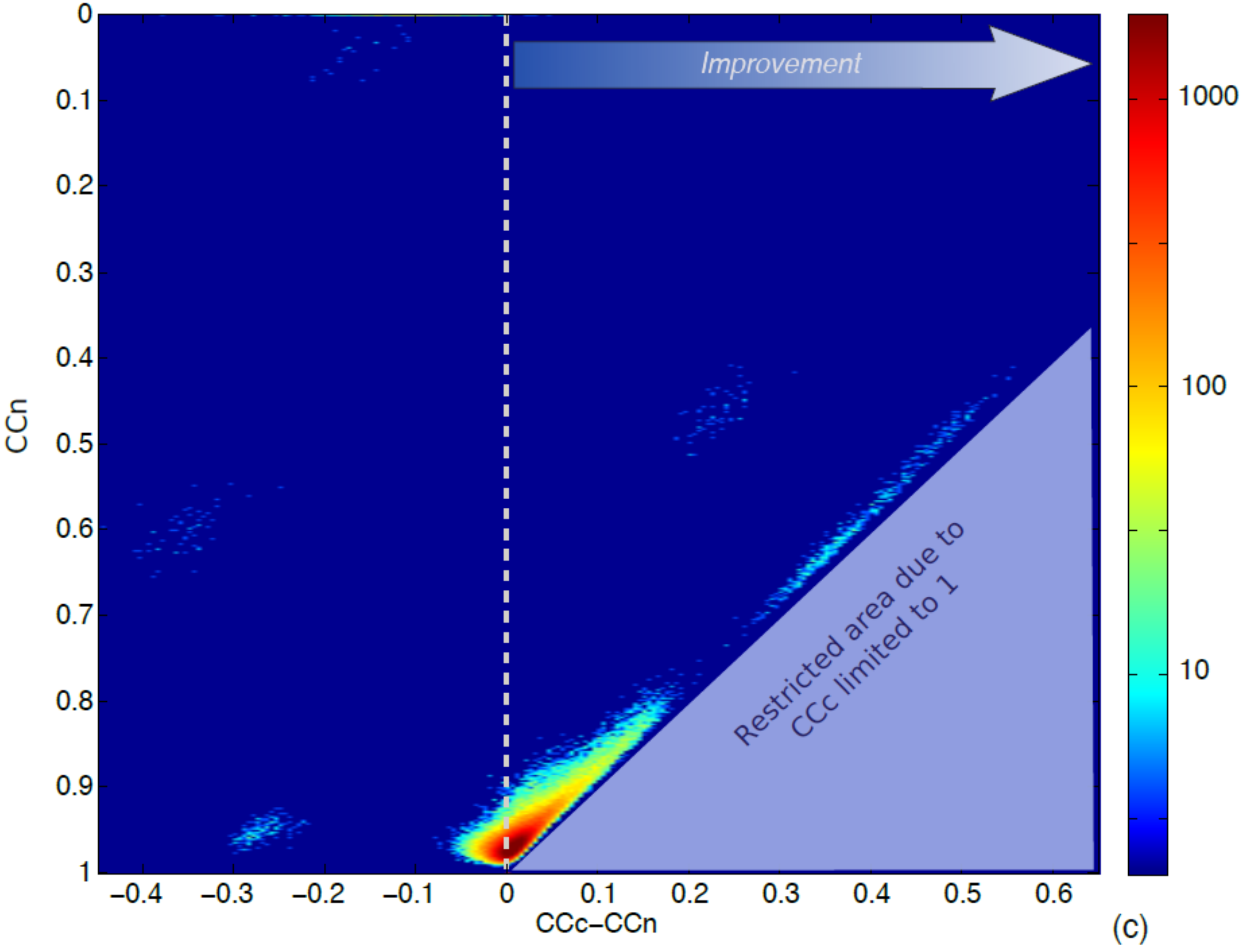
Results: variations over 3.5 months



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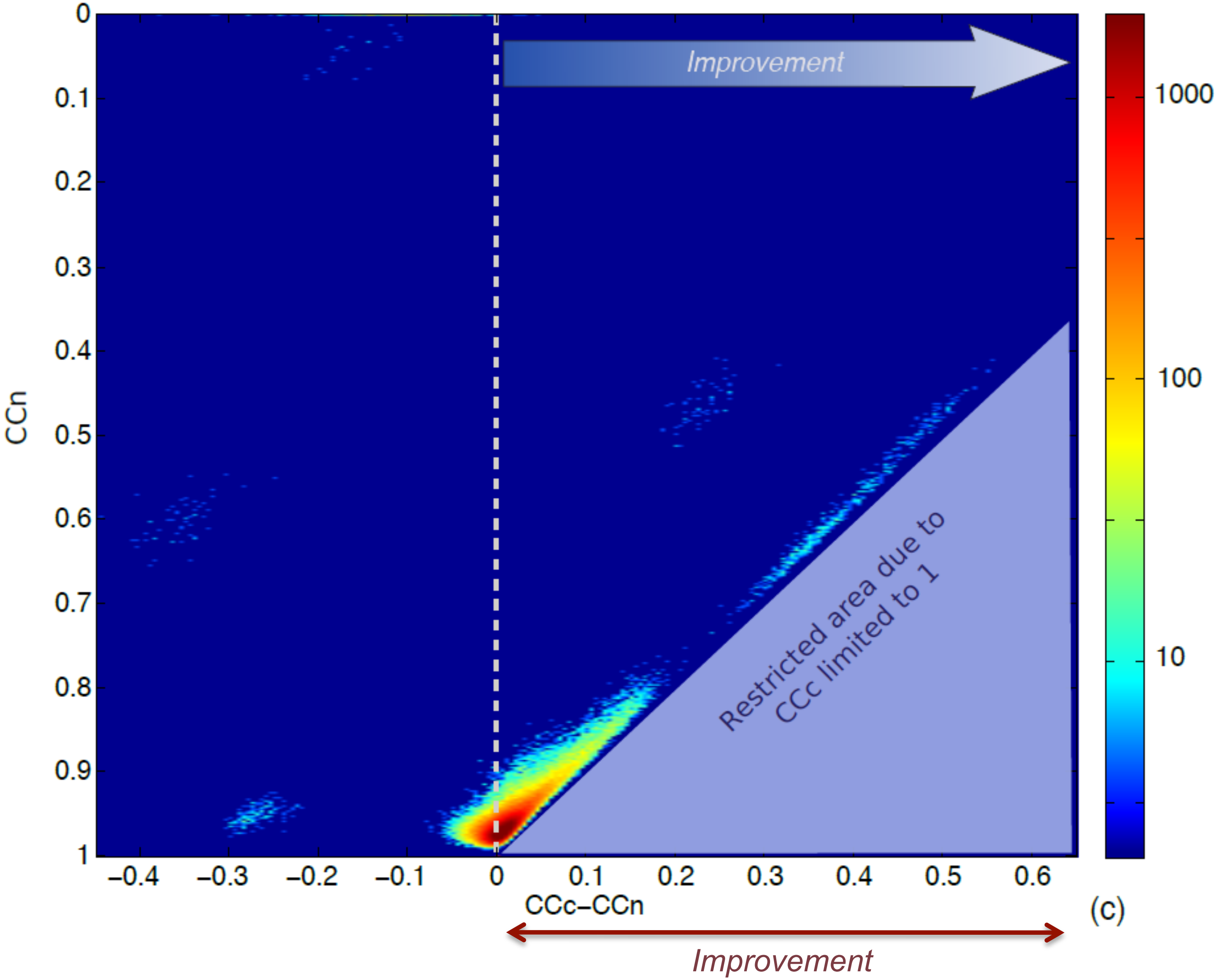

Results: Comparison to theory

Theory:

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Sanchez-Sesma et al. (2011)

→ Fast numerical tool for foward computation and inversion of H/V for a horizontally layered medium (contributions of the different waves) (*HV-inv*, García-Jerez et al., 2016)

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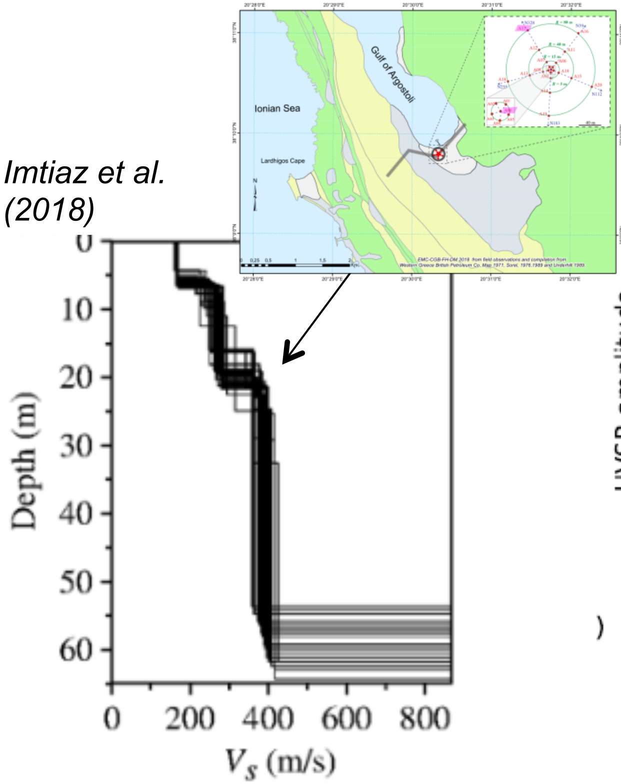
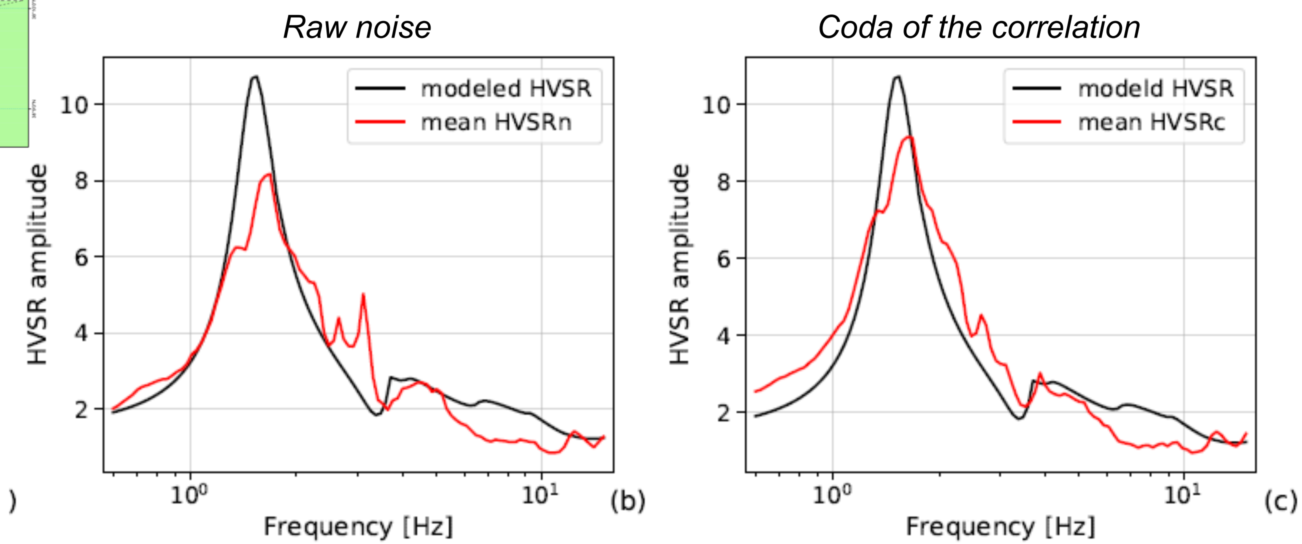




➔ Better fit with the modeled HVSR

Main points

- We propose an alternative procedure to compute the HVSR → extract the part of the noise we want to exploit
- The results tend to show that this method can help stabilizing HVSR measurements and result in HVSR closer to theory => extended use of the single-station HVSR to characterize mechanical properties of the medium
- Assumptions in the theory are not addressed by this approach → Absorption? Partial equipartition?
- Test to perform on other datasets (different configurations ; different noise nature – wave content, origin - ; different variability...)

The near future

Proxy-based Approach

Soil parameters used in Ground Motion Prediction Equations:

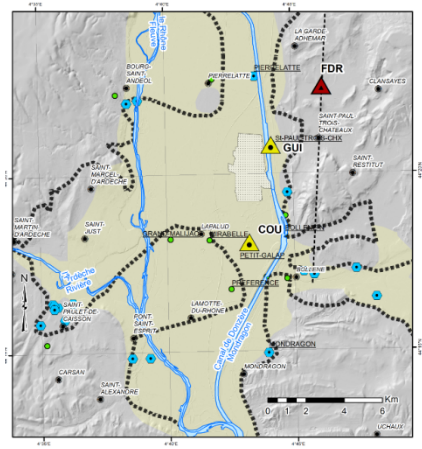
GM=aM + bR + c

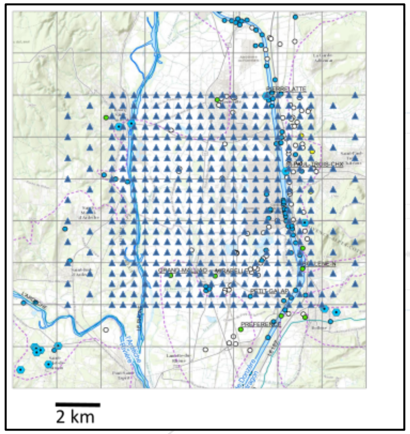
Source Path Site

Specific Approach

Empirical estimation of the ground response

Modelisation of the ground response

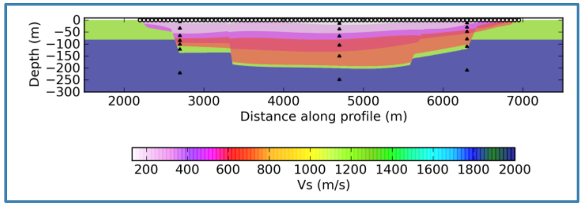




site

Soil model for the numerical simulation

=> Medium characterization



Simulation tool

=> Verification and validation

Foerster et al., 2015

➔ Ne

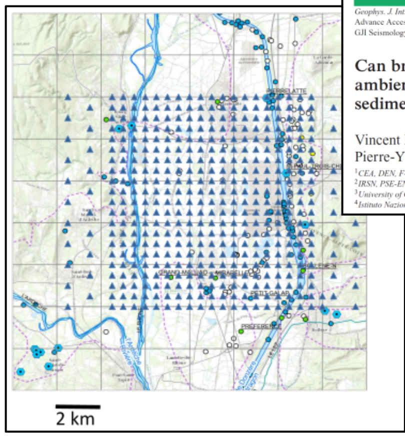
Rhône valley project: passive imaging from a dense acquisition (2020) => 3D Vs model

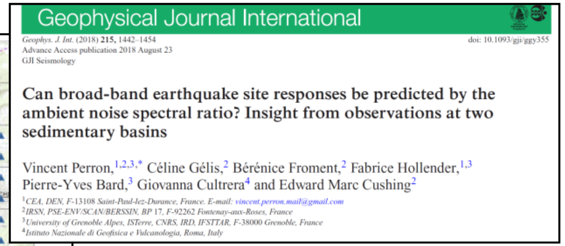
In metropolitan France (low-to-moderate seismicity)

➔ interest of using the ambient noise as data!

In a broader framework…

Noise-based imaging and characterization



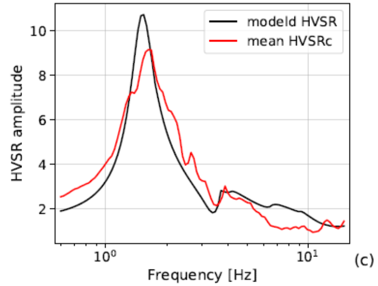

Geophysical Journal International

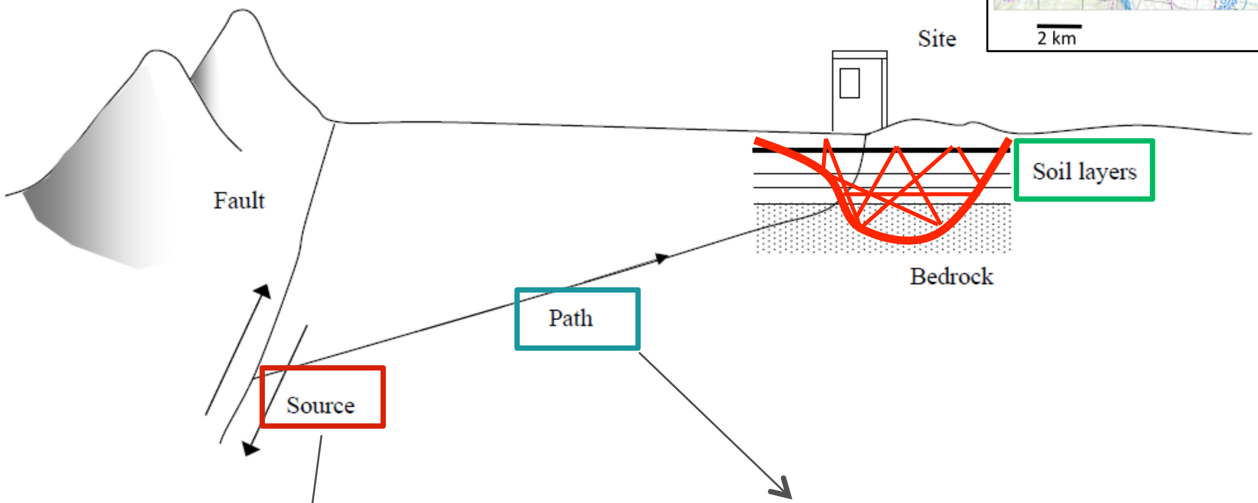
Geophys. J. Int. (2018) 215, 1442–1454
doi: 10.1093/gji/ggy355
Advance Access publication 2018 August 23
GJI Seismology

Can broad-band earthquake site responses be predicted by the ambient noise spectral ratio? Insight from observations at two sedimentary basins

Vincent Perron,[1,2,3,*] Céline Gélis,[2] Bérénice Froment,[2] Fabrice Hollender,[1,3] Pierre-Yves Bard,[3] Giovanna Cultrera[4] and Edward Marc Cushing[2]

[1] CEA, DEN, F-13108 Saint-Paul-lez-Durance, France. E-mail: vincent.perron.mail@gmail.com
[2] IRSN, PSE-ENV/SCAN/BERSSIN, BP 17, F-92262 Fontenay-aux-Roses, France
[3] University of Grenoble Alpes, ISTerre, CNRS, IRD, IFSTTAR, F-38000 Grenoble, France
[4] Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy





+ attenuation, complex propagation…

« Common application » of the noise correlation technique (Vs imaging)
+ attenuation…

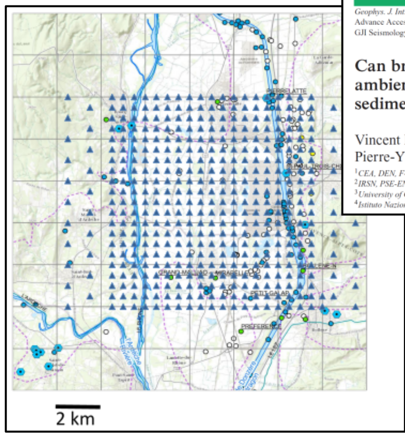
e.g. HR fault imaging;

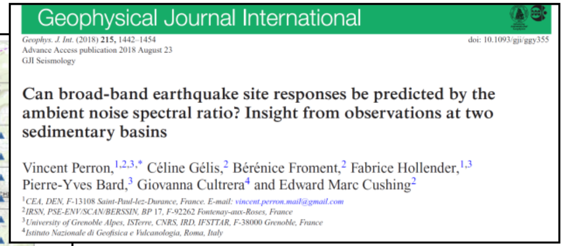
Physics-based...end goal but not the near future (in France)

+ understanding of the deformation processes…

In a broader framework…

Noise-based imaging and characterization

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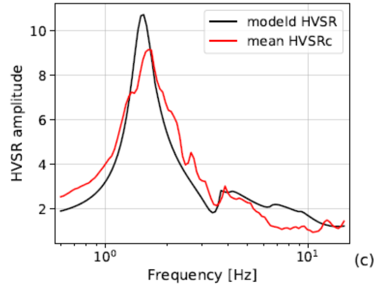
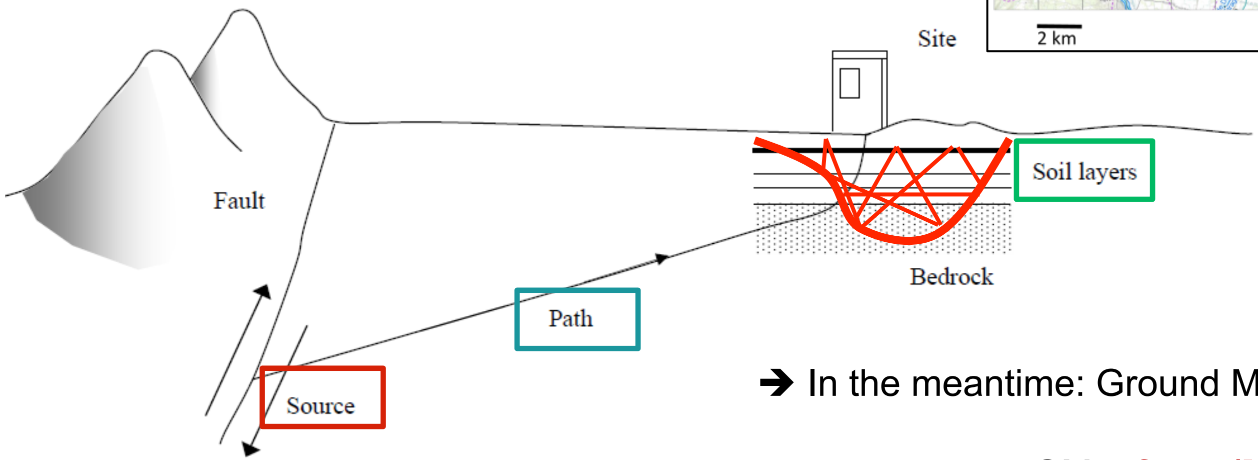
GJI Seismology

Can broad-band earthquake site responses be predicted by the ambient noise spectral ratio? Insight from observations at two sedimentary basins

Vincent Perron,[1,2,3,*] Céline Gélis,[2] Bérénice Froment,[2] Fabrice Hollender,[1,3] Pierre-Yves Bard,[3] Giovanna Cultrera[4] and Edward Marc Cushing[2]

[1] CEA, DEN, F-13108 Saint-Paul-lez-Durance, France. E-mail: vincent.perron.mail@gmail.com
[2] IRSN, PSE-ENV/SCAN/BERSSIN, BP 17, F-92262 Fontenay-aux-Roses, France
[3] University of Grenoble Alpes, ISTerre, CNRS, IRD, IFSTTAR, F-38000 Grenoble, France
[4] Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy

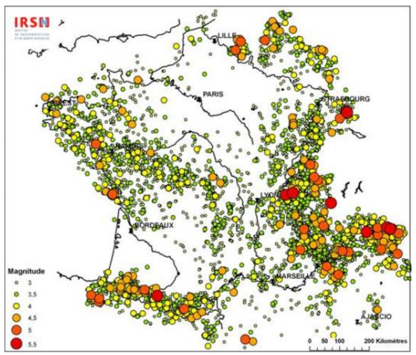


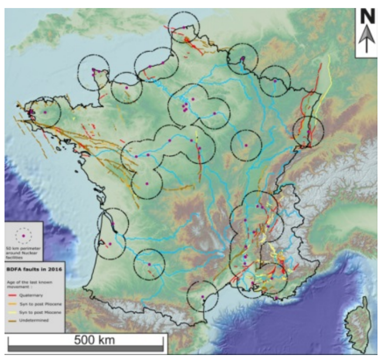


+ attenuation, complex propagation…

➔ In the meantime: Ground Motion Prediction Equations (GMPEs):

GM = $\mathbf{f_{source}(M, mechanism…)}$ + $f_{path}(R)$ + f_{site}



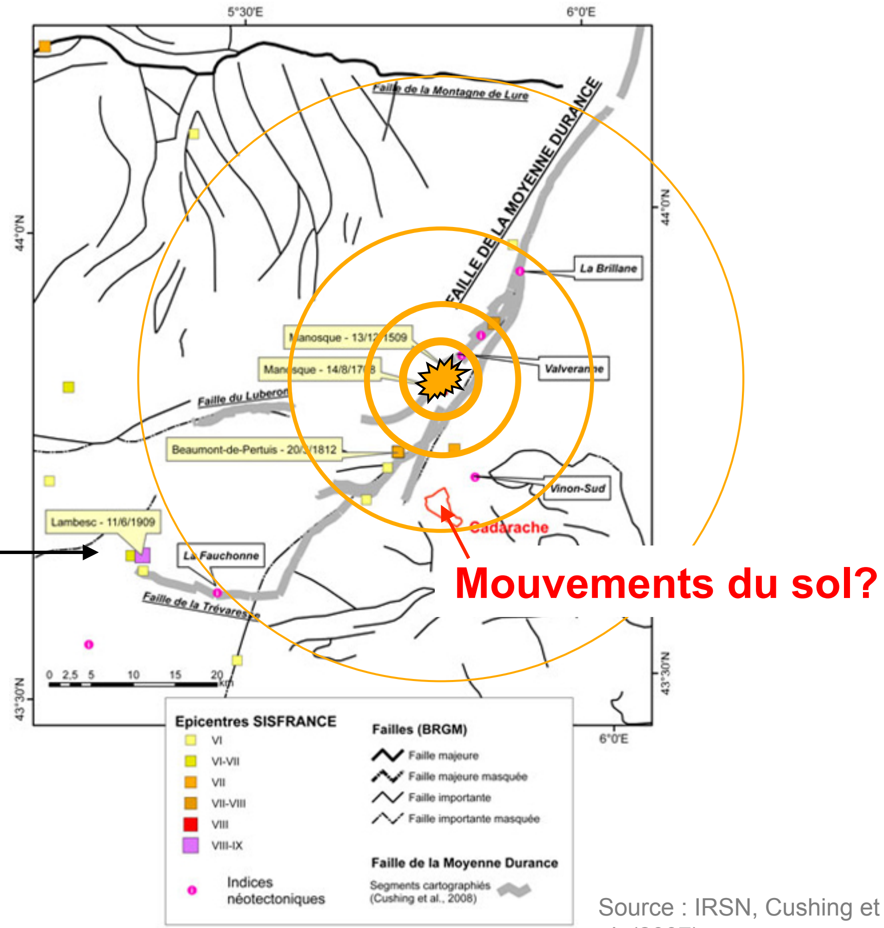


➔ Source characterization (active faults, seismicity localization)
➔ Understanding of the deformation processes in this low-to-moderate seismicity area

MERCI !

Contexte (diapo. tirée de la soutenance de thèse de V. Perron)

- Aléa sismique site-spécifique : Déterminer pour un site donné, quels peuvent être les mouvements du sol associés à un/des scénario(s) de séismes probables dans une période de temps fixée.



Source : IRSN, Cushing et al. (2007)

Lambesc (1909)

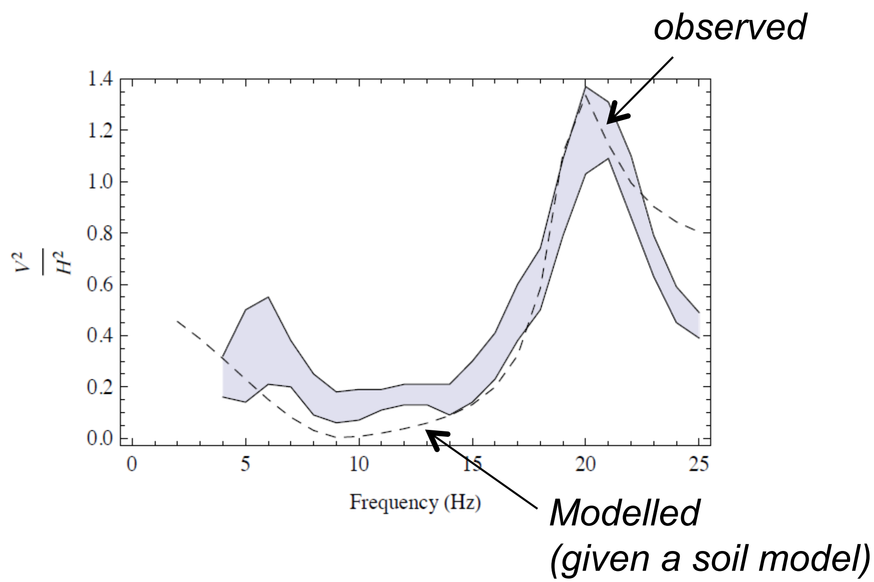
- M ~ 6.0
- 46 morts / 250 blessés

Diffuse Field Assumption

→ Studies by Margerin (2009), Margerin et al. (2009):

. Theory of equipartition in a layered elastic half-space
. Application on 10 earthquake codas at Pinyon Flats Observatory => ratio of Vert. to Hor. kinetic energies (V^2/H^2)

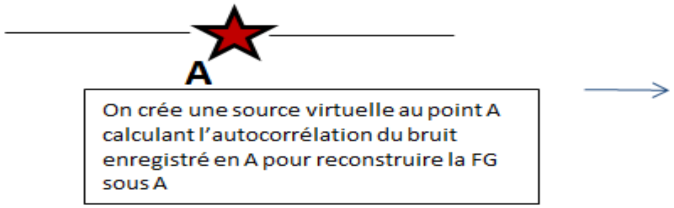
« the partition of energy in the seismic coda contains information on the local geological structure »

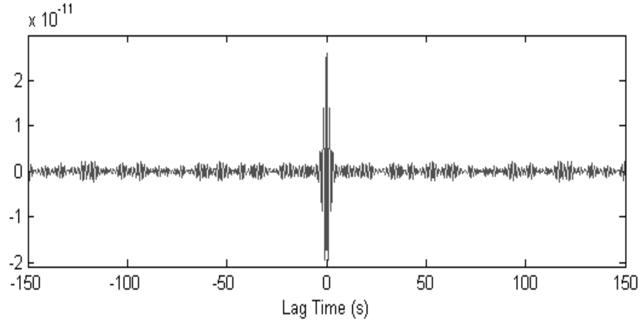


Our Approach: using the coda of noise autocorrelation

Idea : use the advantages of both seismic noise (easy to implement, readily recordable) and the coda waves (diffuse character)

b) On calcule l'autocorrélation du signal en A pour extraire la partie déterministe



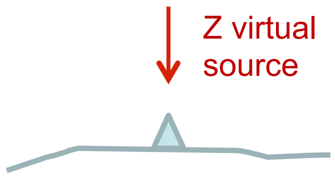


Le centre correspond au temps zéro dû à la symétrie de l'autocorrélation

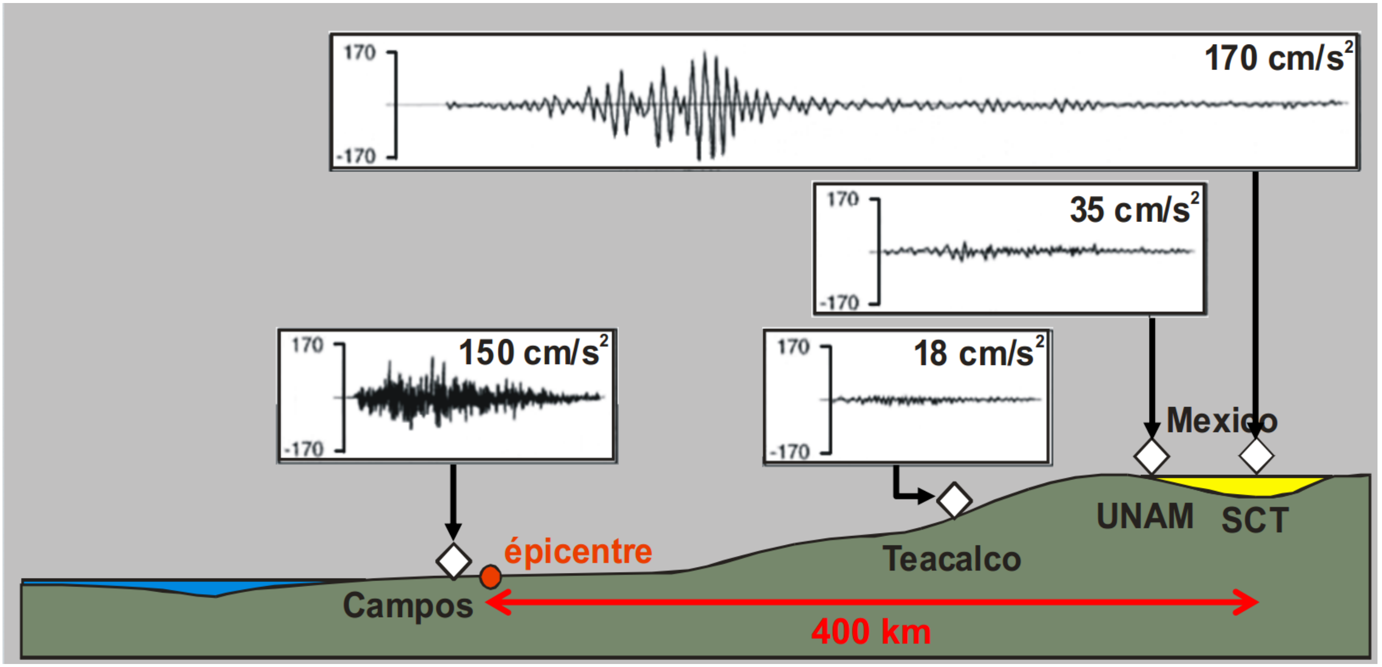
Noise correlation tensor:

$$\begin{pmatrix} ZZ & ZE & ZN \\ EZ & EE & EN \\ NZ & NE & NN \end{pmatrix}$$

→ Vertical virtual source (Z) => record on Z, N and E

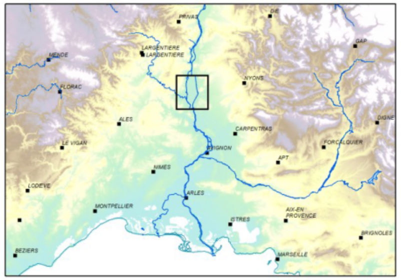


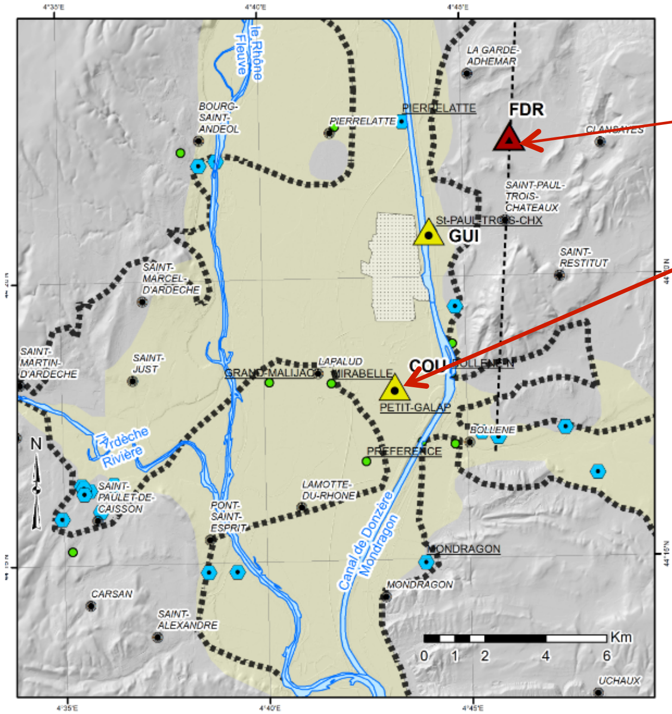
1985 Mexico Earthquake (M8.0): *« first evidence of site effects »*

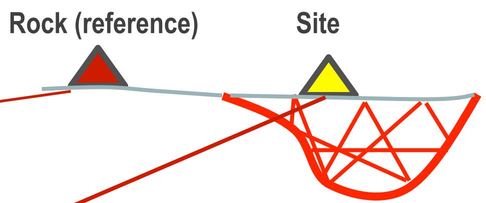


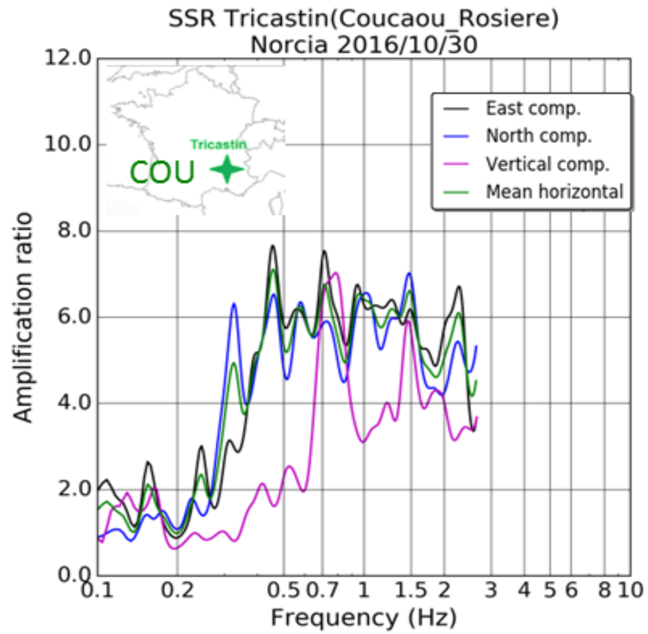
e.g. Celebi (1987)

Site effects in the french Rhône Valley

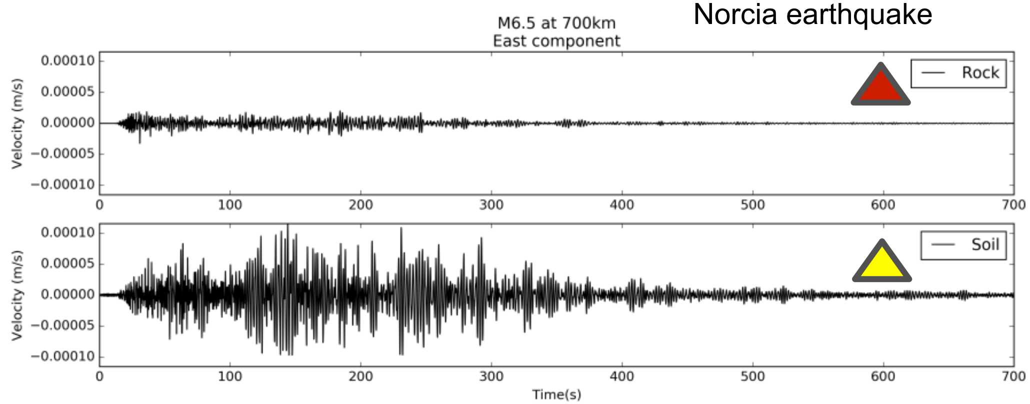




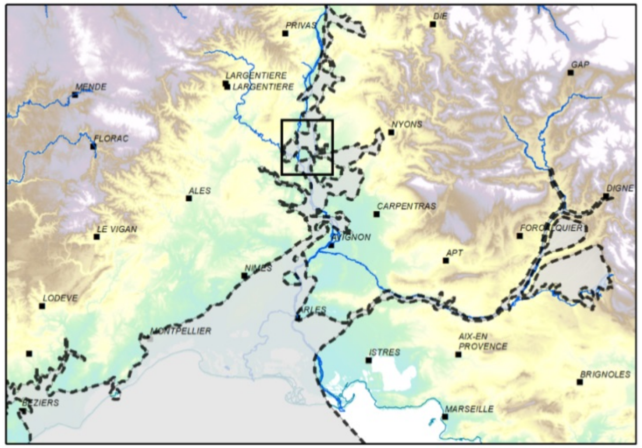




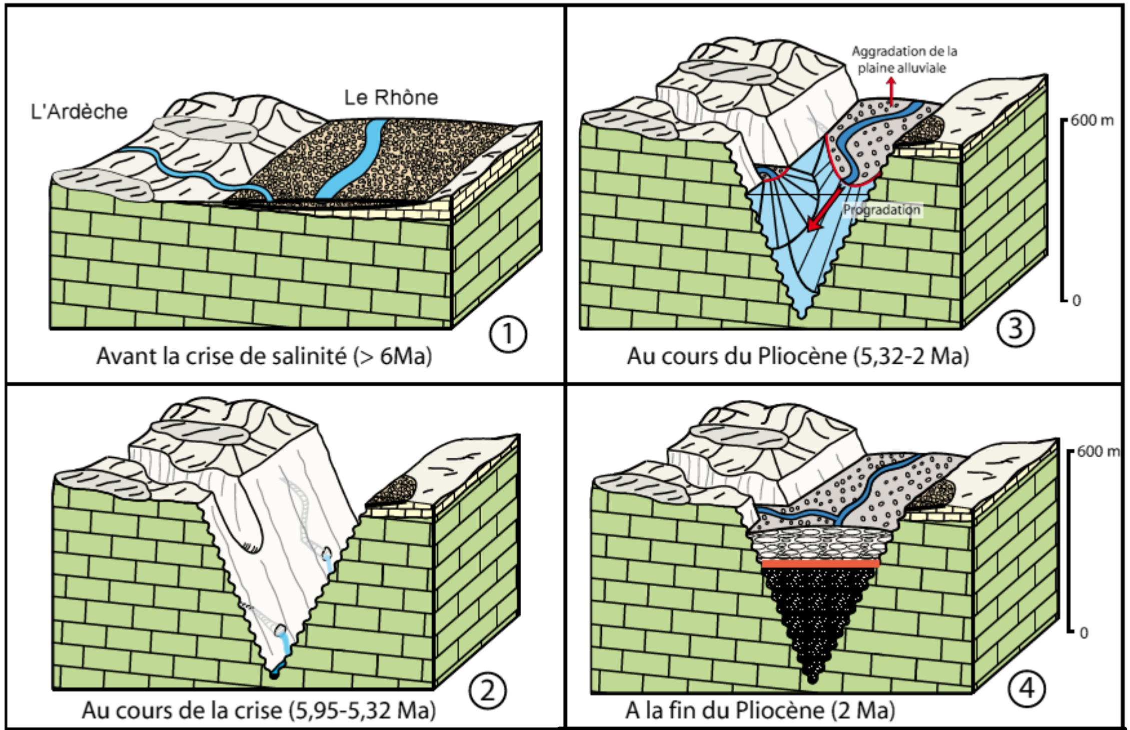
Norcia earthquake



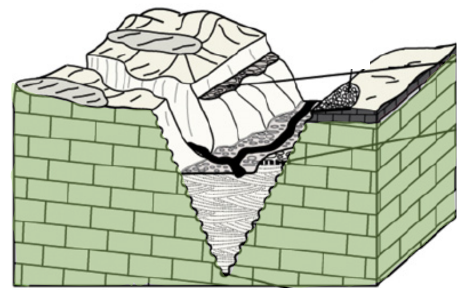
Configuration géologique dans la vallée du Rhône



Vikos Canyon, N Greece - 490 m deep



Mocochain et al., 2006
Tassy et al., 2013



Géologie actuelle

Physical interpretations

- **Interpretation 1**: Transfer function of vertically incident S-waves (e.g. Nakamura et al., 1989 & 2000)

  → *« body-wave based theories »*

- **Interpretation 2**: Rayleigh waves ellipticity or Airy phase of Love (e.g. Nogoshi & Igarashi, 1971 ; Kono & Ohmachi, 1989)

  → *« surface-wave based theories »*

⇒ *Propose an explanation of the possible origin of the H/V lower-frequency peak , but do not insert this explanation in a theory of the seismic noise wavefield => no information about the overall shape*

→ *« full-wavefield based theories »*

. Numerical simulations (e.g. Lanchet & Bard, 1994, 1995 ; Fäh et al., 2001 ; Bonnefoy-Claudet et al., 2006):

noise = wavefield resulting from a multitude of « random » sources

. **Diffuse Field Assumption** (e.g. Margerin et al., 2009 ; Sanchez-Sesma et al., 2011)

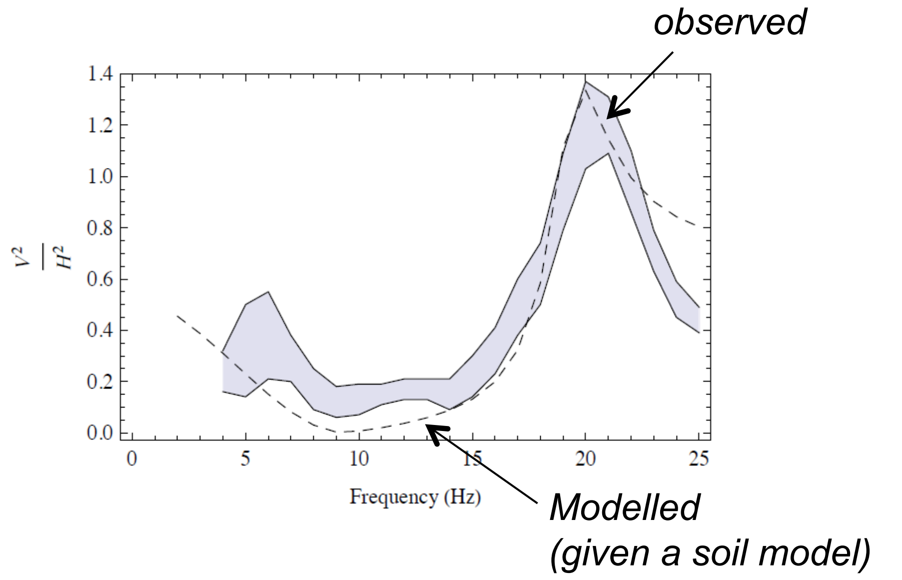
Diffuse, equipartitioned wavefield

Diffuse Field Assumption

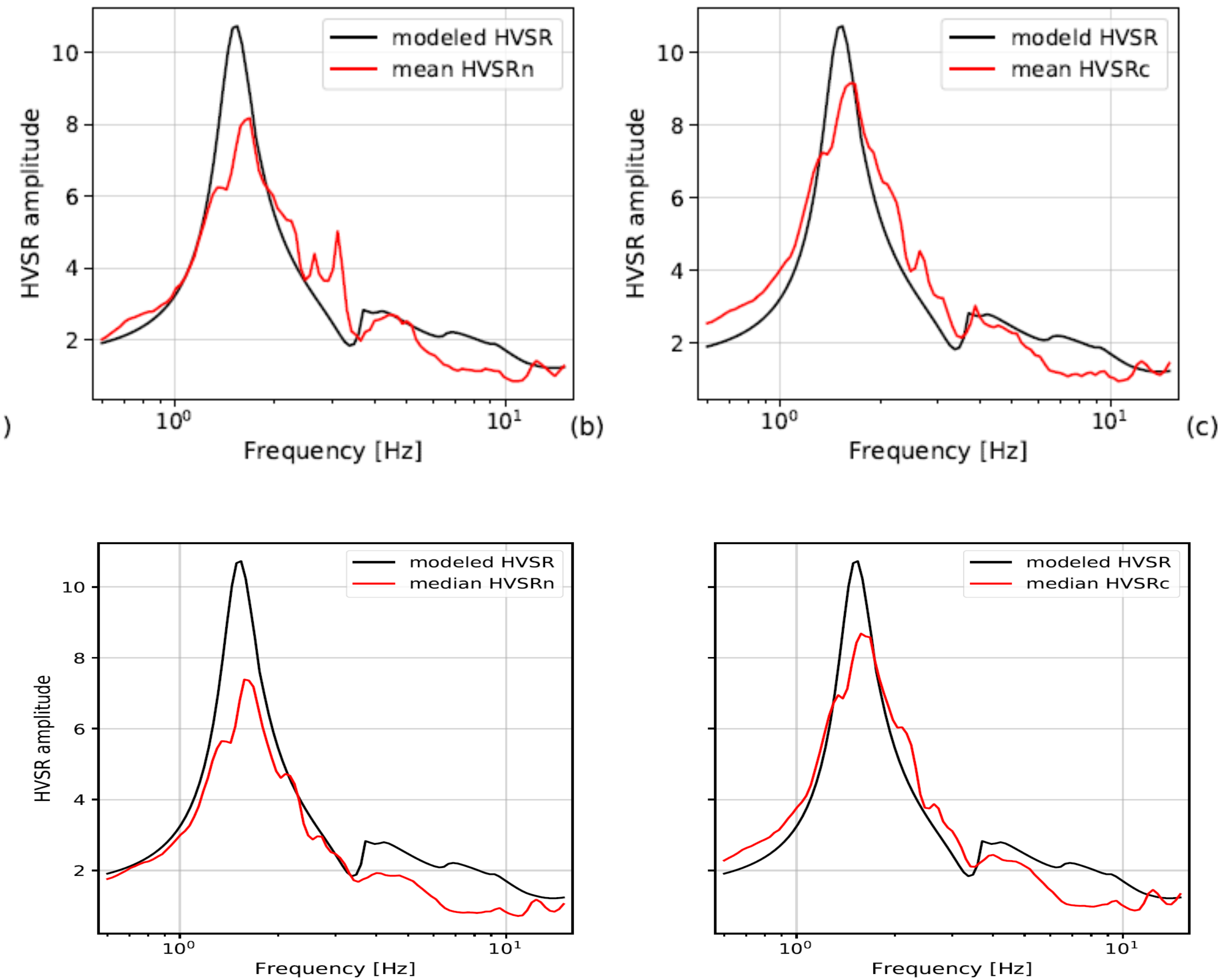
→ Studies by Margerin (2009), Margerin et al. (2009):

. Spectral decomposition of the elastic wave operator in a stratified half-space
. Write an equipartitioned wavefield (white noise distributed over all the modes of the system)
. Application on 10 earthquake codas at Pinyon Flats Observatory => V^2/H^2

« the partition of energy in the seismic coda contains information on the local geological structure »



Results: Comparison to theory



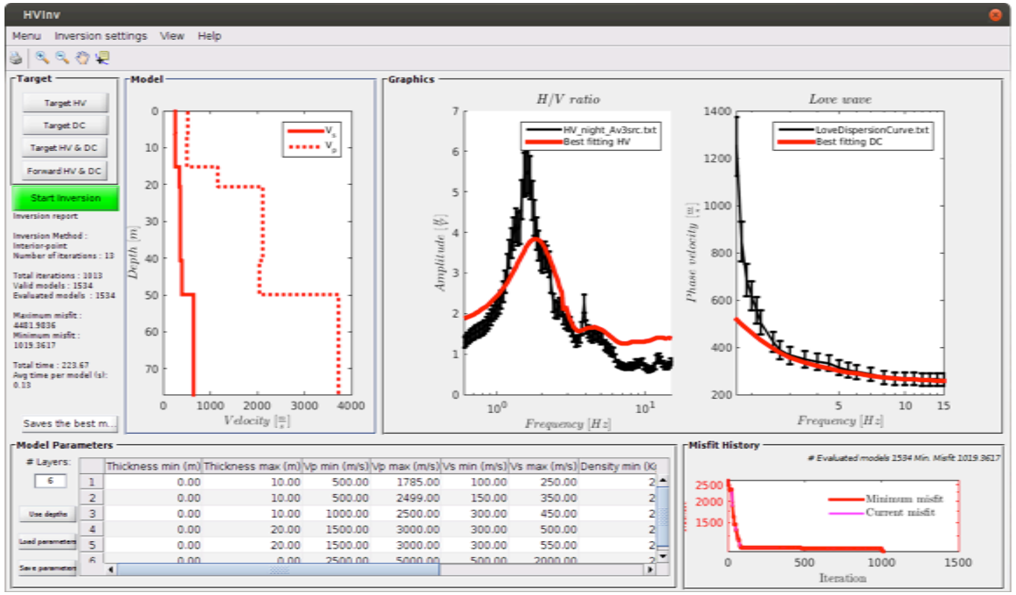
Results: Comparison to theory

Based on the DFA formulation proposed by Sanchez-Sesma et al. (2011), some studies have explored the properties of H/V from a modelling perspective:

Fast numerical tool for foward computation and inversion of H/V for a horizontally layered medium (*HV-inv*, García-Jerez et al., 2016)

Green's function formulation based on the contour integration method in the complex wavenumber plane. Allows for the identification and isolation of the contribution of the different waves (P-SV, SH, Rayleigh and Love)

Following this approach, García-Jerez et al. (2016) and Piña-Flores et al. (2017) propose an inversion scheme to assess the soil elastic parameters from surface measurements, especially H/V.



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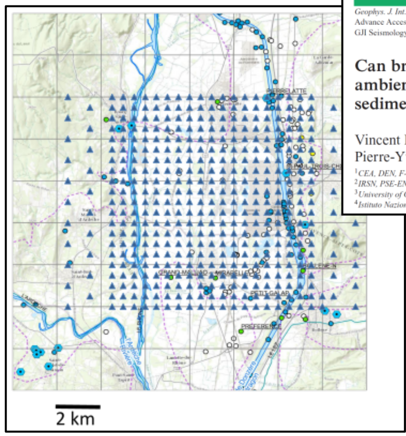

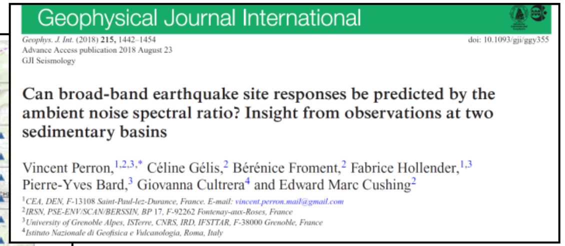
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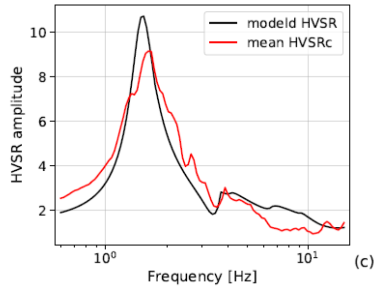
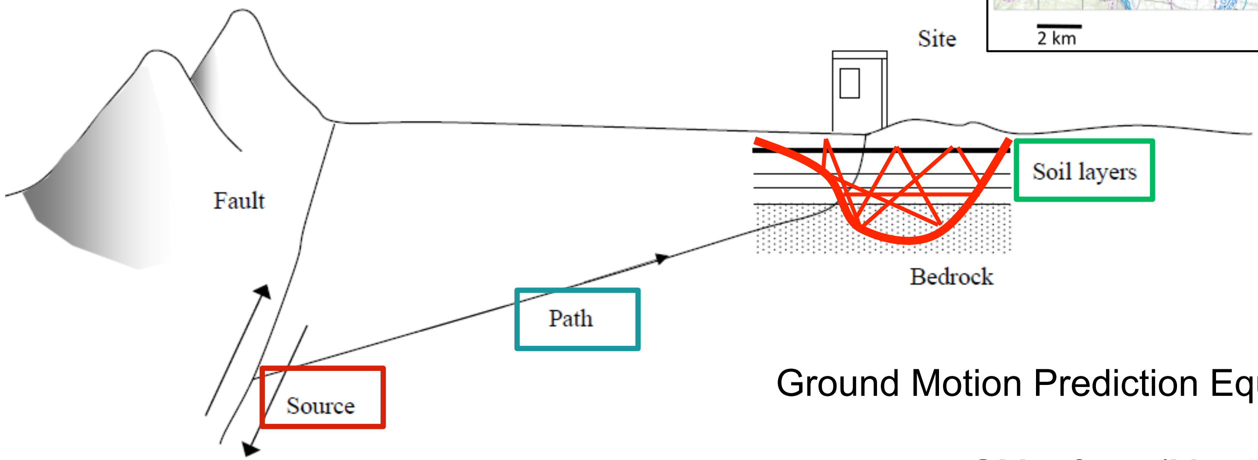




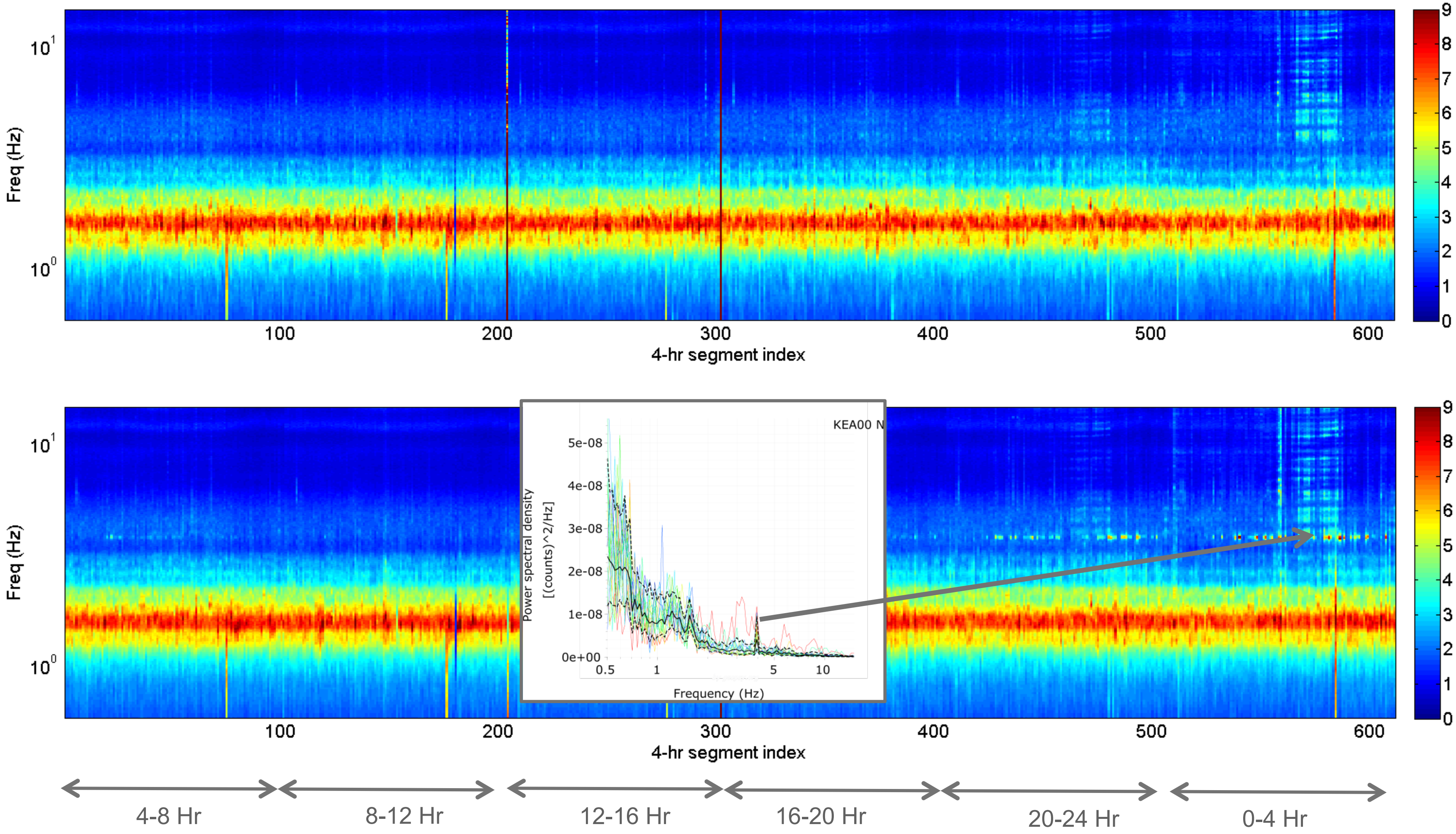
+ attenuation, complex propagation…

Ground Motion Prediction Equations (GMPEs):

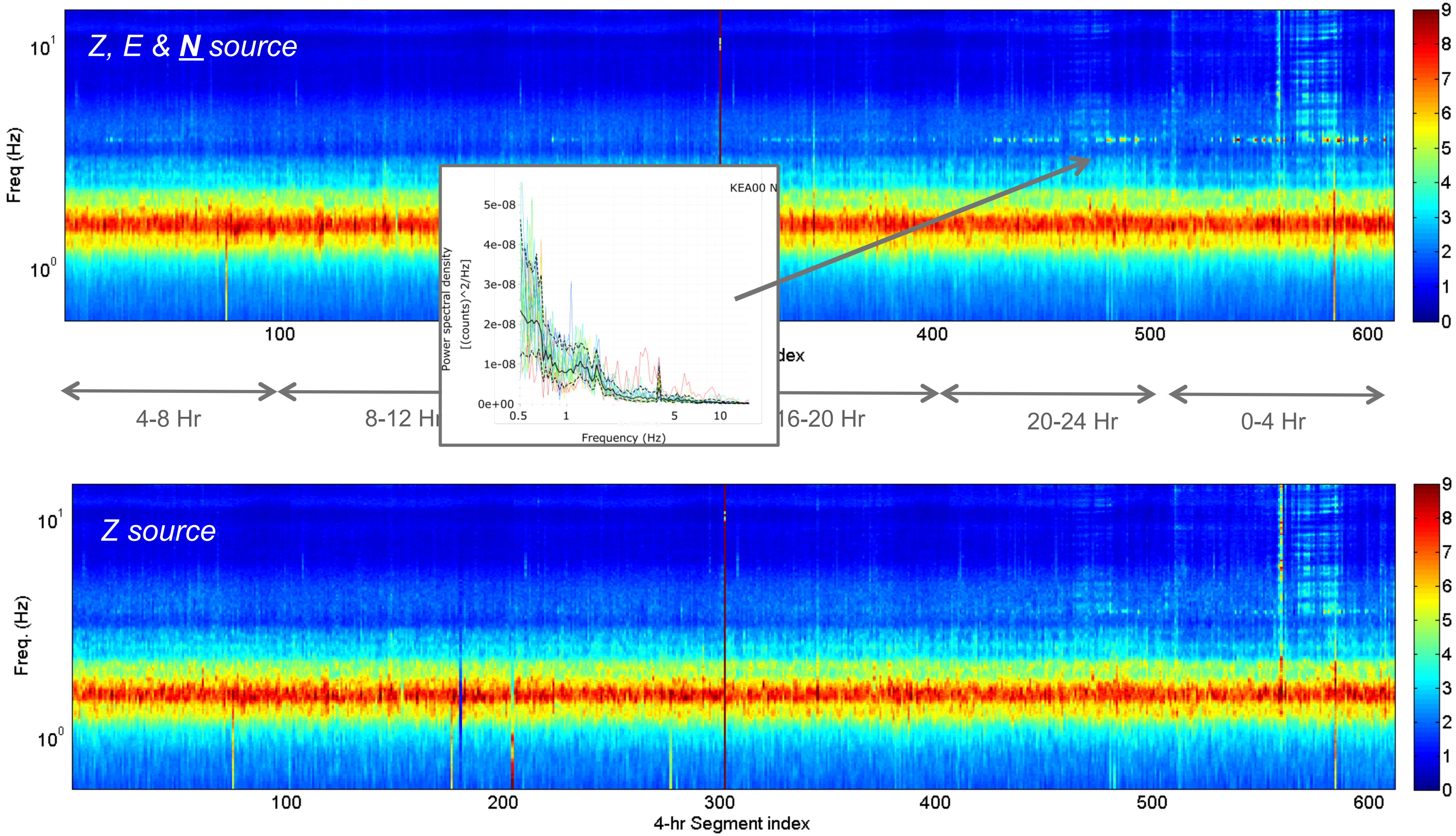
$$GM = f_{source}(M, \text{mechanism…}) + f_{path}(R) + f_{site}$$

➔ Integrate 2D variability (attenuation…)

Results: variations over 3.5 months



Results: 3.8 Hz artifact



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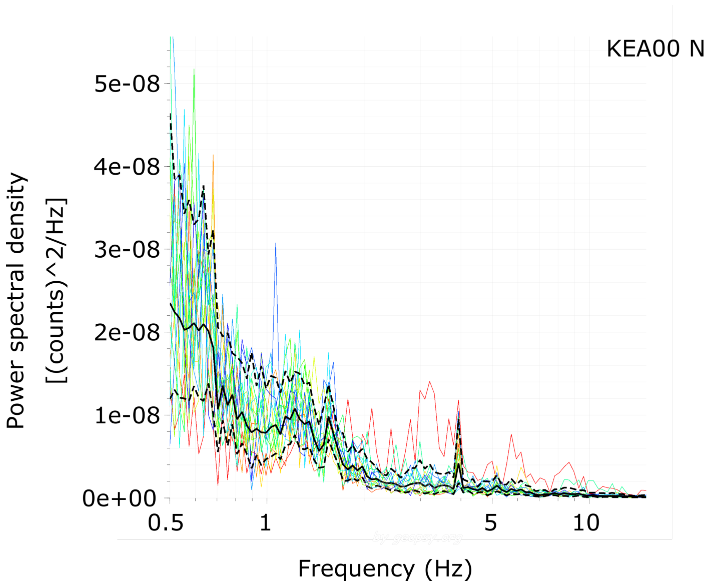
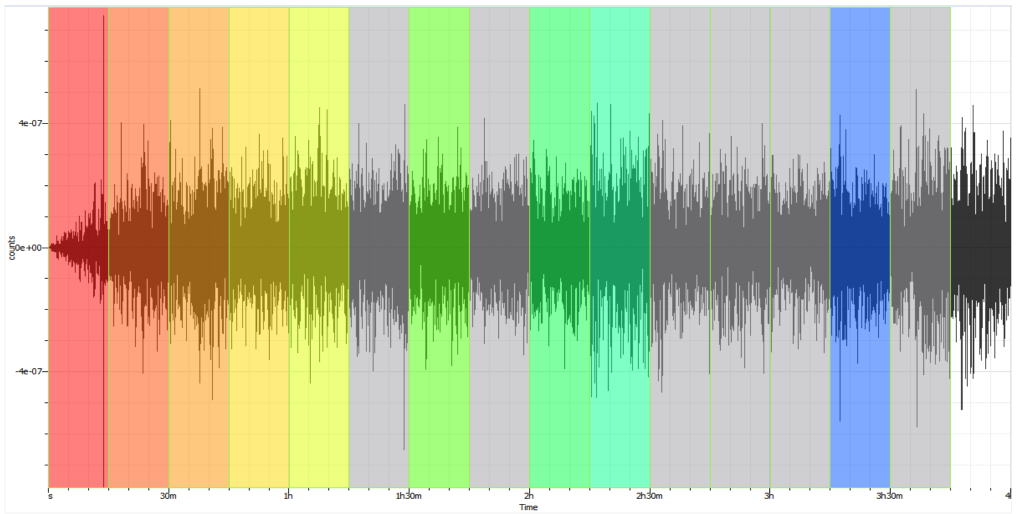
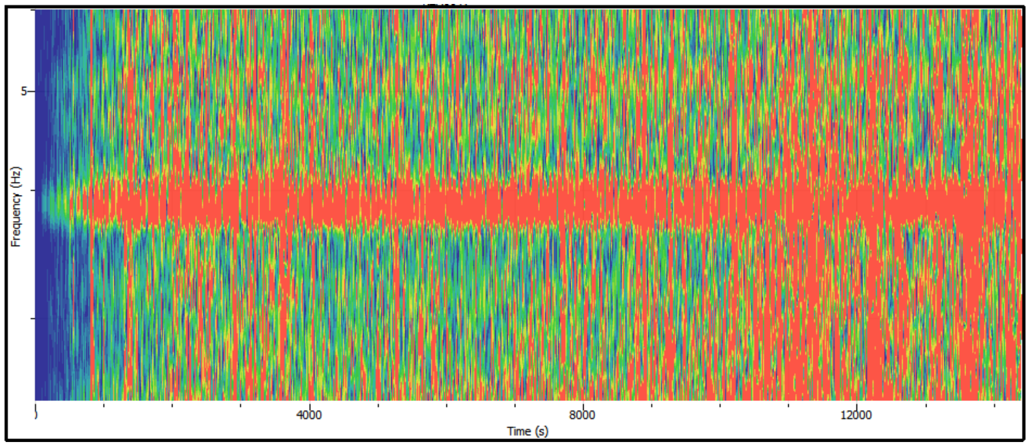


An example of problematic 4-hr segment :
Day #81 – 0-4hr

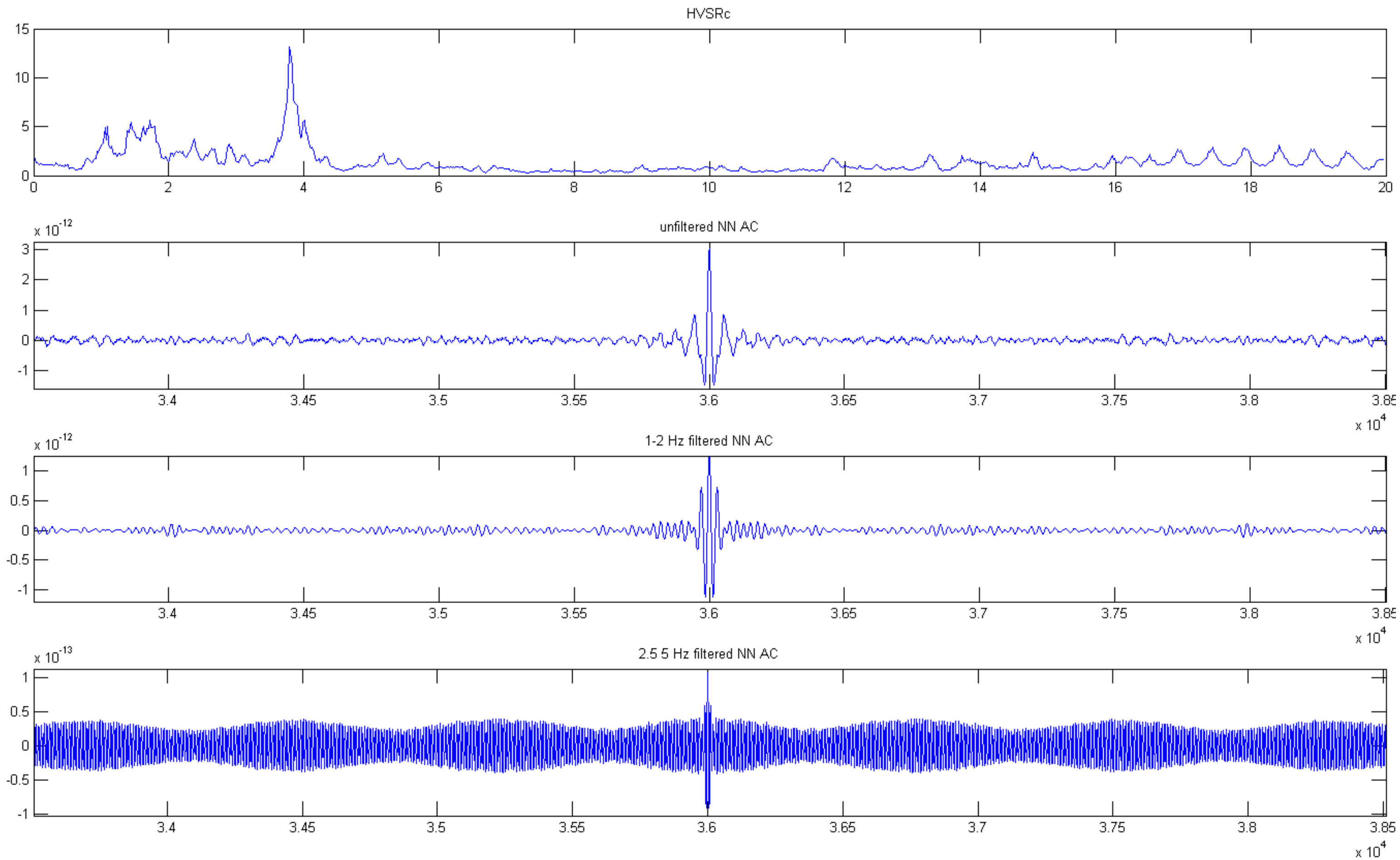




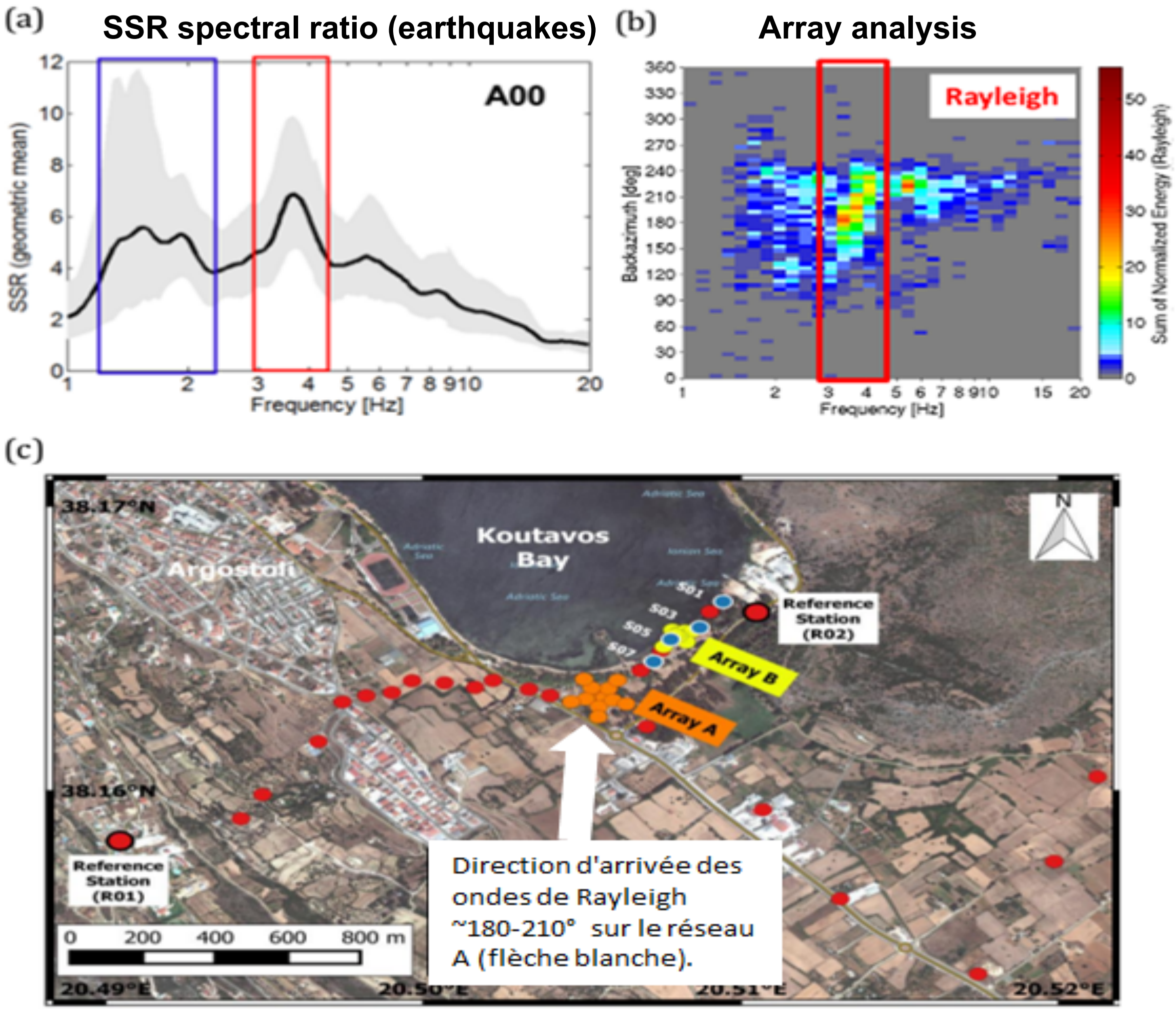
The 3.8-Hz peak is dominant over almost all the 4-hr segment (nothing clear in the temporal signal)

Results: 3.8 Hz artifact

An example of problematic 4-hr segment :
Day #81 – 0-4hr



The 2.5-5 Hz NN correlation is dominated by the source autocorrelation



Modified after Imtiaz, 2015