ITINERIS

Geophysics and natural risks: instruments and principles of data analysis

Module D: The Ambient Seismic Noise for subsurface characterization

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Ministero dell'Università e della Ricerca

Italiadomani

Who am I?

Master degree in Geological Sciences at University of Bari in 2011

- *Numerical modelling of wave propagation in homogeneous media*

Phd in Geophysics at University of Bologna «Alma Mater Studiorum» in 2015

- *Attenuation tomography of Campi Flegrei Caldera*

Research fellow at CNR, Tito Scalo, PZ since 2017

Crustal models in induced seismicity contexts; Earthquake seismology; Urban geophysics; earthquake engineering

Fixed term researcher at CNR, Tito Scalo, PZ since 2023

Research Interests:

Earthquake Seismology, Seismic Tomography, Near Surface Geophysics, Earthquake Engineering

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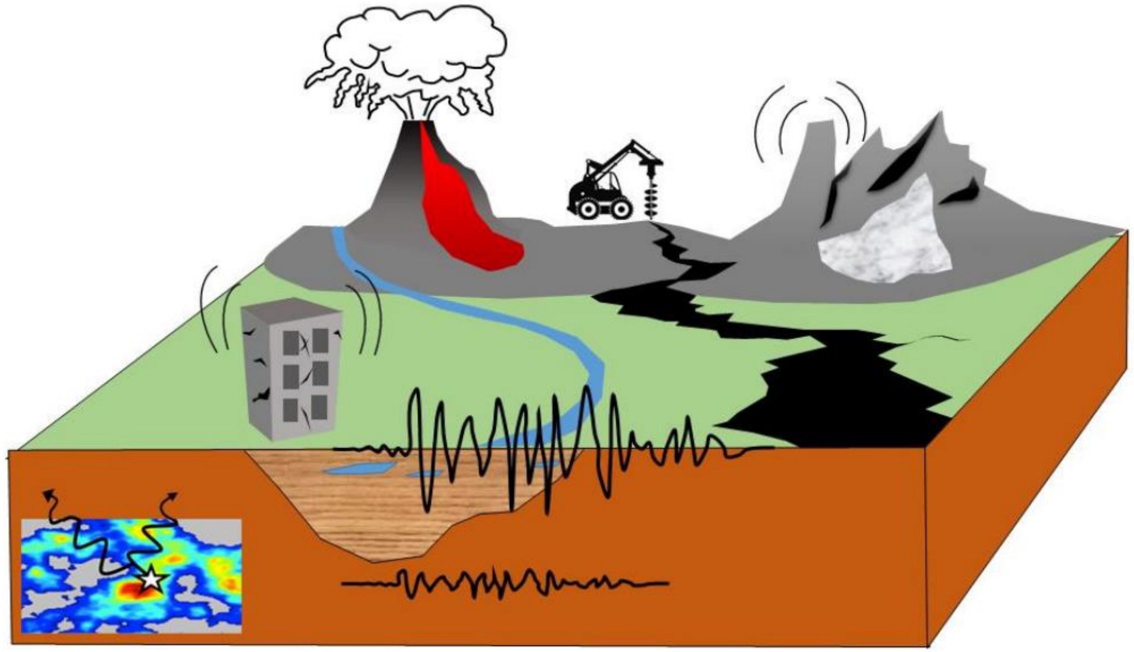
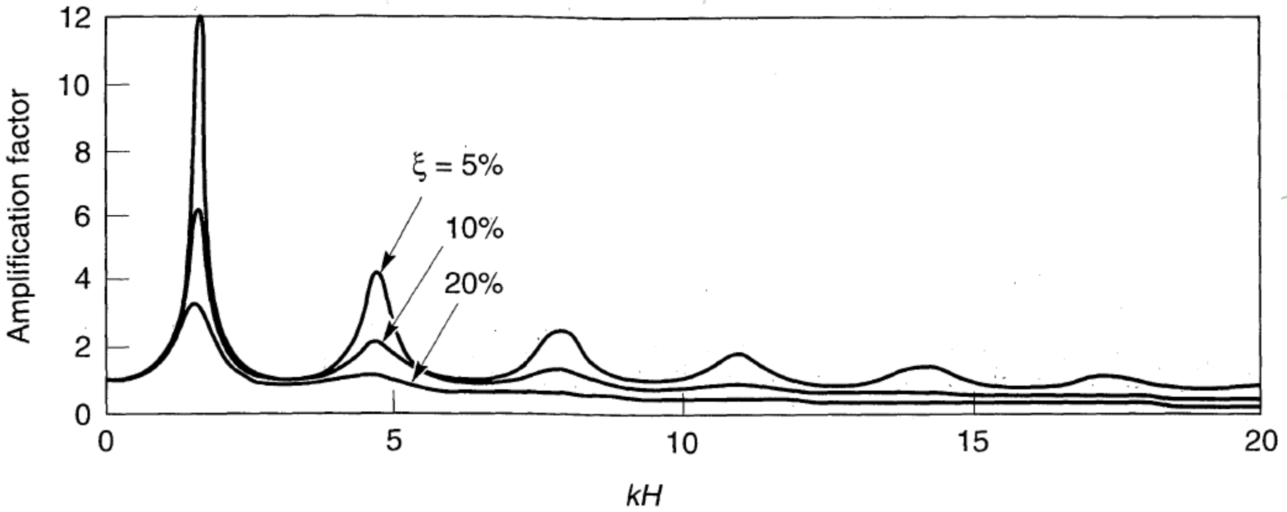
SCHEDULE OF THE MODULE
Introduction: the importance of Ambient Seismic Noise and its properties (1h)
Single Station Method: HVSR technique (1h 30’)
Array Based Methods (2h)
Practicing with Geopsy (1h 30’)

For what scientific reasons are we interested in ambient vibration?



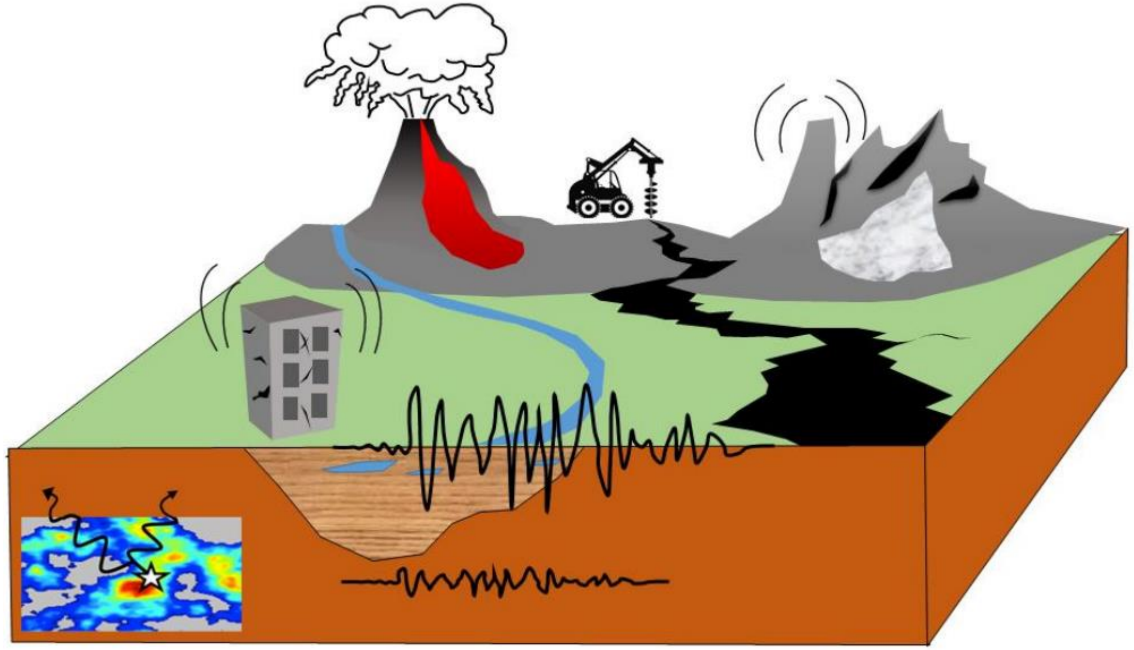
Key ingredients controling ground motion (de)amplification:
Geometry (1D,2D,3D) ;
mechanical and (an-)elastic properties (***Vs***, attenuation)

Fundamental frequency(ies) of a soil



Lanzo and Silvestri, 1999

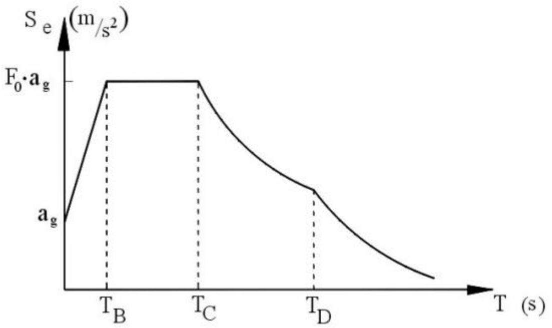
For what scientific reasons are we interested in ambient vibration?



Proxy for building code site amplification : Vs30

$$V_{S,30} = \frac{30m}{\sum_{i=1}^{N} \frac{H_i}{Vs_i}}$$

Design earthquake



$$0 \le T < T_B \qquad S_e(T) = a_g \cdot S \cdot \eta \cdot F_o \cdot \left[\frac{T}{T_B} + \frac{1}{\eta \cdot F_o}\left(1 - \frac{T}{T_B}\right)\right]$$

$$T_B \le T < T_C \qquad S_e(T) = a_g \cdot S \cdot \eta \cdot F_o$$

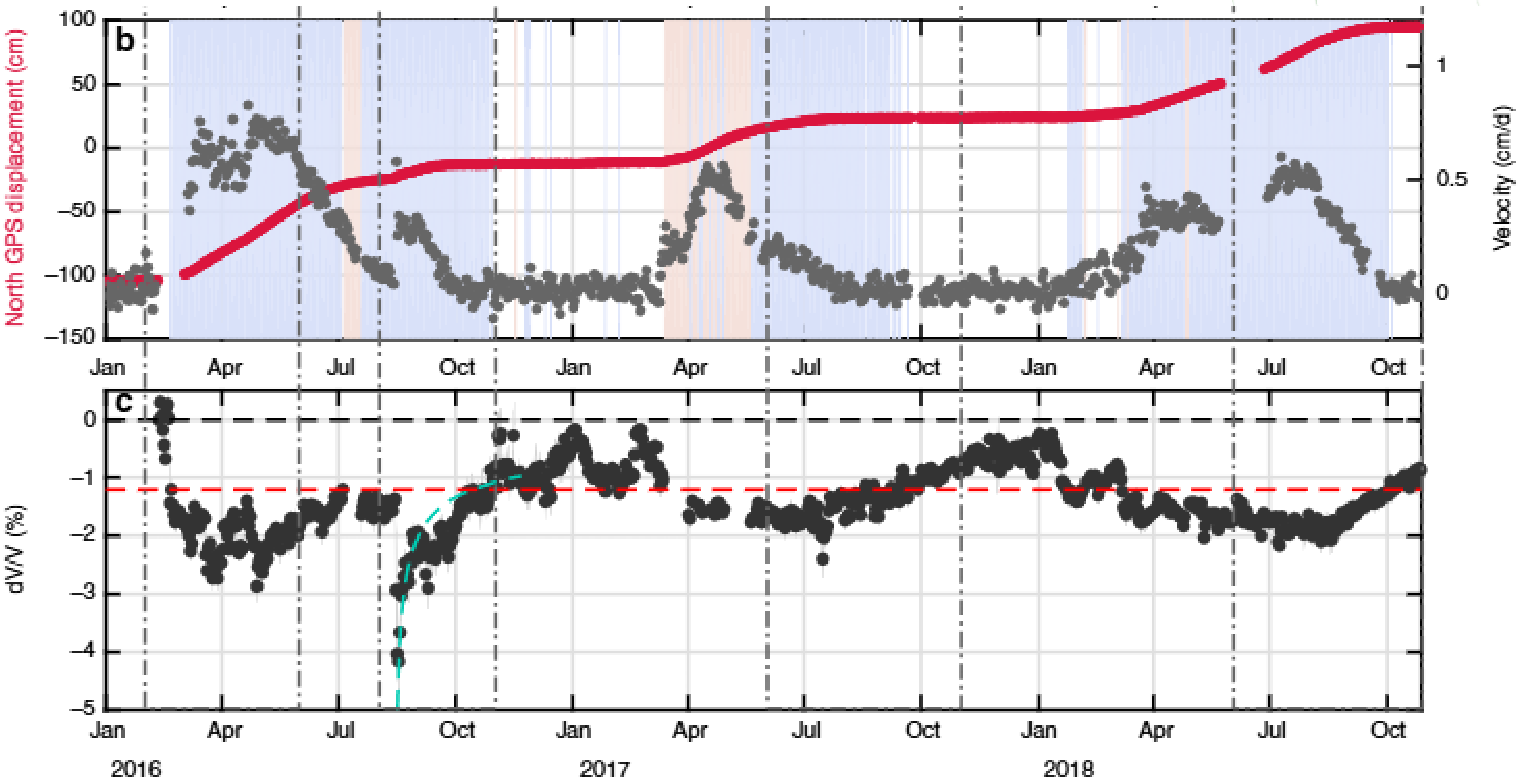
$$T_C \le T < T_D \qquad S_e(T) = a_g \cdot S \cdot \eta \cdot F_o \cdot \left(\frac{T_C}{T}\right)$$

$$T_D \le T \qquad S_e(T) = a_g \cdot S \cdot \eta \cdot F_o \cdot \left(\frac{T_C \cdot T_D}{T^2}\right)$$

$$S = S_S \cdot S_T$$ *Soil coefficient*

Category	
A	Vs > 800 m/s
B	360 m/s < Vs < 800 m/s
C	180 m/s < Vs < 360 m/s
D	100 m/s < Vs < 180 m/s
E	Vs similar to C-D but shallower bedrock

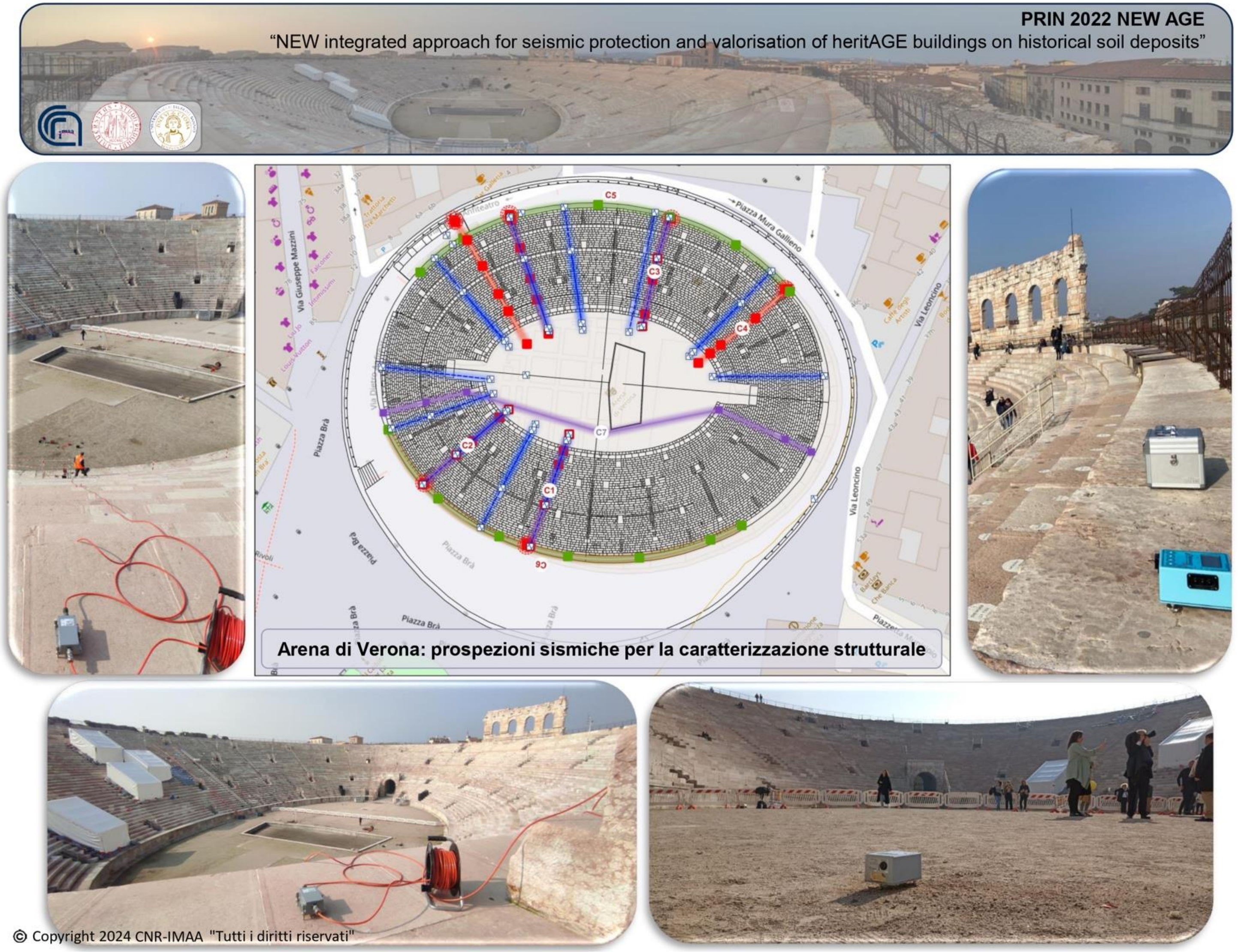
For what scientific reasons are we interested in ambient vibration?



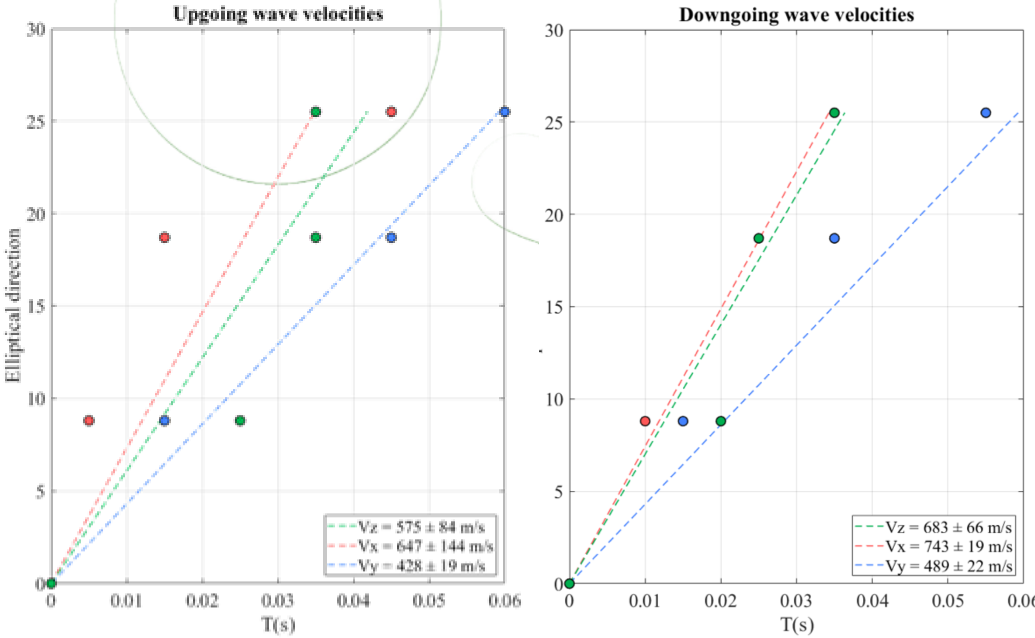
Proxy for landslide monitoring: dv/V

Bontemps et al., 2020, Nat. Comm.

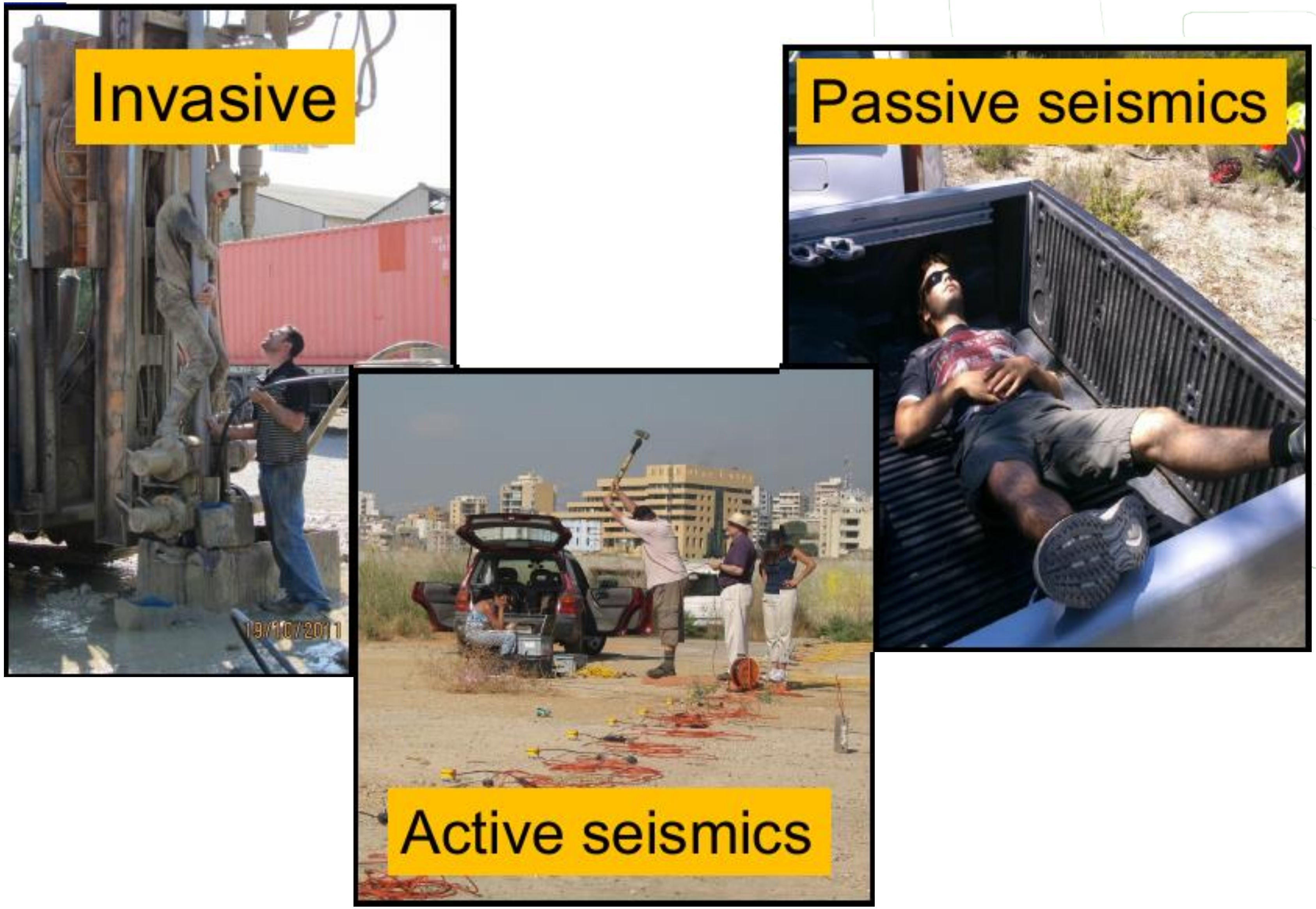
For what scientific reasons are we interested in ambient vibration?

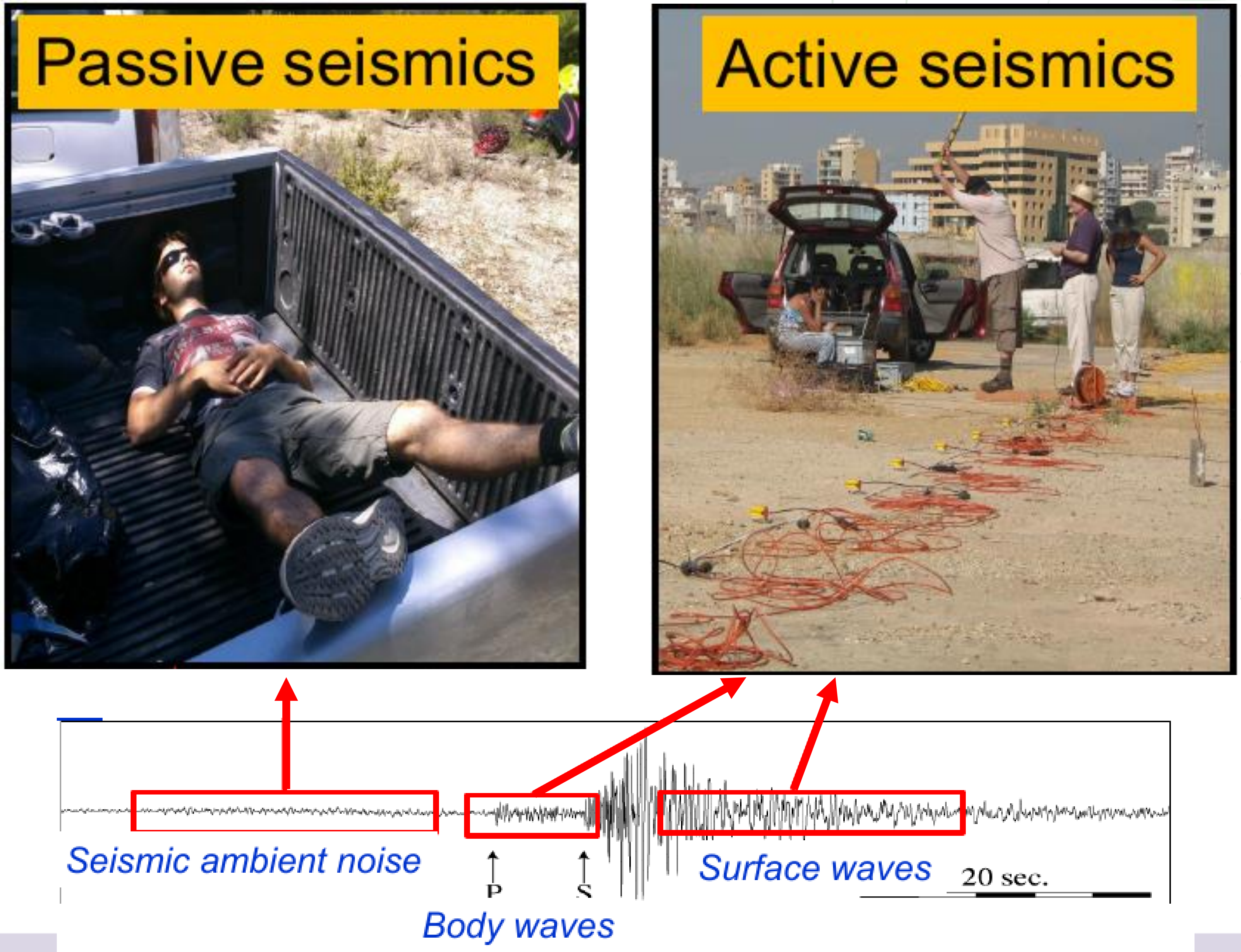


Proxy for civil engineering structures and cultural heritage health monitoring: *Vs*



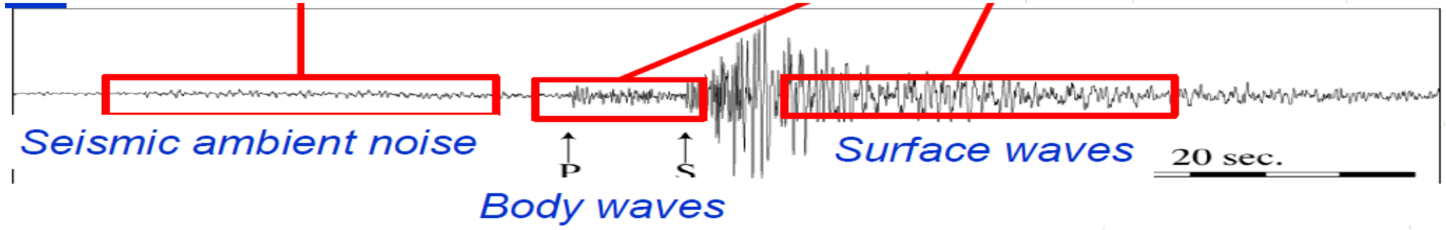
For what economic reasons are we interested in ambient vibration?




Passive seismics
Active seismics
Seismic ambient noise
P
S
Surface waves
20 sec.
Body waves

What is the Ambient Seismic Noise

Small ground vibrations (displacements of the order of 10^{-4} 10^{-3} cm) everywere recorded on the Earth



"Noise is the part of the data that we choose not to explain" (Scales in Snieder, 1998)

Microseisms

- Long Period Noise (T > 1 s; Frequency < 1 Hz)

NATURAL SOURCES

(sea waves, big atmospheric perturbations) Far sources: surface waves contribution (Rayleigh waves) in their fundamental mode

Microtremors

- Short Period Noise (T < 1 s; Frequency >1 Hz)

ANTHROPIC SOURCES

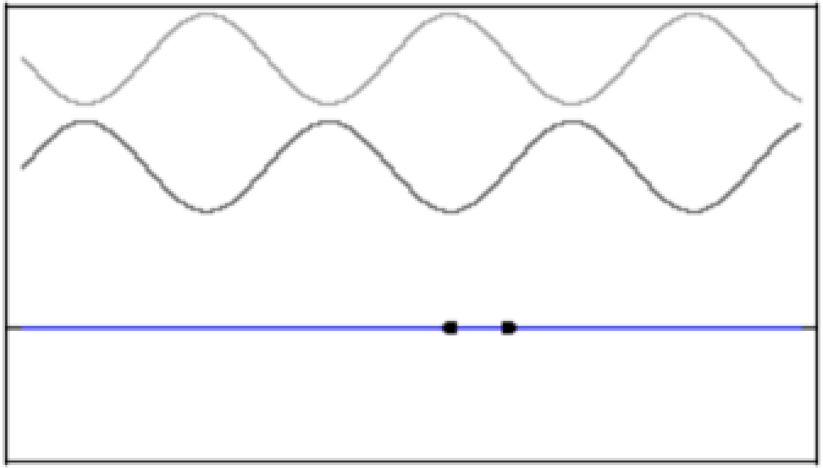
(Vehicle trafic, industrial activities, local wind) Local Sources: both body and surface waves. As to the latter, both fundamental and higher modes

What is the **Ambient Seismic Noise** composed of?

Incident wave

On Shore

Coast line

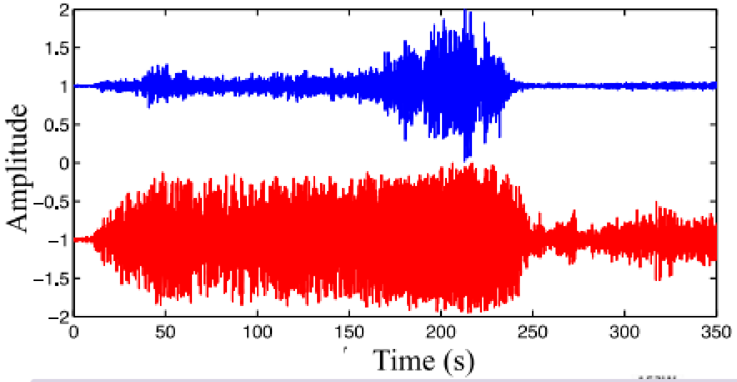


Incident wave

Reflected wave

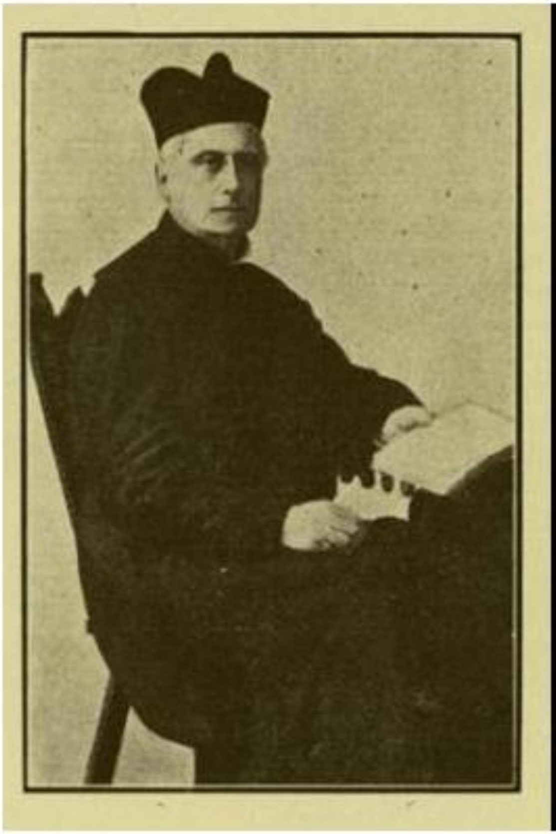
Standing wave

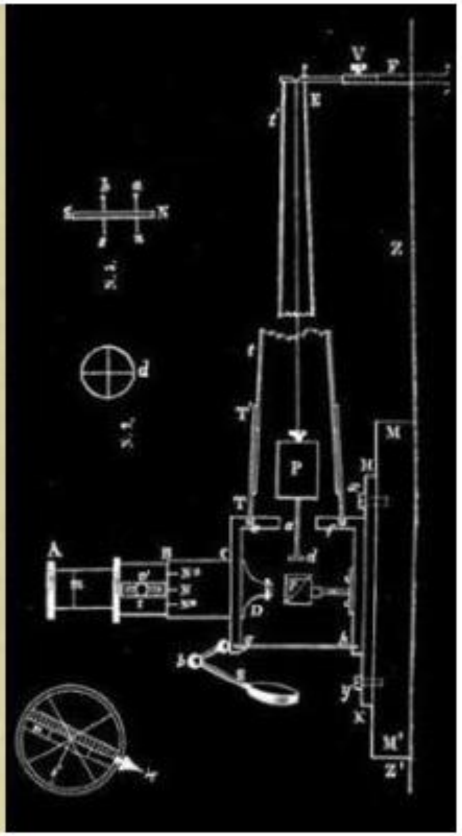
Large wavelength sea waves generate ambient vibrations due to the beating generated by the interference of ocean waves reflected from the coastline. This standing wave acts as a striker on the seafloor generating wave trains that propagate within the crust.



Other sources of natural origin include streams, tremors from volcanic activity, and subsurface fluid circulation.

Ambient noise in late 20th century

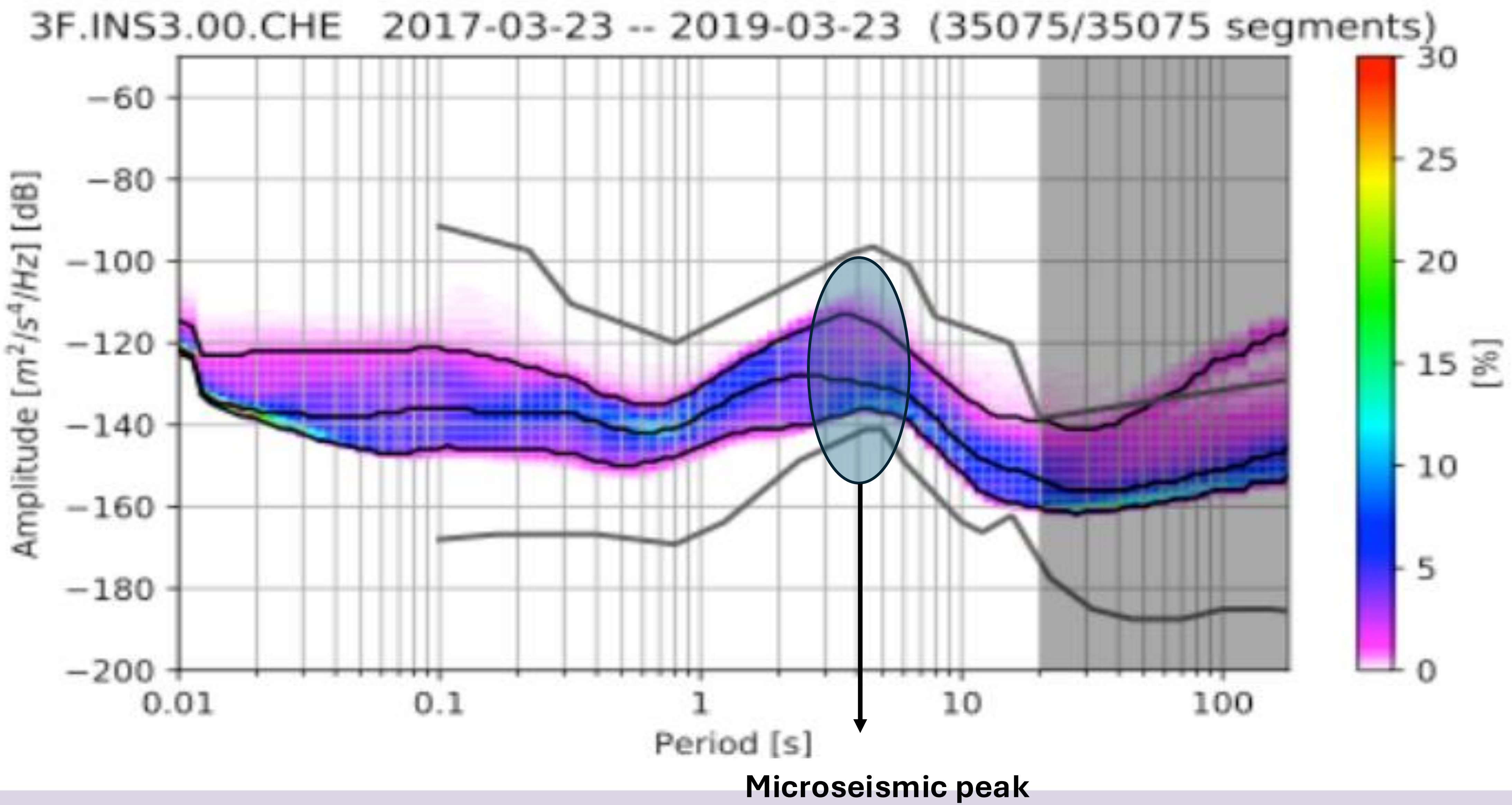




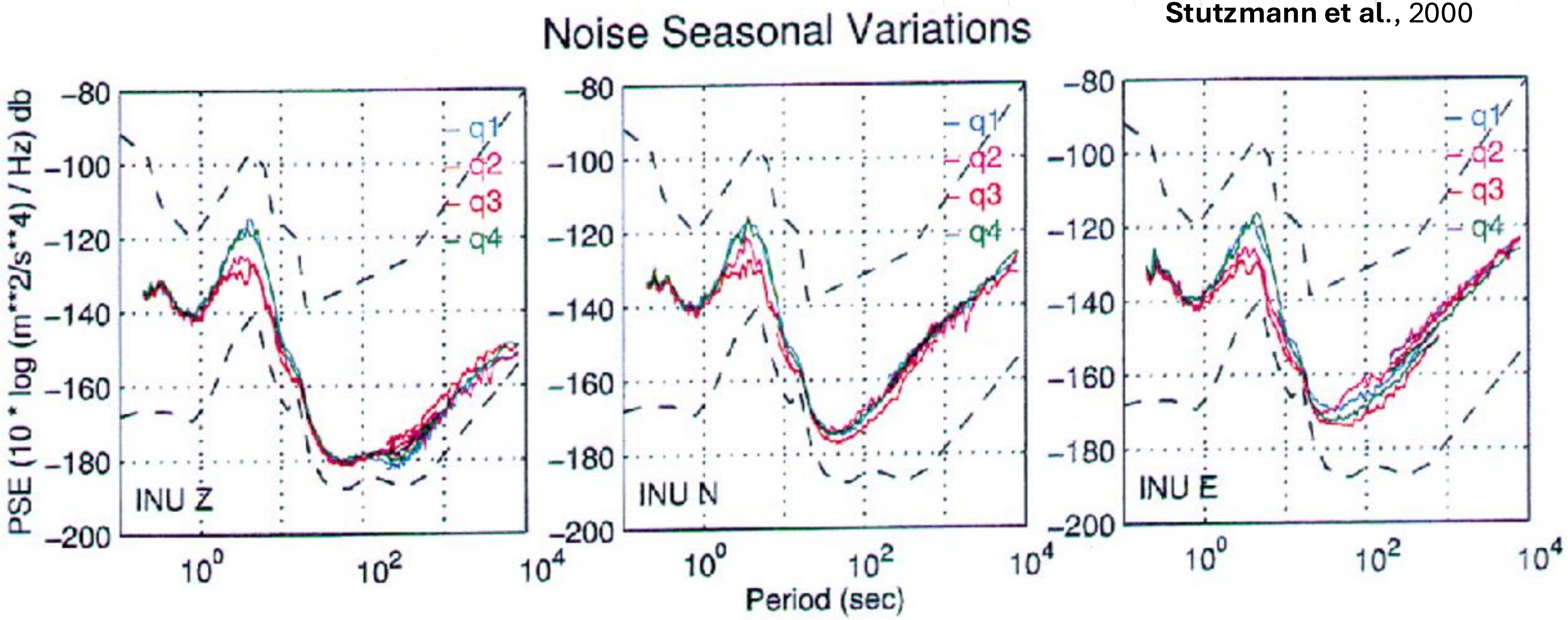
Timoteo Bertelli (1826– 1905)

The father of «microseisms»

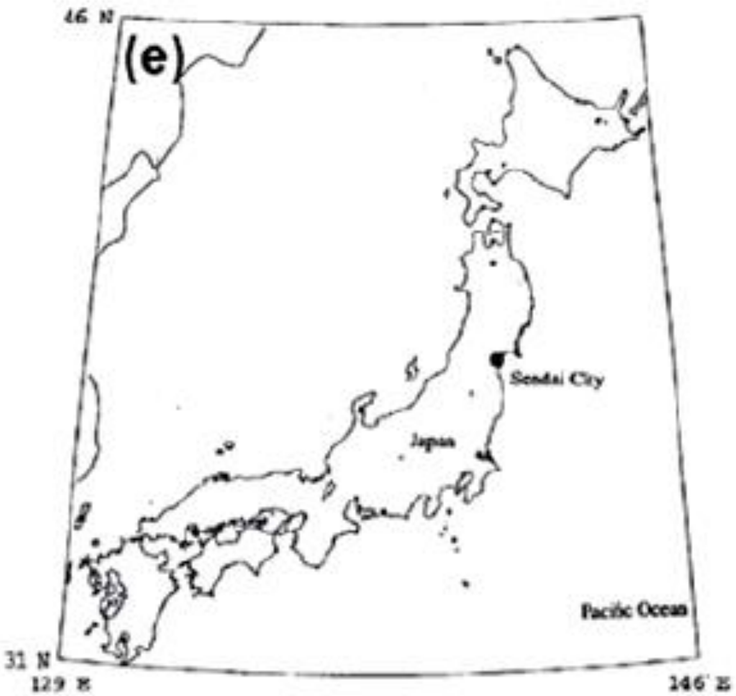
"The microseismic movements of an isolated pendulum often occur contemporaneously with distant earthquakes; others occur during continued barometric depressions; and the movements have a maximum in winter and a minimum in summer."


3F.INS3.00.CHE 2017-03-23 -- 2019-03-23 (35075/35075 segments)
Amplitude [$m^2/s^4/Hz$] [dB]
−60
−80
−100
−120
−140
−160
−180
−200
0.01
0.1
1
10
100
Period [s]
30
25
20
15
10
5
0
[%]
Microseismic peak

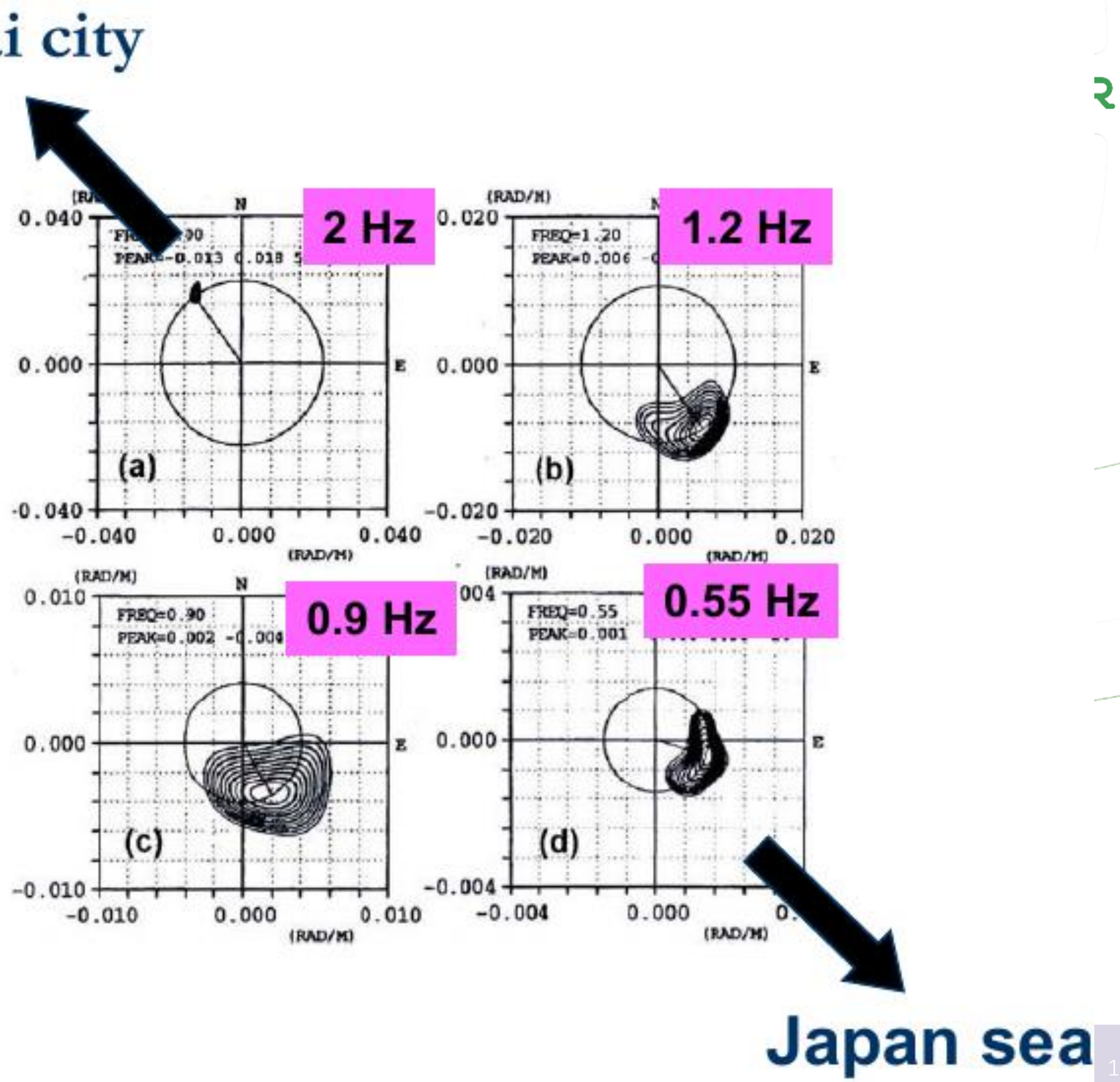
Stutzmann et al., 2000

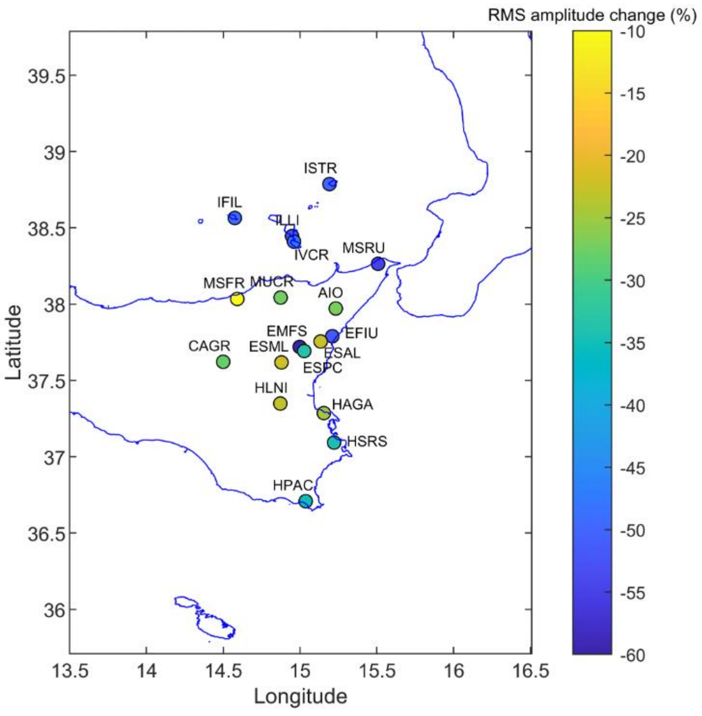


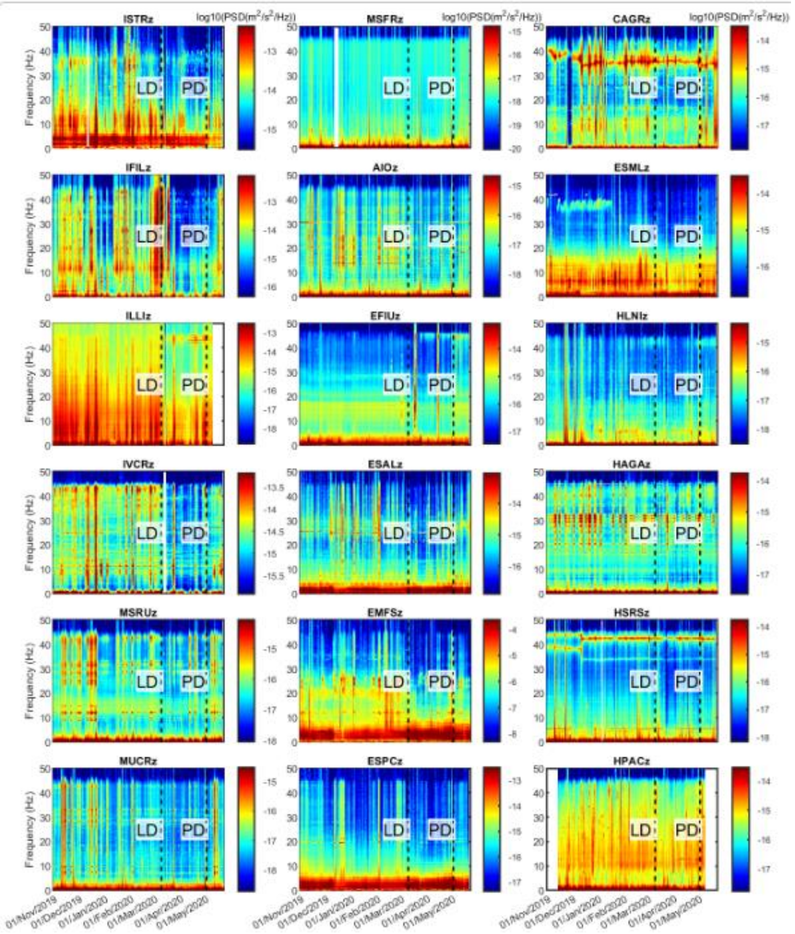
q1: January – March ; q2: April – June; q3: July – September; q4: October – December.

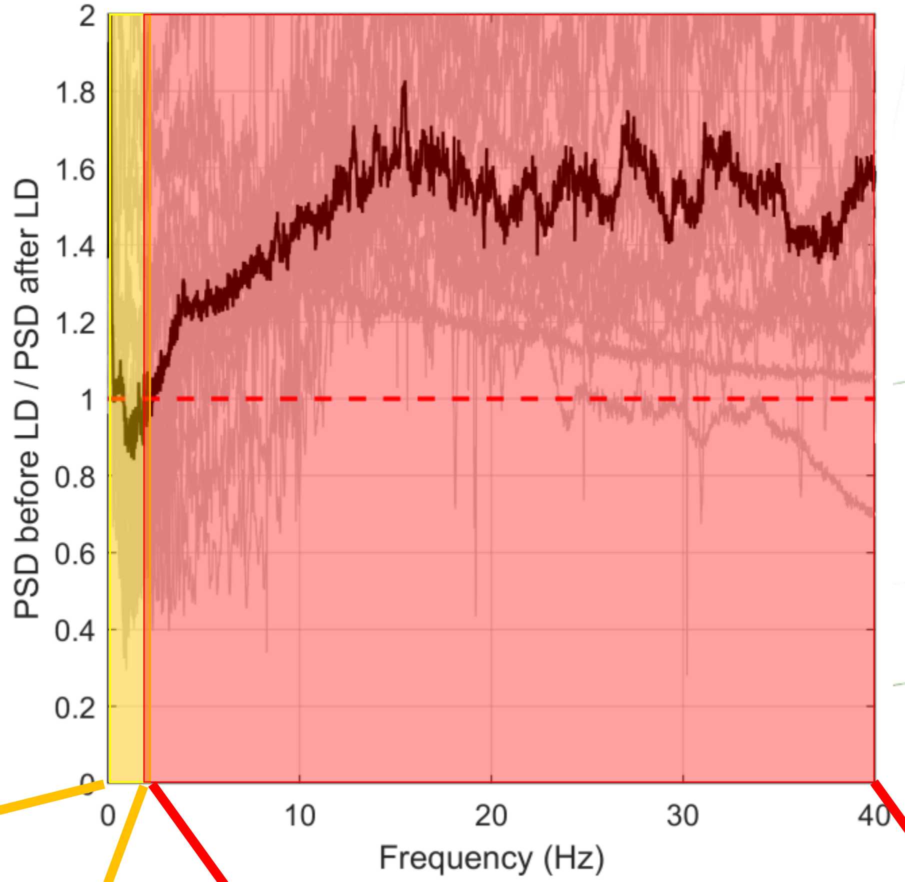


Satoh et al. (2001)









10 – 40 Hz

Cannata et al., 2021, Front. Earth.Sci.

Natural Sources

Anthropic sources

Origin of the **Seismic Noise**

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Below 1 Hz	Close to 1 Hz	Above 1 Hz
↓	↓	↓
oceanic and large scale meteorological conditions	wind effects and local meteorological conditions	human activities

Microseisms

Microtremors

SUMMARY

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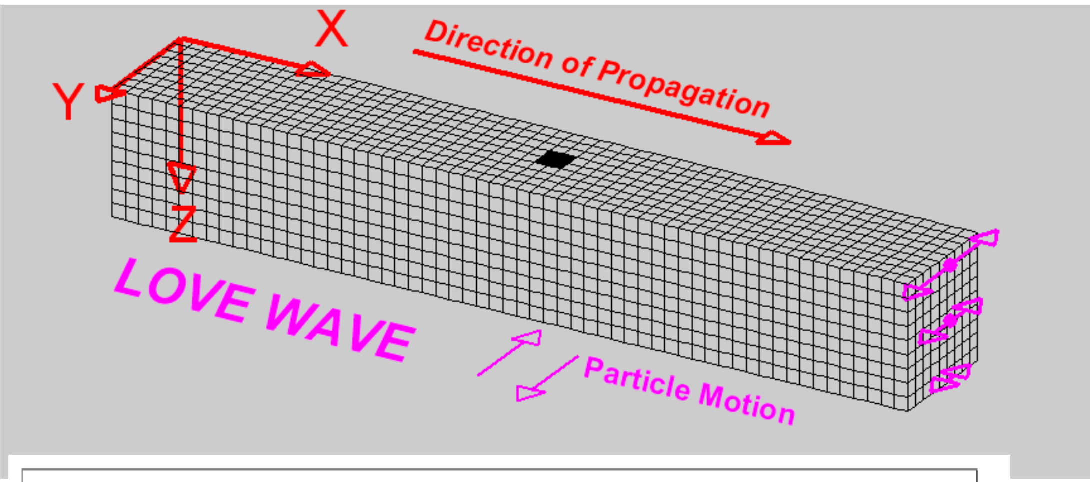
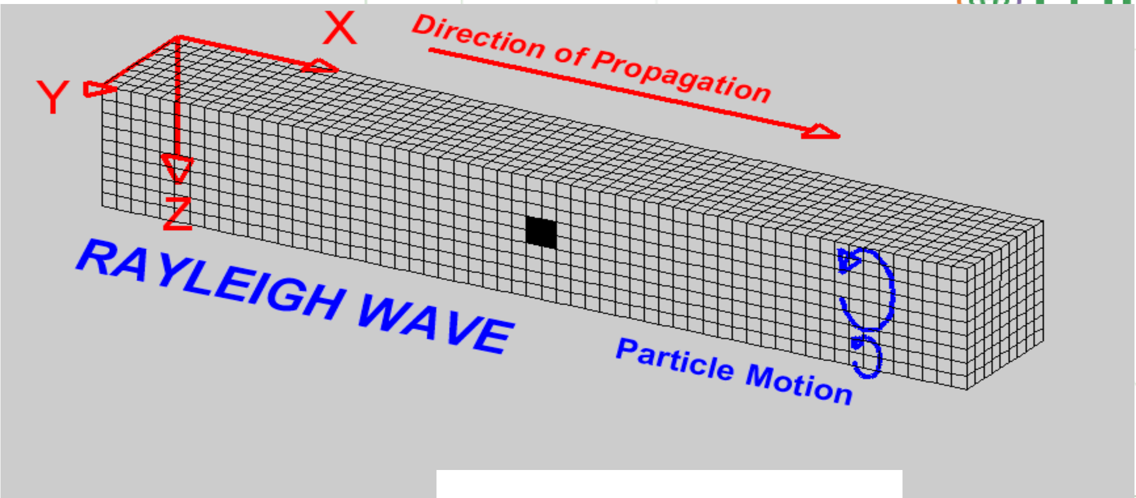
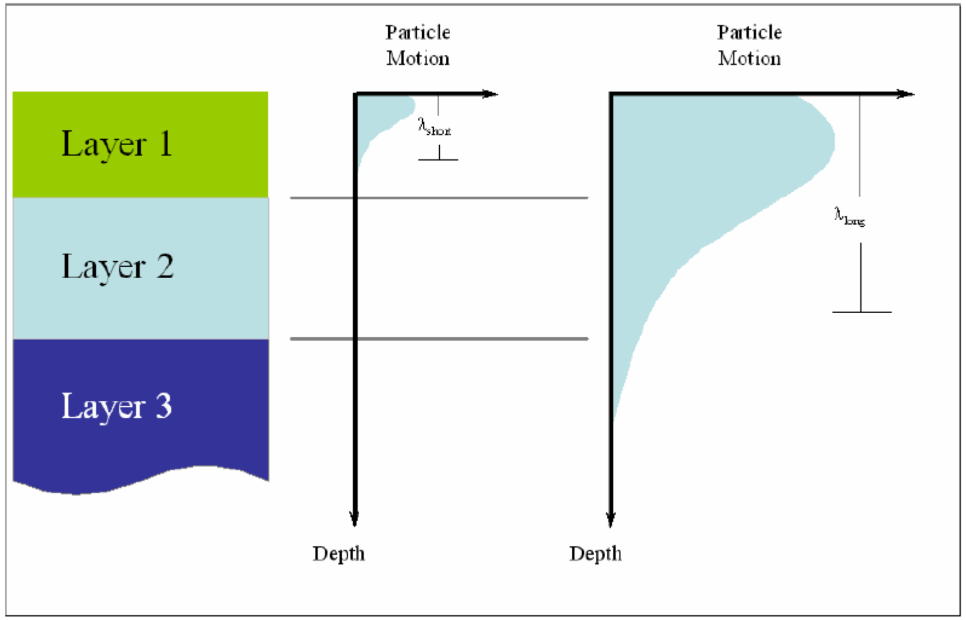
MICROSEISMS	MICROTREMORS
• Far Sources	• Local Sources
• Surface waves	• Surface and body waves
• Rayleigh waves	• Rayleigh and Love waves
• Fundamental mode	• Fundamental and higher modes

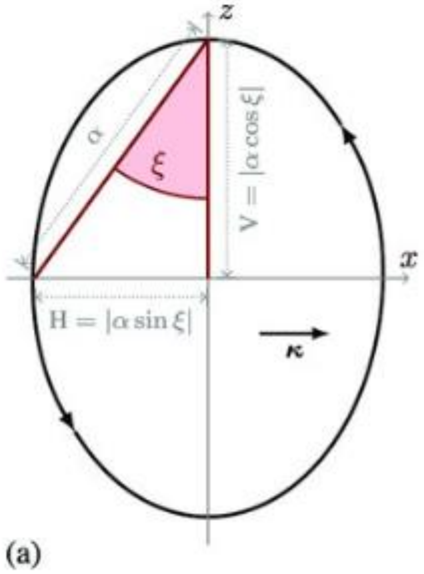
ABOUT SURFACE WAVES





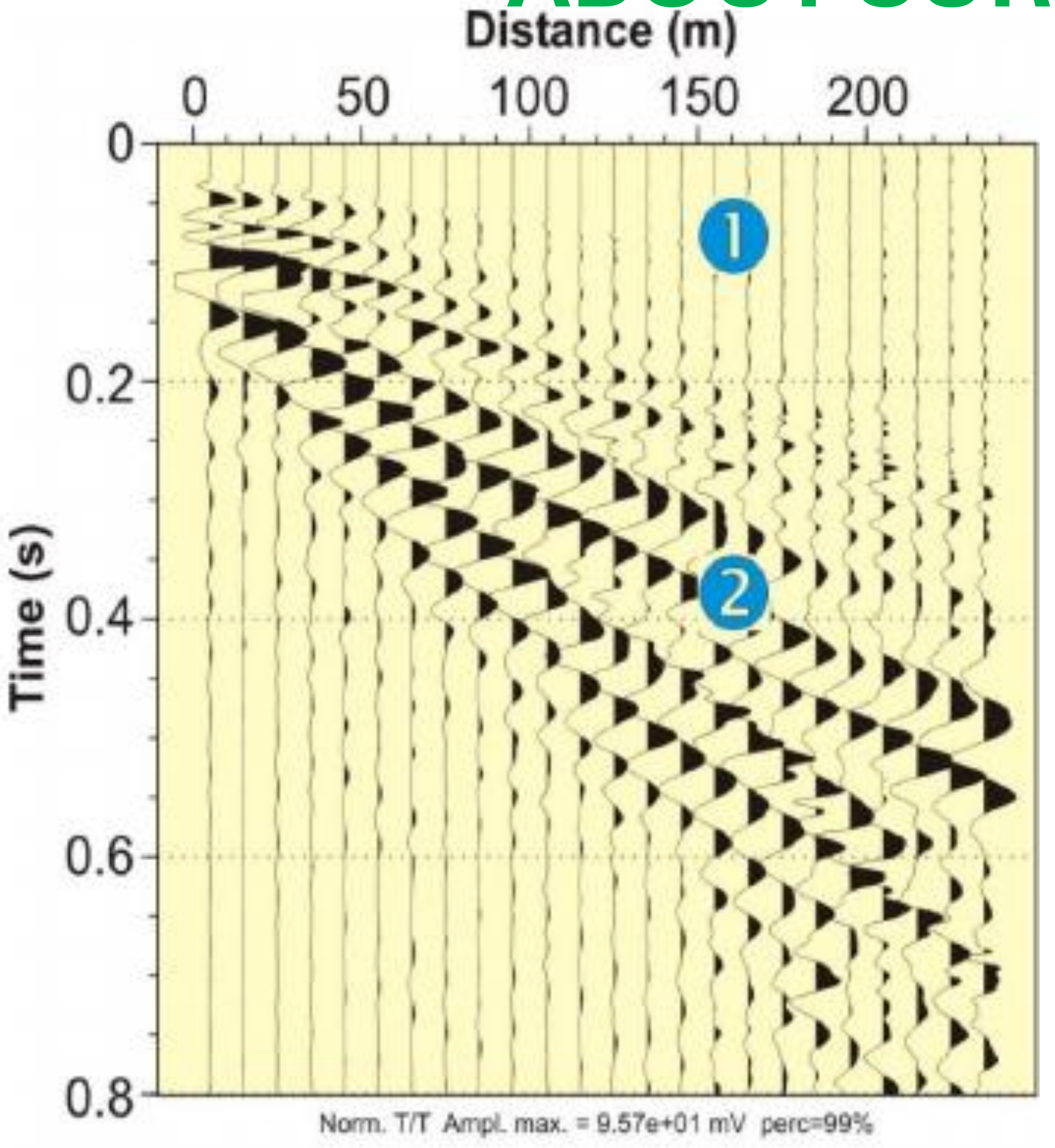


DISPERSIVE BEHAVIOR OF SURFACE WAVES



ELLIPTICITY OF RAYLEIGH WAVES

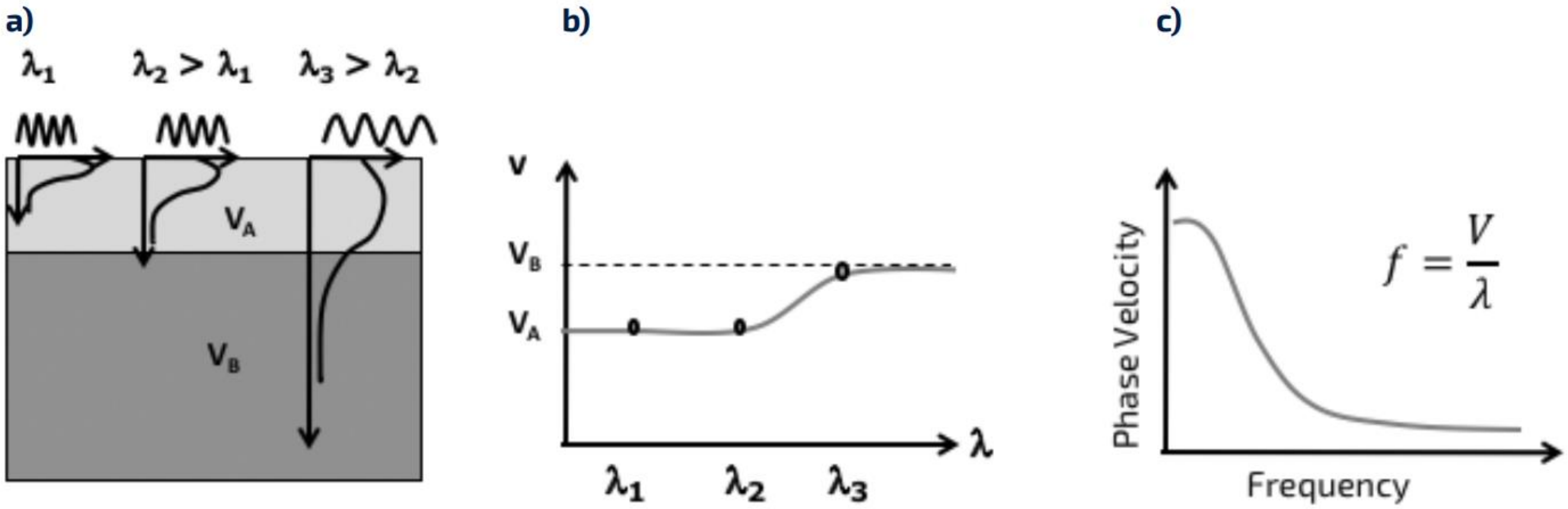
ABOUT SURFACE WAVES

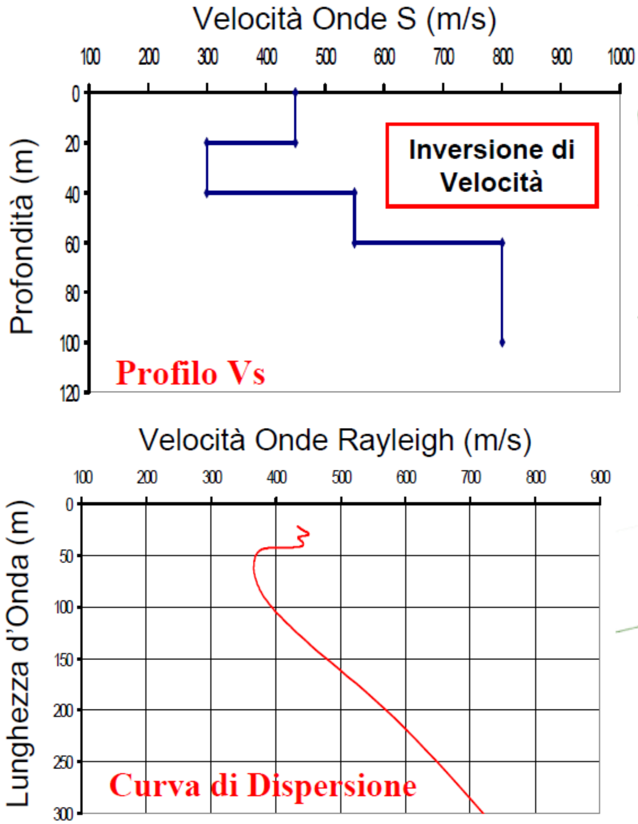


200 g dynamite shot
Raw data 'normalized' trace-by-trace

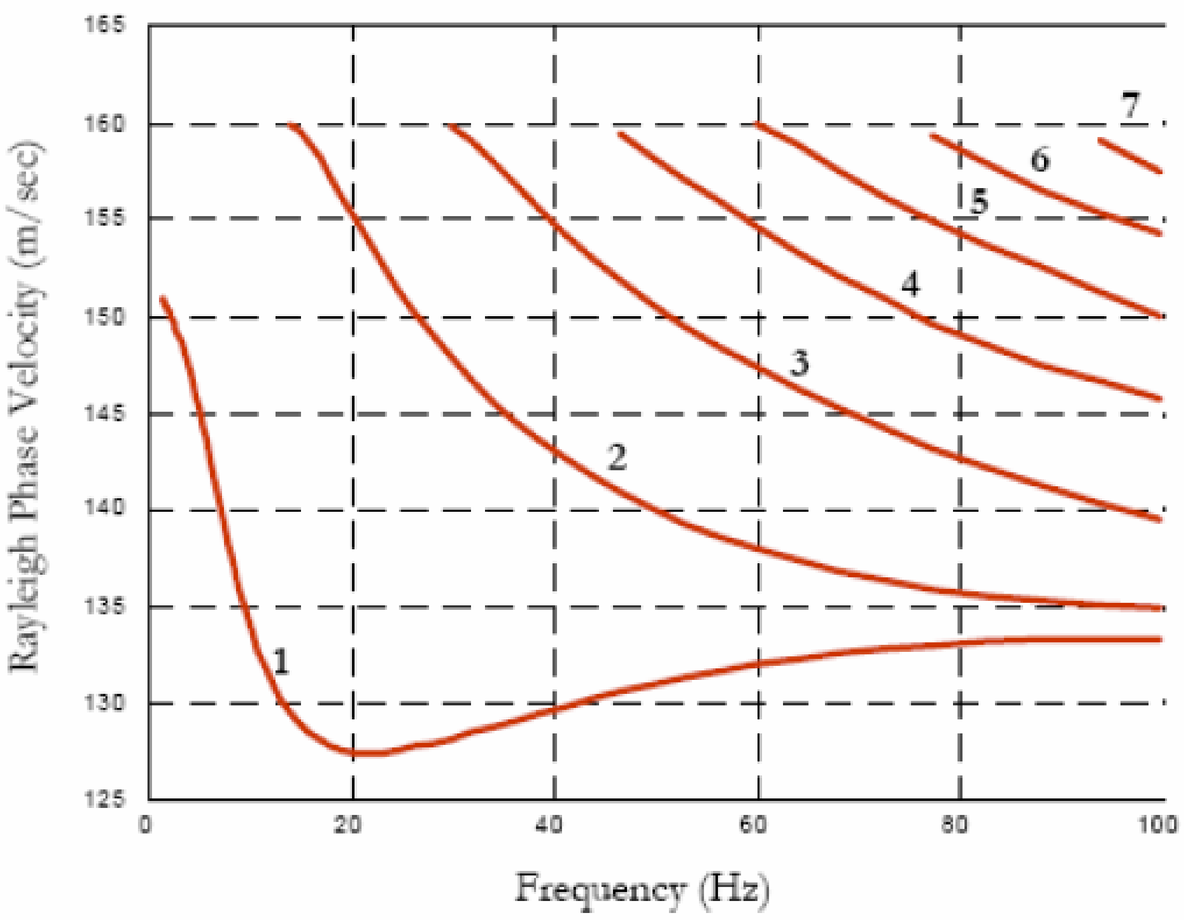
1. Direct and refracted waves
2. Surface waves

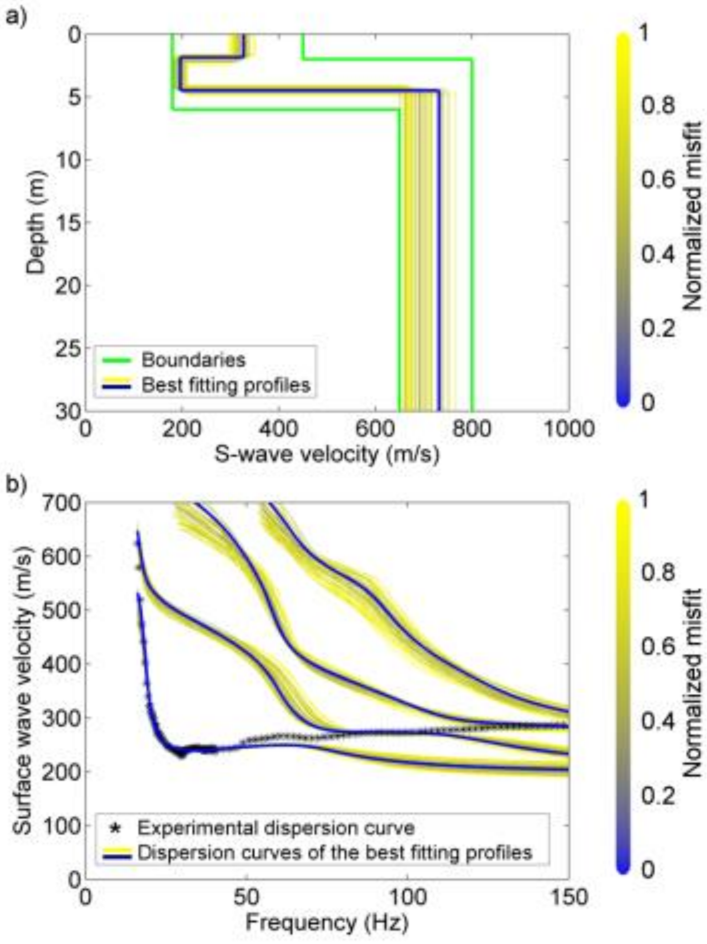
On the dispersive behavior





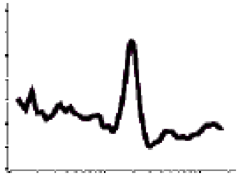
MULTIMODAL PROPAGATION PHENOMENON





How Ambient Noise can help us in deriving information on site conditions?

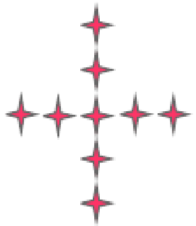
Single station



H/V method

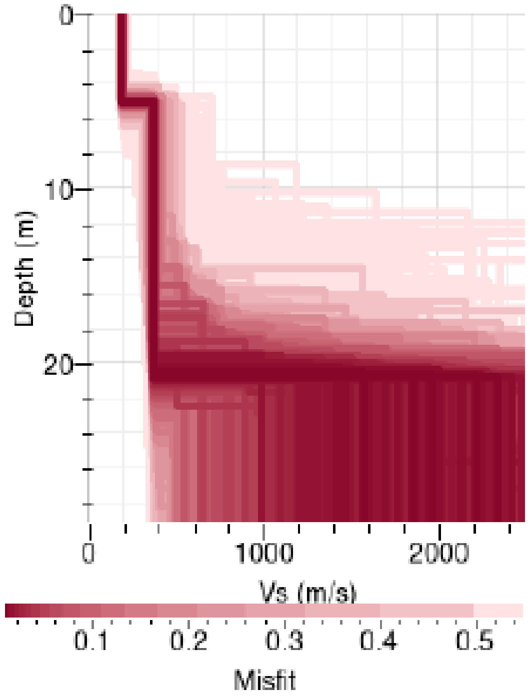
Output: site resonance frequency

Array of stations (with synchroneous records)

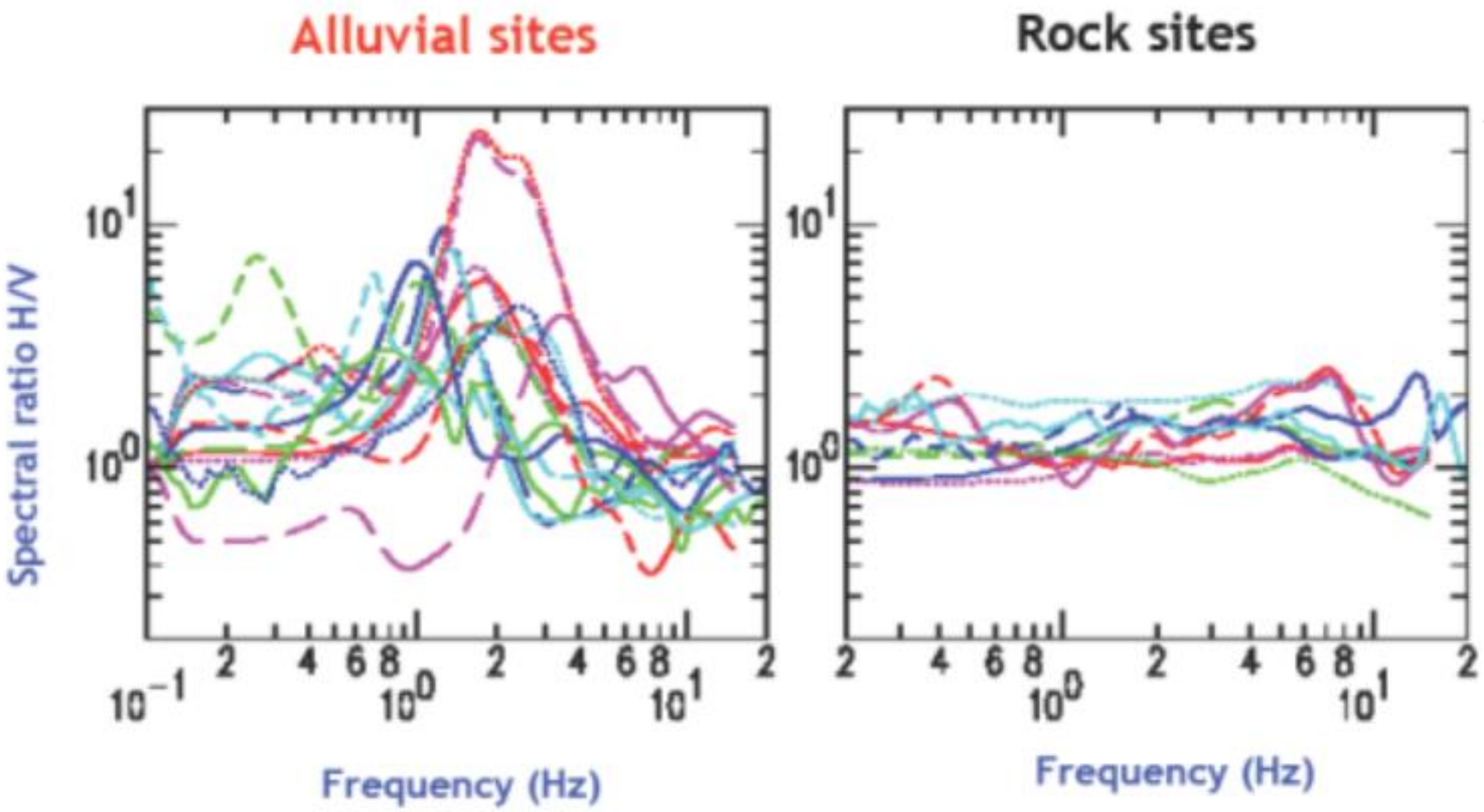


Study wave propagation between motion sensors

Output: shear wave velocity vs. depth

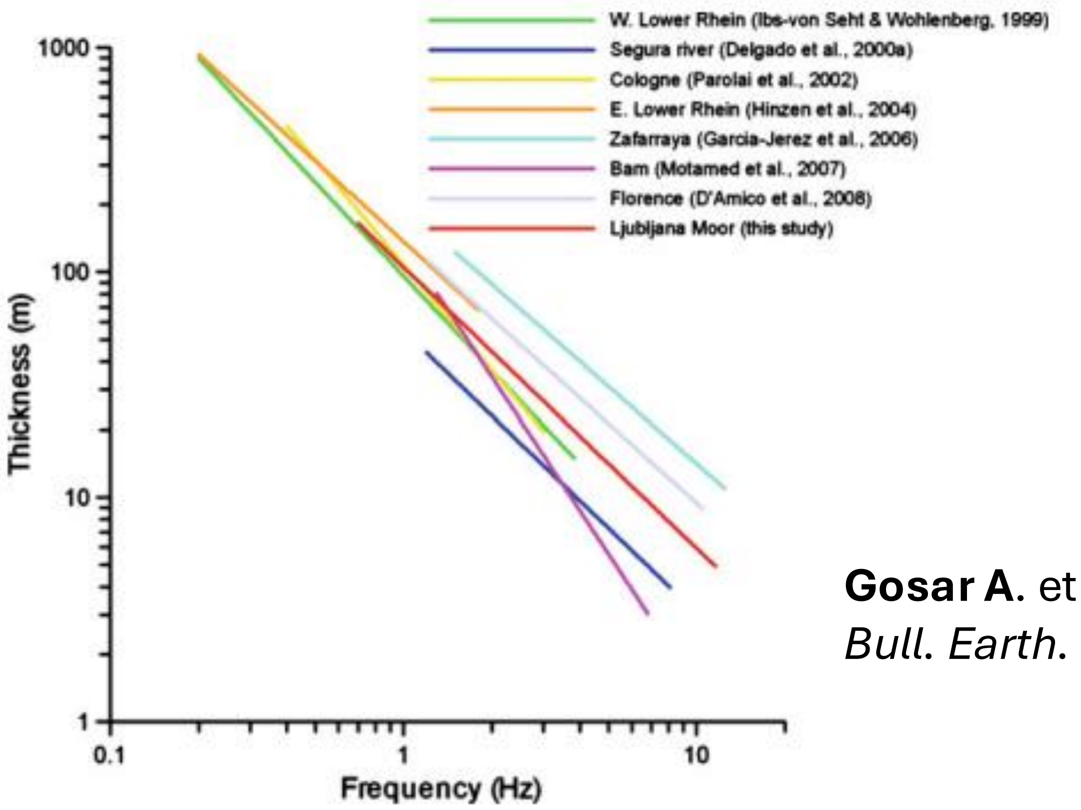


Single Station measurement: H/V technique (HVSR)



Single Station measurement: H/V technique (HVSR)

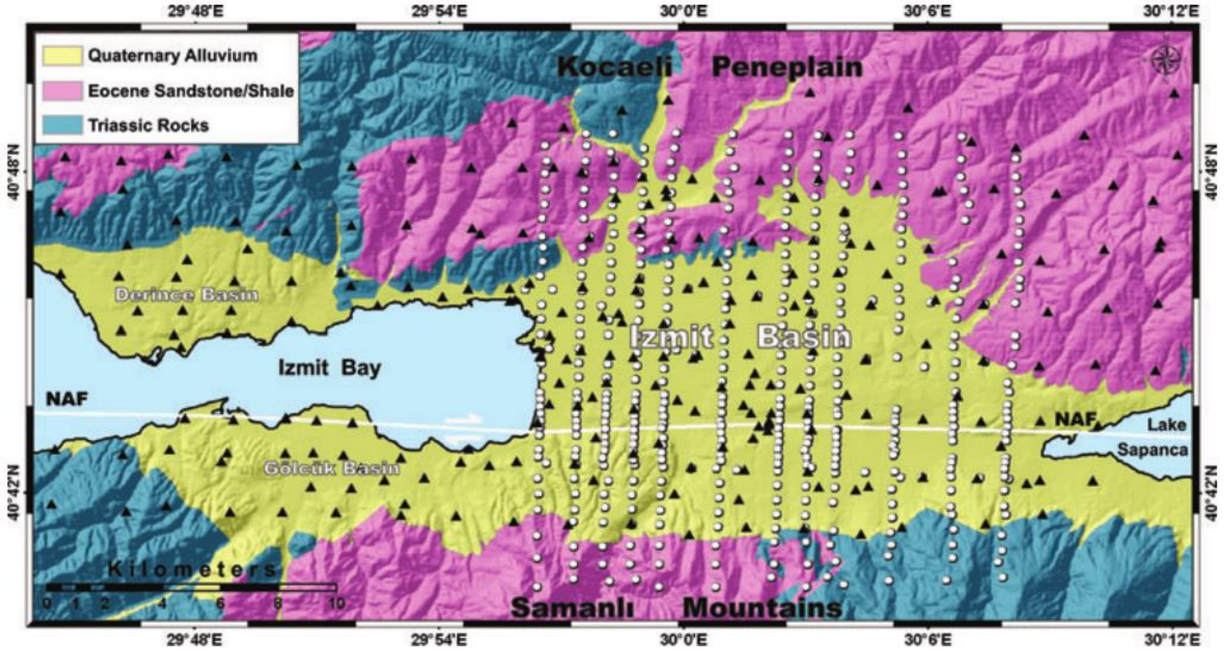
Correlation between H/V peak frequencies and sediment thickness



Gosar A. et al., 2010,
Bull. Earth. Eng.

Single Station measurement: H/V technique (HVSR)

Correlation between H/V peak frequencies and sediment thickness

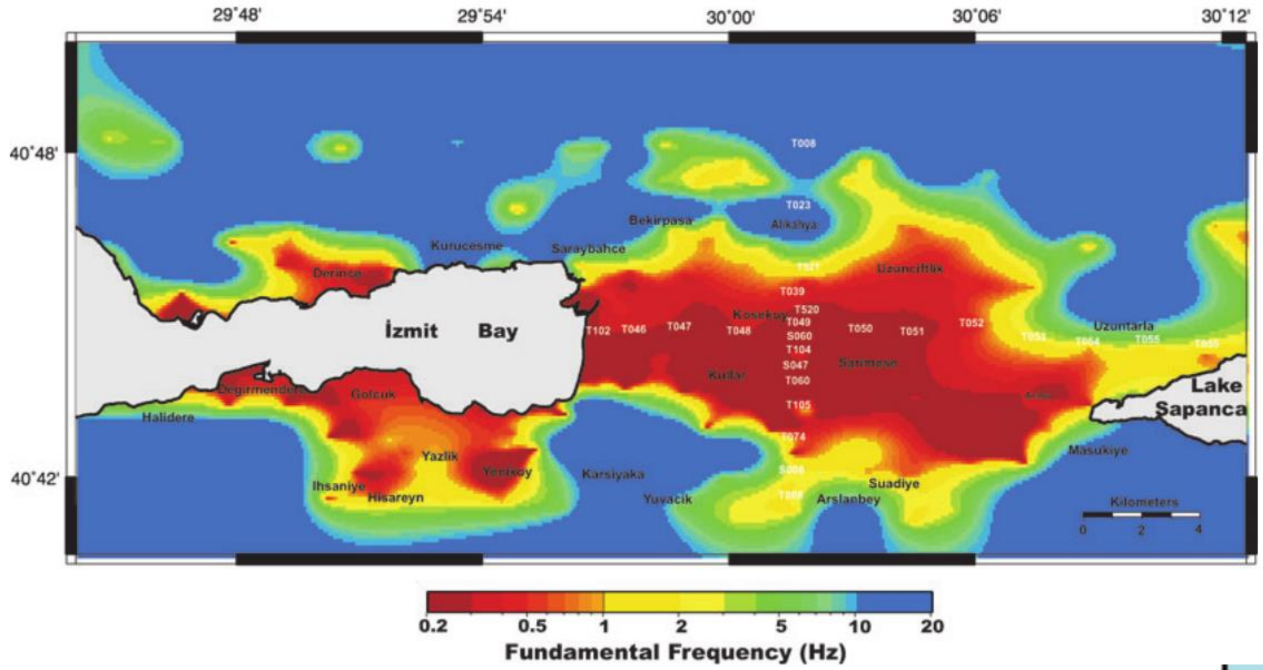


Investigation of 3-D basin structures in the İzmit Bay area by single-station microtremor and gravimetric methods

Ozalaybey et al., 2011, *Geophys. J. Int.*

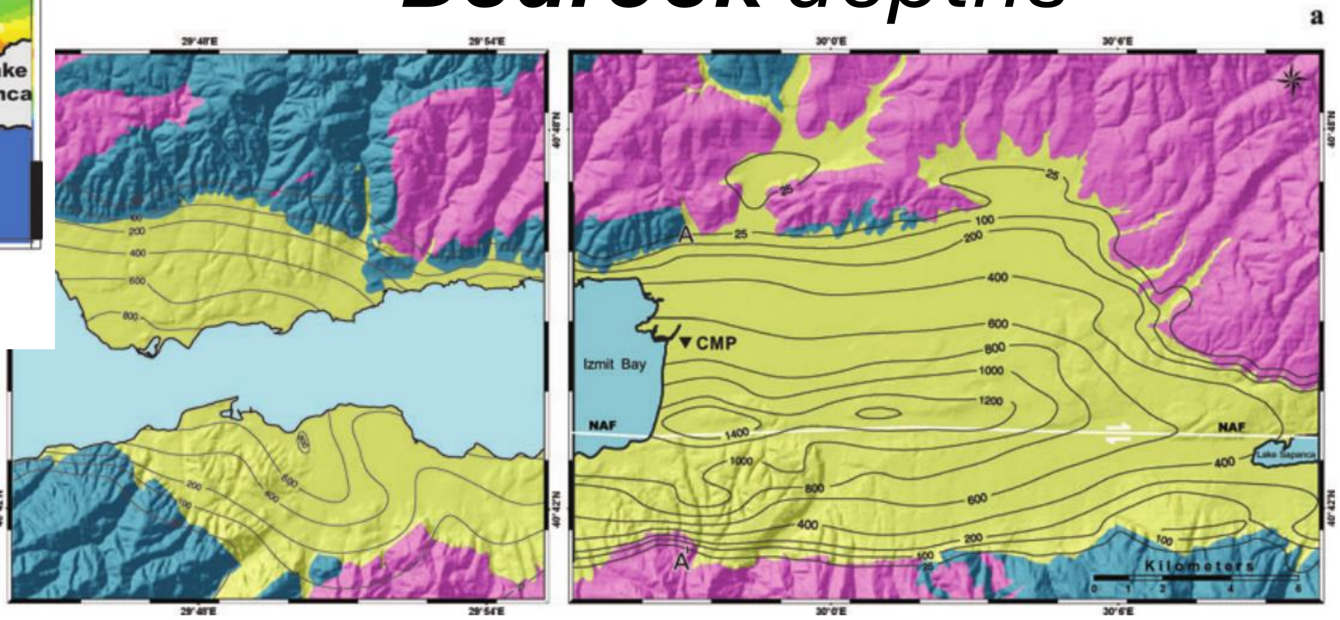
Single Station measurement: H/V technique (HVSR)

Correlation between H/V peak frequencies and sediment thickness



***H/V** peak frequencies*

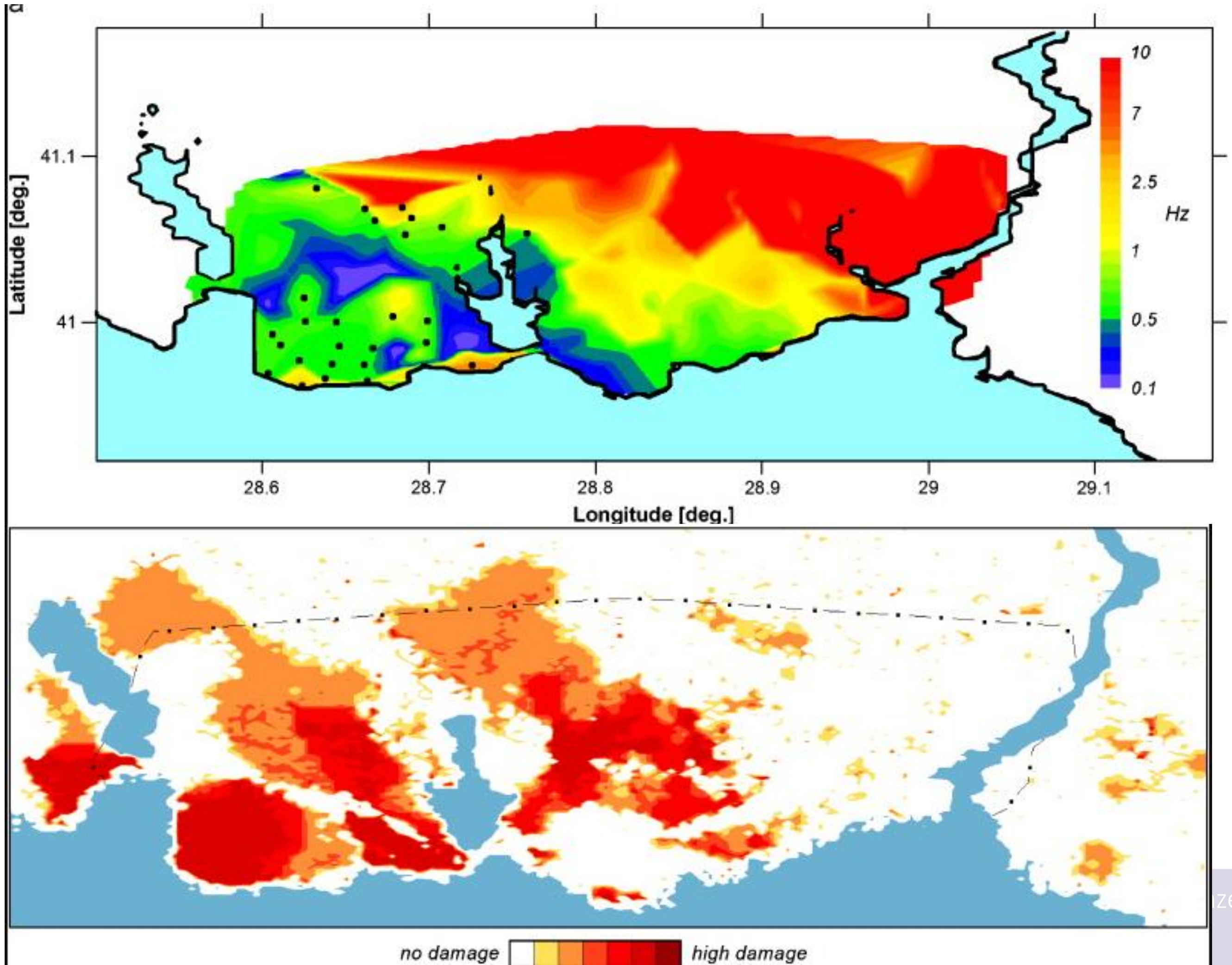
***Bedrock** depths*



Ozalaybey et al., 2011, *Geophys. J. Int.*

Single Station measurement: H/V technique (HVSR)

Correlation between H/V peak frequencies and damage distribution

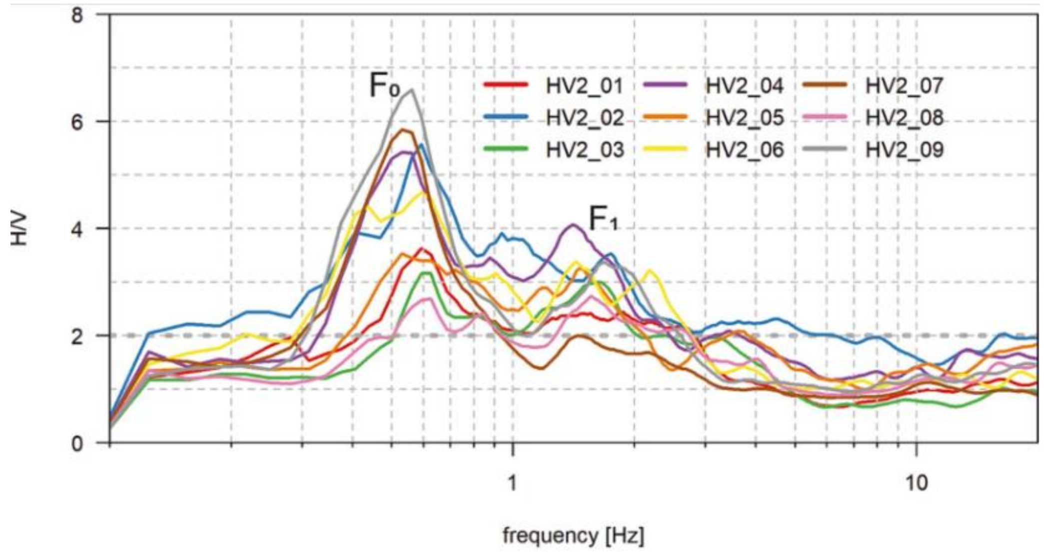


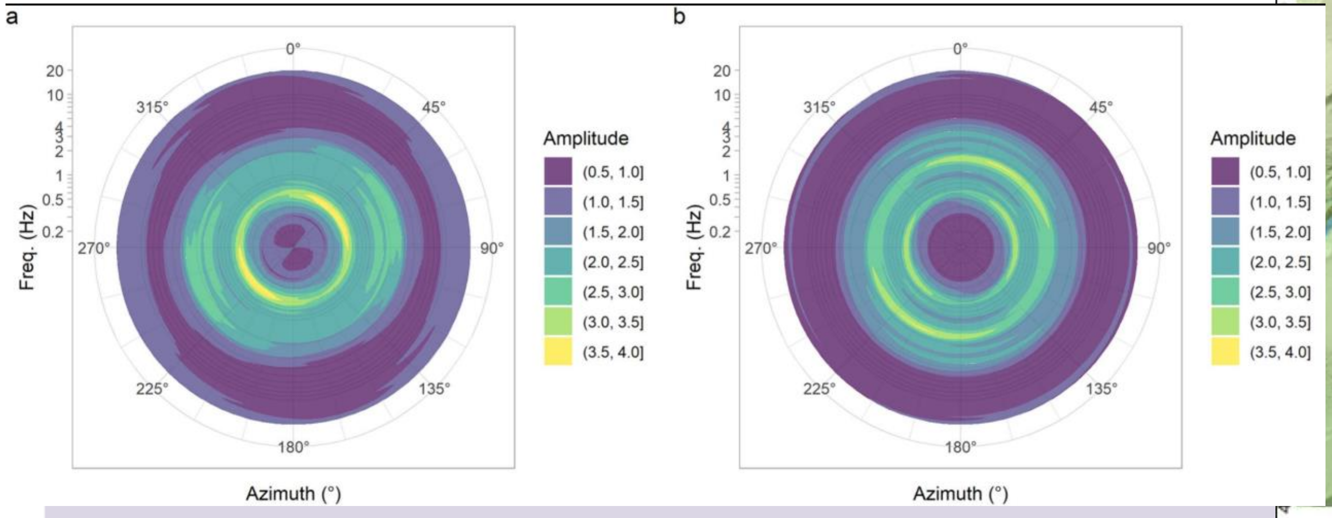
Picozzi et al., 2009, *Soil Dynamics and Earth Eng.*

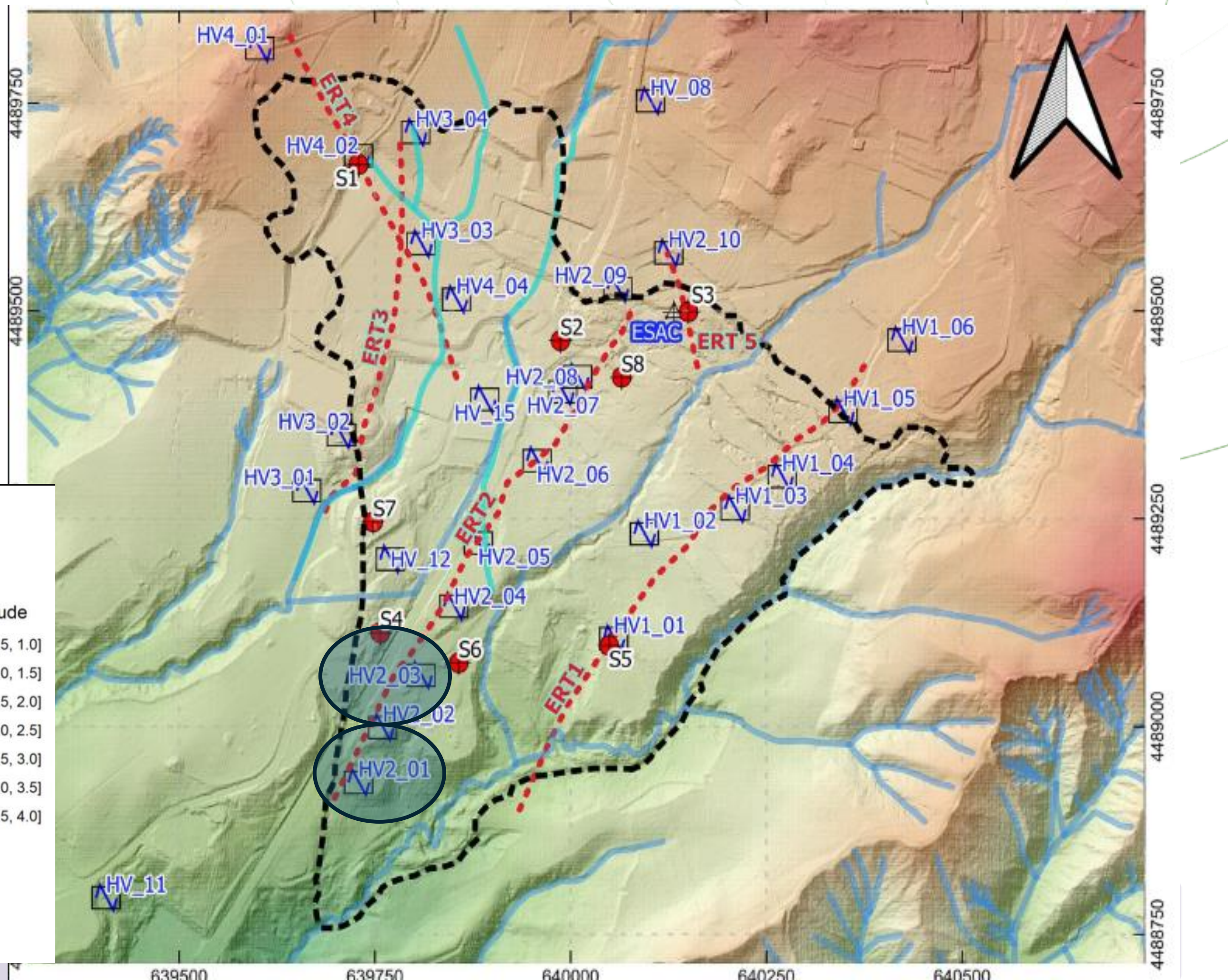
Site characterization by seismic noise in Istanbul, Turkey

Single Station measurement: H/V technique (HVSR) - Correlation of directional HVSR with landslide movement

Calamita et al., 2023, *Engineering Geology*



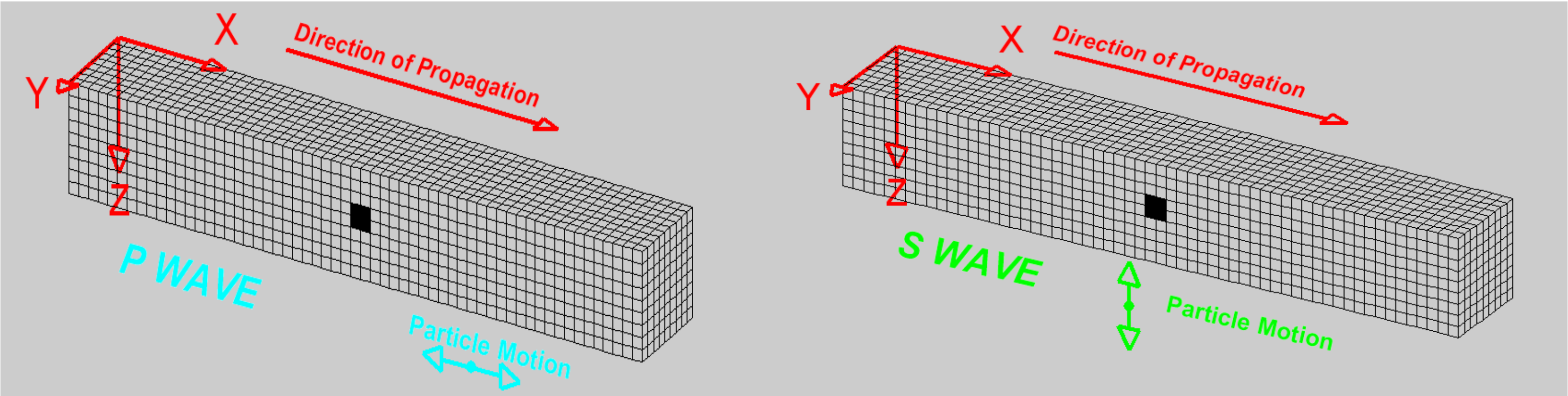




Single Station measurement: H/V technique (HVSR) – Nakamura (1984)

$$\frac{H}{V} = \frac{H_{body} + H_{Love} + H_{Rayleigh}}{V_{body} + V_{Rayleigh}}$$

Body waves   Surface waves

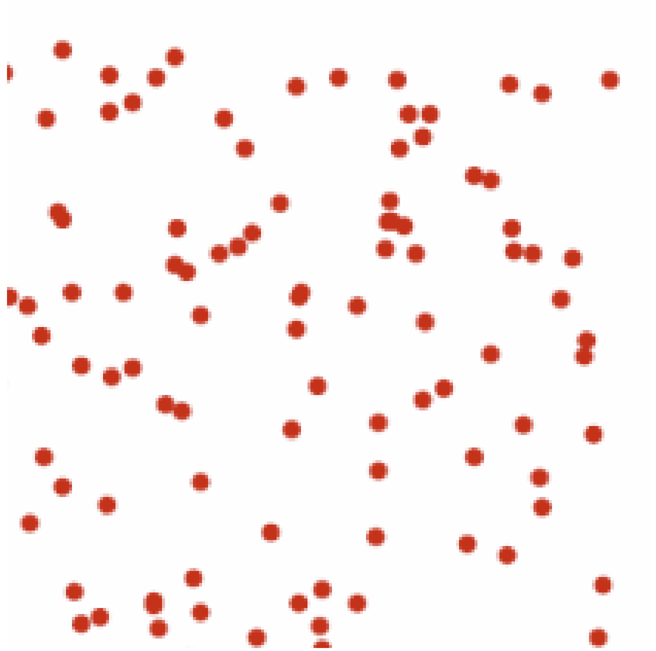


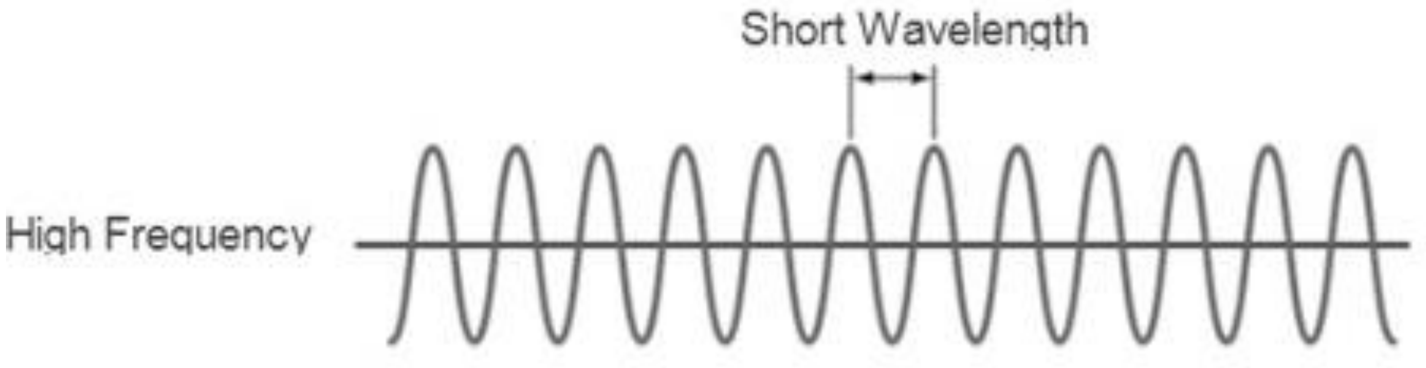
The main contribution related to body waves is due to local sources. Only low frequencies are affected by remote sources

Single Station measurement: H/V technique (HVSR) – Nakamura (1984)

Hypothesis 1: $H/V = H_{body}/V_{body}$

Random distribution of sources
with independent activation times





High sensitivity to ground irregularities:
Reflection/refraction/scattering

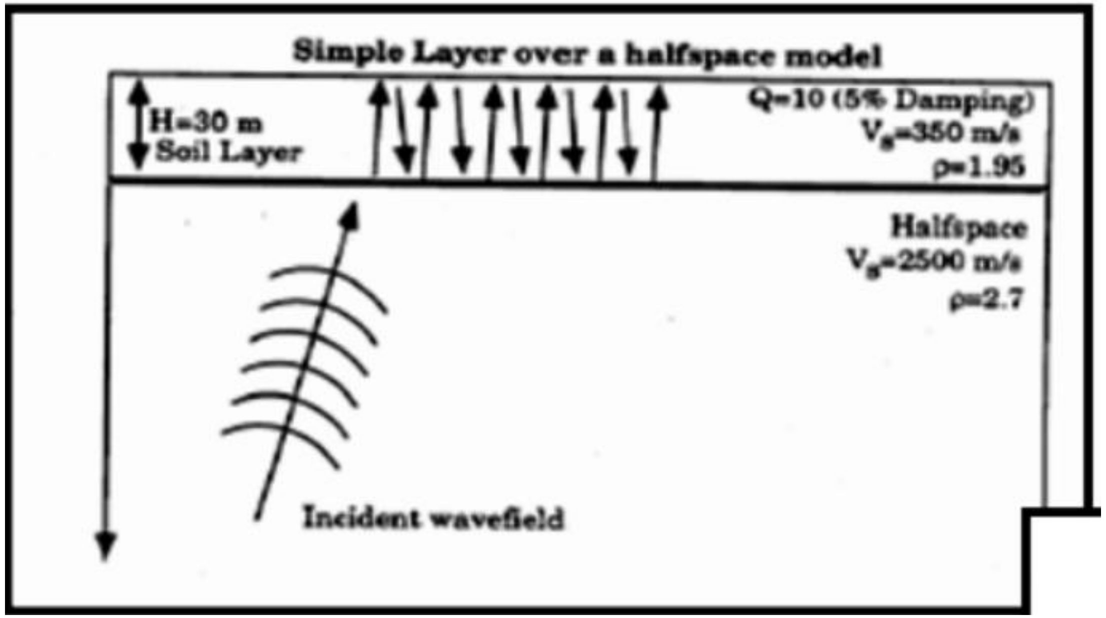
RANDOMIZATION OF THE ANGLES OF EMERGENCE, OF THE AMPLITUDE OF THE DIFFERENT PHASES THAT, AVERAGED OVER TIME, MAKE THE RATIO OF VERTICAL AND HORIZONTAL AMPLITUDES TEND TOWARD UNITY.

Single Station measurement: H/V technique (HVSR) – Nakamura (1984)

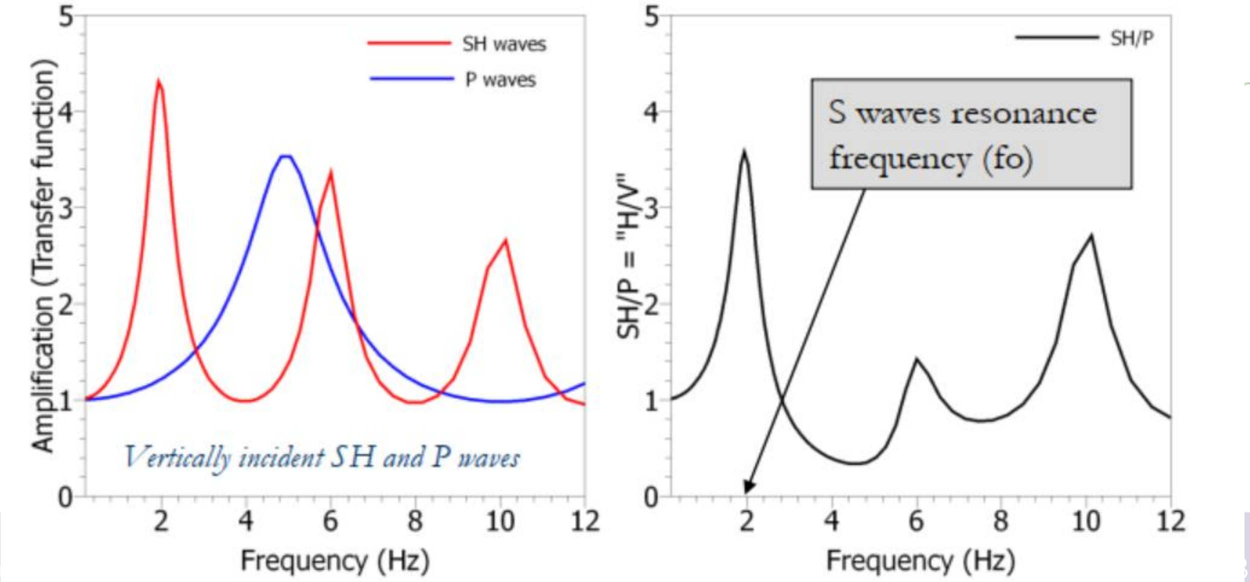
Hypothesis 1: H/V = H_{body}/V_{body}

$$f_0 = \frac{V_S}{4H}$$

RESONANCE FREQUENCY (FUNDAMENTAL MODE)



Thickness (m)	Vp (m/s)	Vs (m/s)	Density (kg/m3)	Qp	Qs
25	500	200	2000	50	25
infinite	2000	1000	1000	50	25

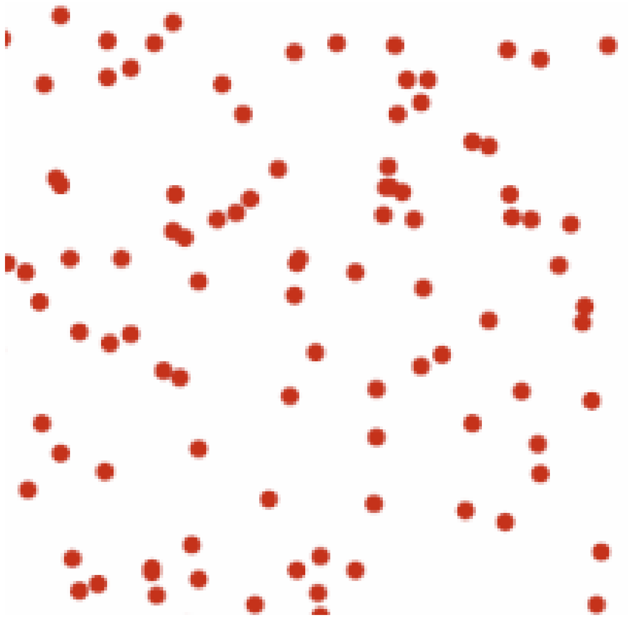


Resonance phenomena occur for both **S** waves and **P** waves

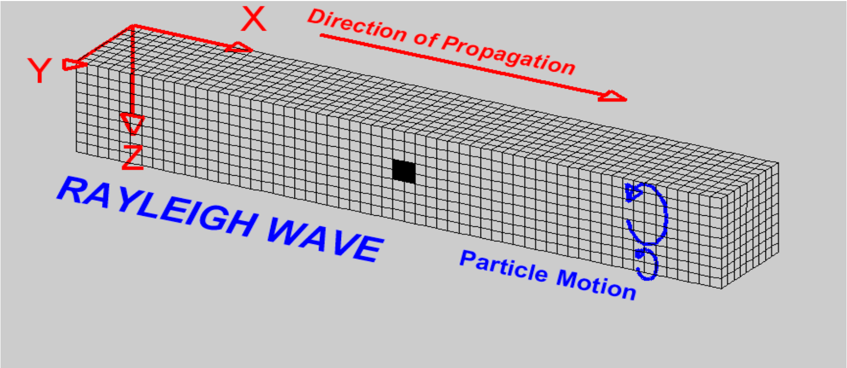
Single Station measurement: H/V technique (HVSR) – Nakamura (1984)

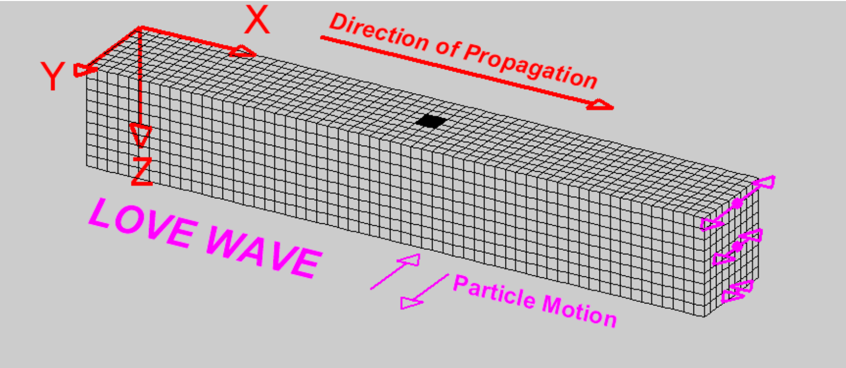
Hypothesis 2: $H/V = H_{surface}/V_{surface}$

Random distribution of sources
with independent activation times



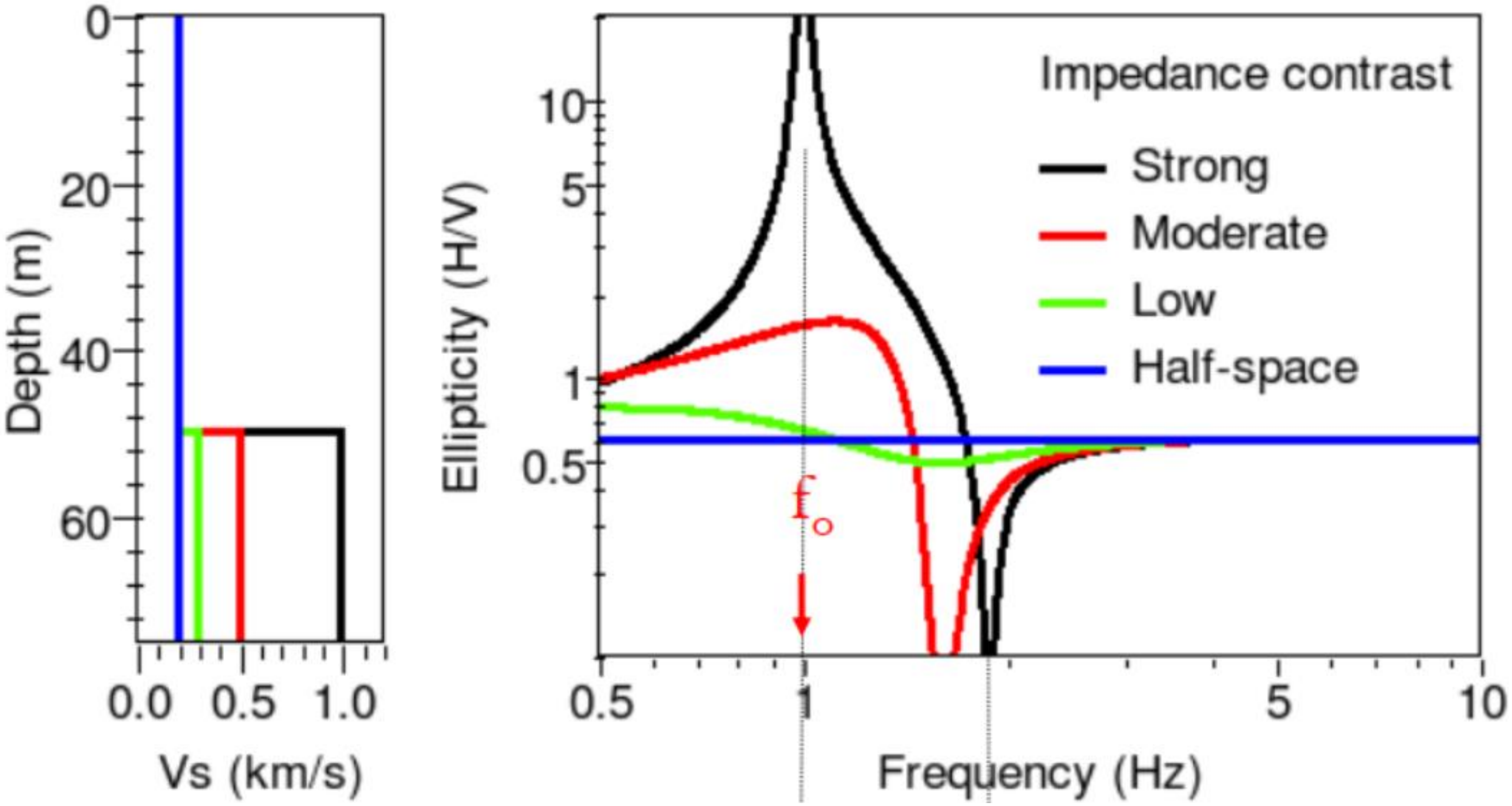
Different spatial scales with respect to body waves: The equivalent average source reasonably provides the same contribution to horizontal and vertical component of motion





Single Station measurement: H/V technique (HVSR) – Nakamura (1984)

Hypothesis 2_R: $H/V = H_{Rayleigh}/V_{Rayleigh}$



For strong velocity contrast, f_0 is very close to $f_{ellipticity}$

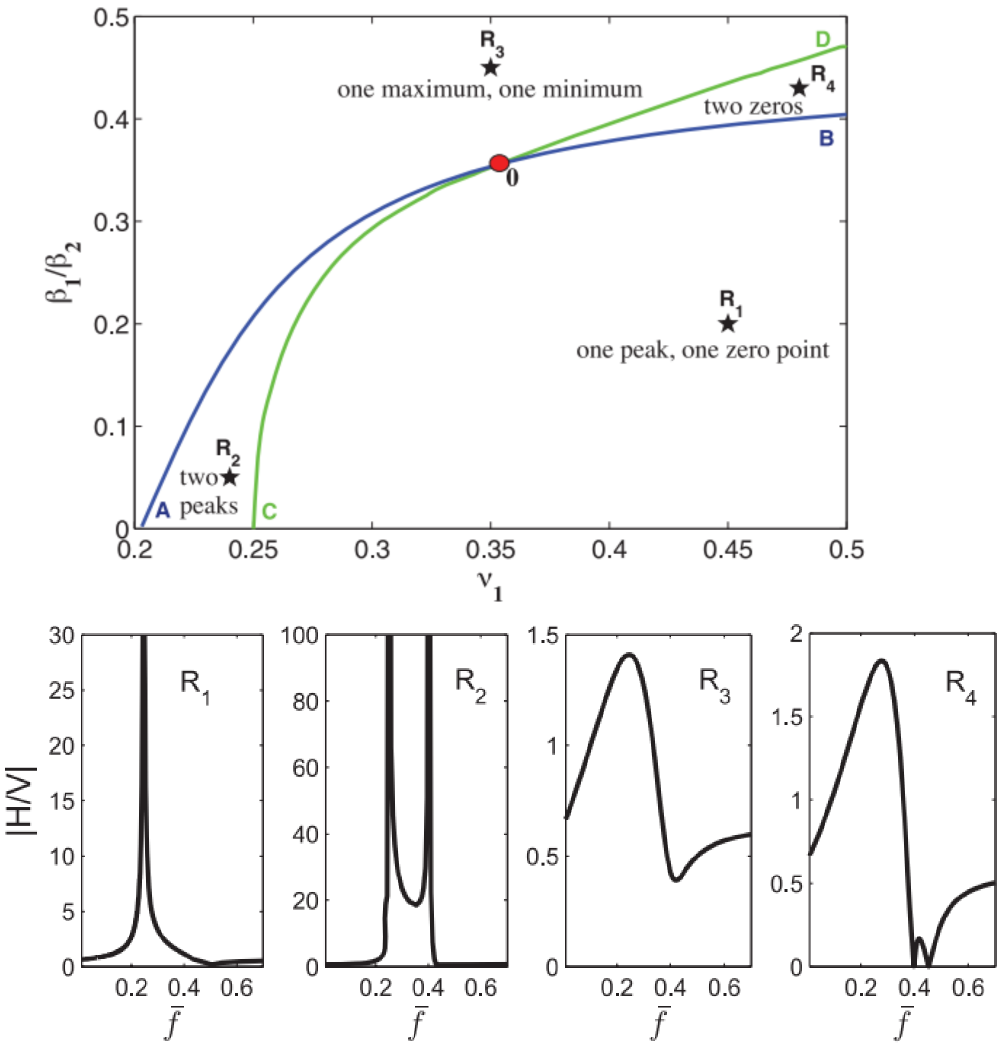
$$V_S = 200\ m/s$$

$$H = 50\ m$$

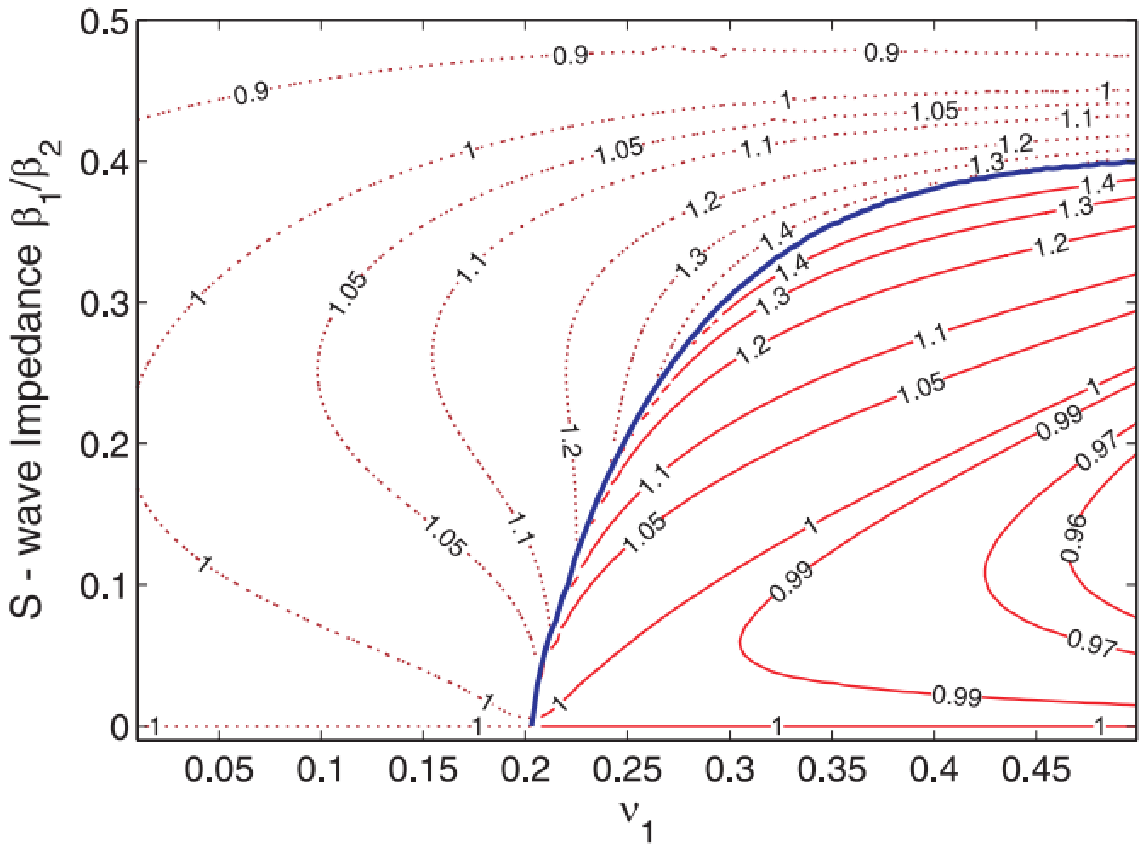
f_0= 1 Hz

Single Station measurement: H/V technique (HVSR) – Nakamura (1984)

Hypothesis 2_R: $H/V = H_{Rayleigh}/V_{Rayleigh}$

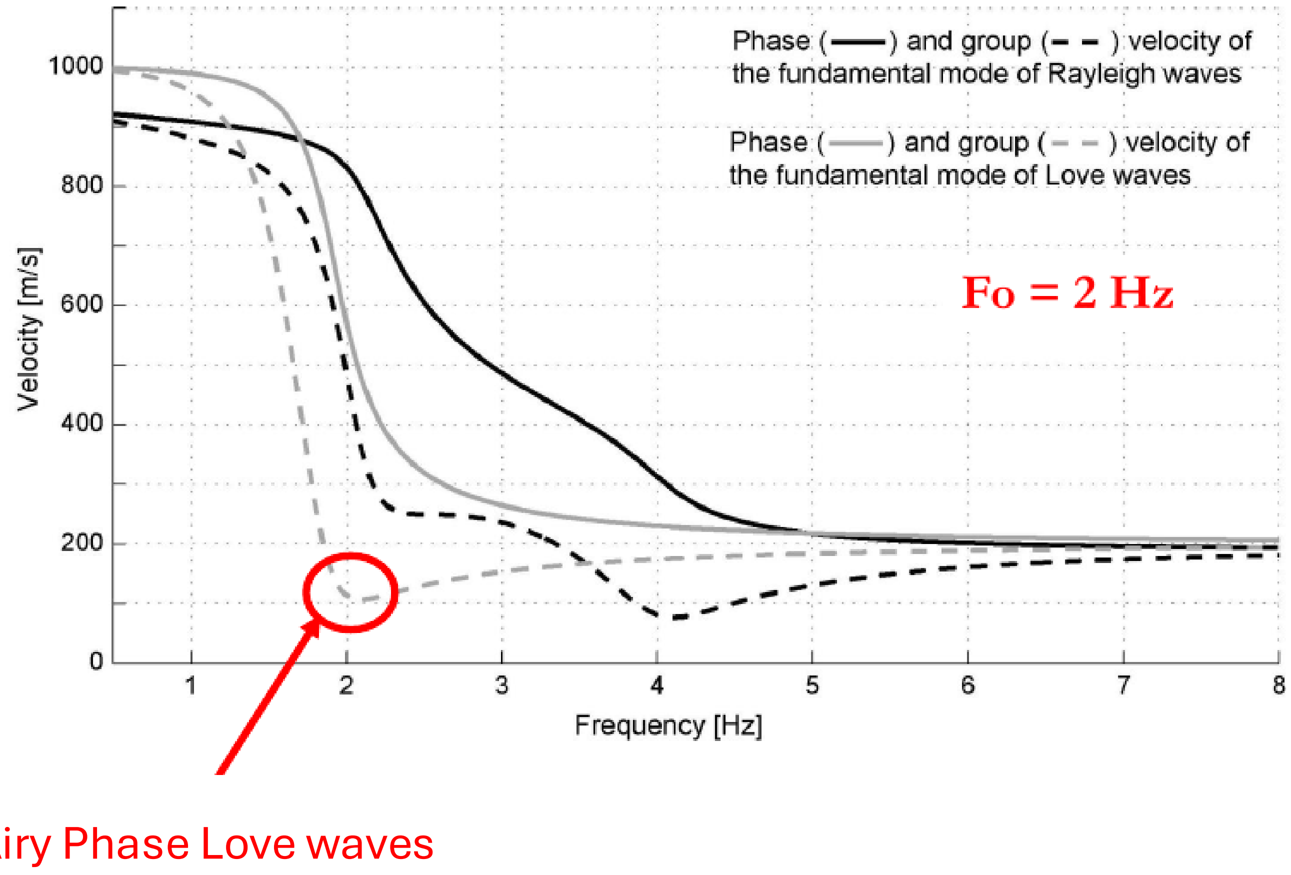


From Tuan et al., *2011*, *Geopys. J. Int.*



Single Station measurement: H/V technique (HVSR) – Nakamura (1984)

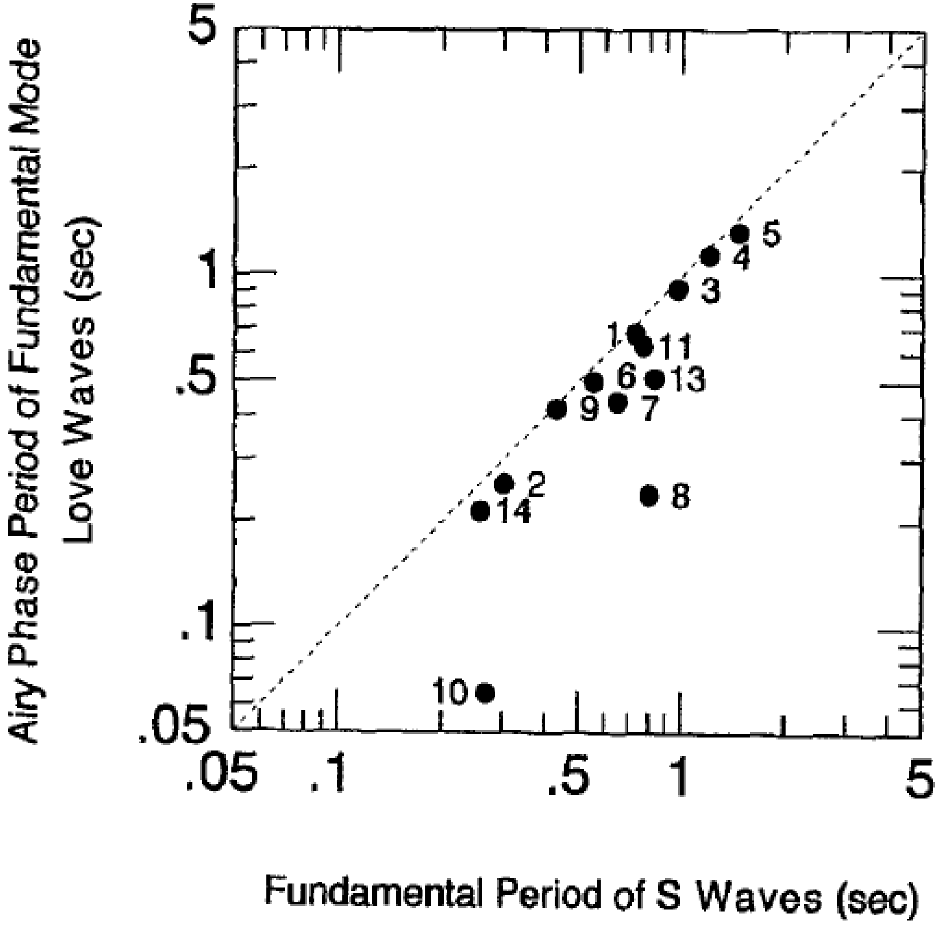
Hypothesis 2_L: H/V = H_{Love}

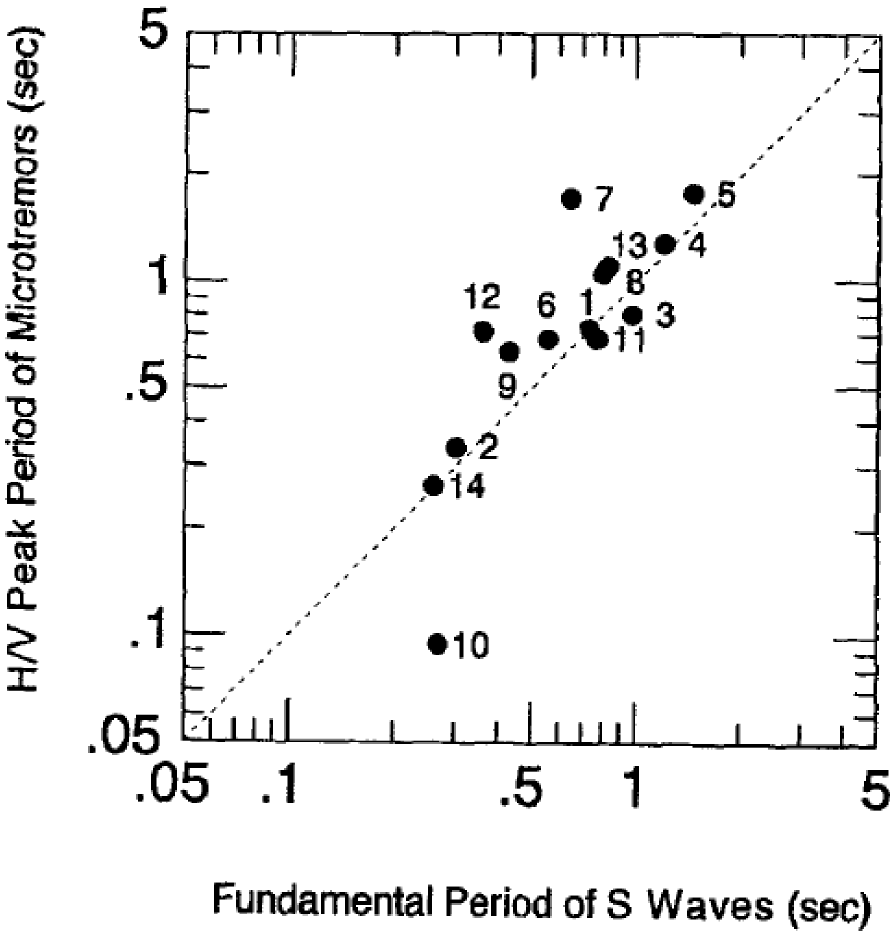


Single Station measurement: H/V technique (HVSR) – Nakamura (1984)

Hypothesis 2: $H/V = H_{surface}/V_{surface}$

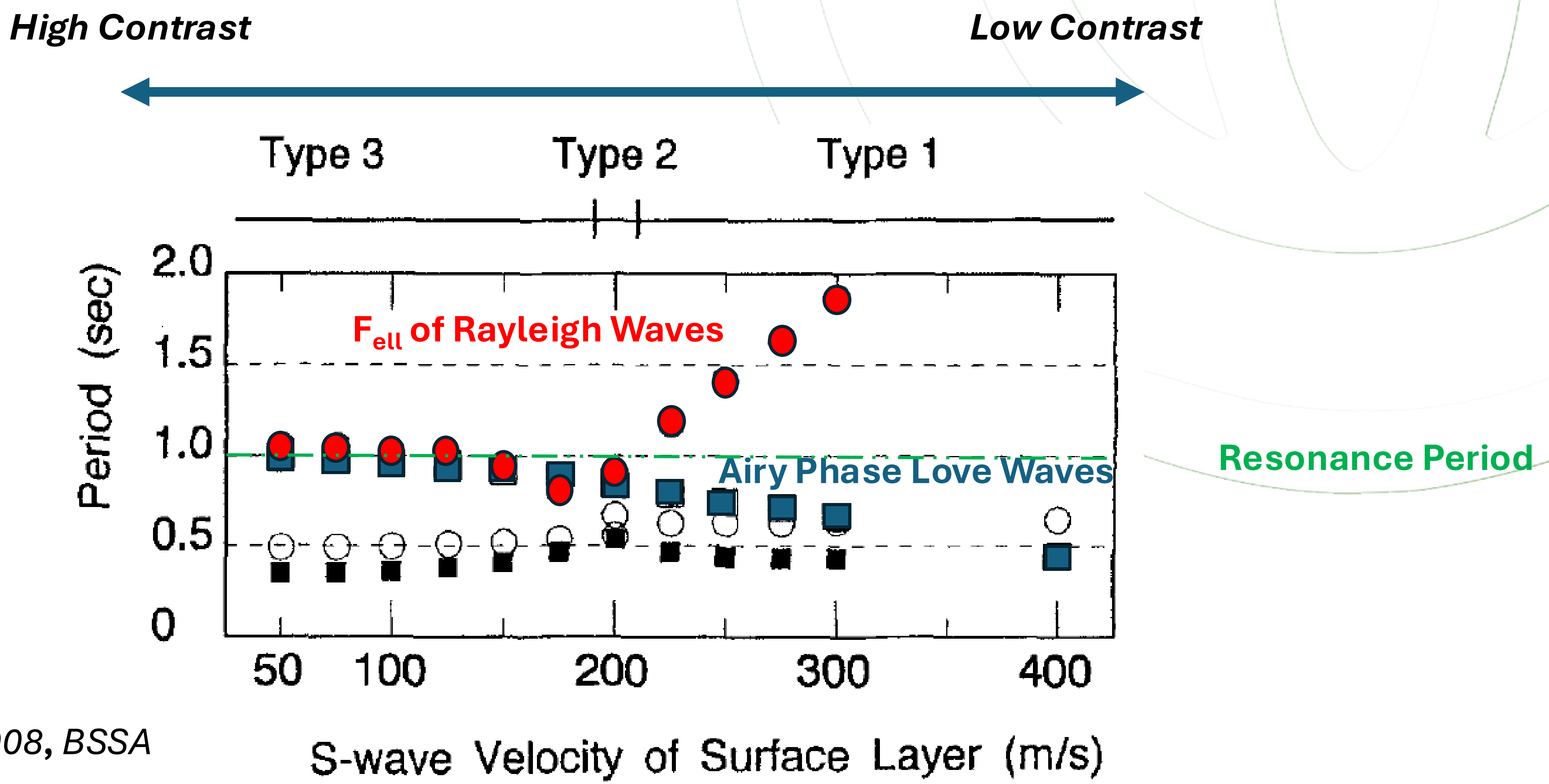
From Konno and Omachi., *2008*, *BSSA*





Single Station measurement: H/V technique (HVSR) – Nakamura (1984)

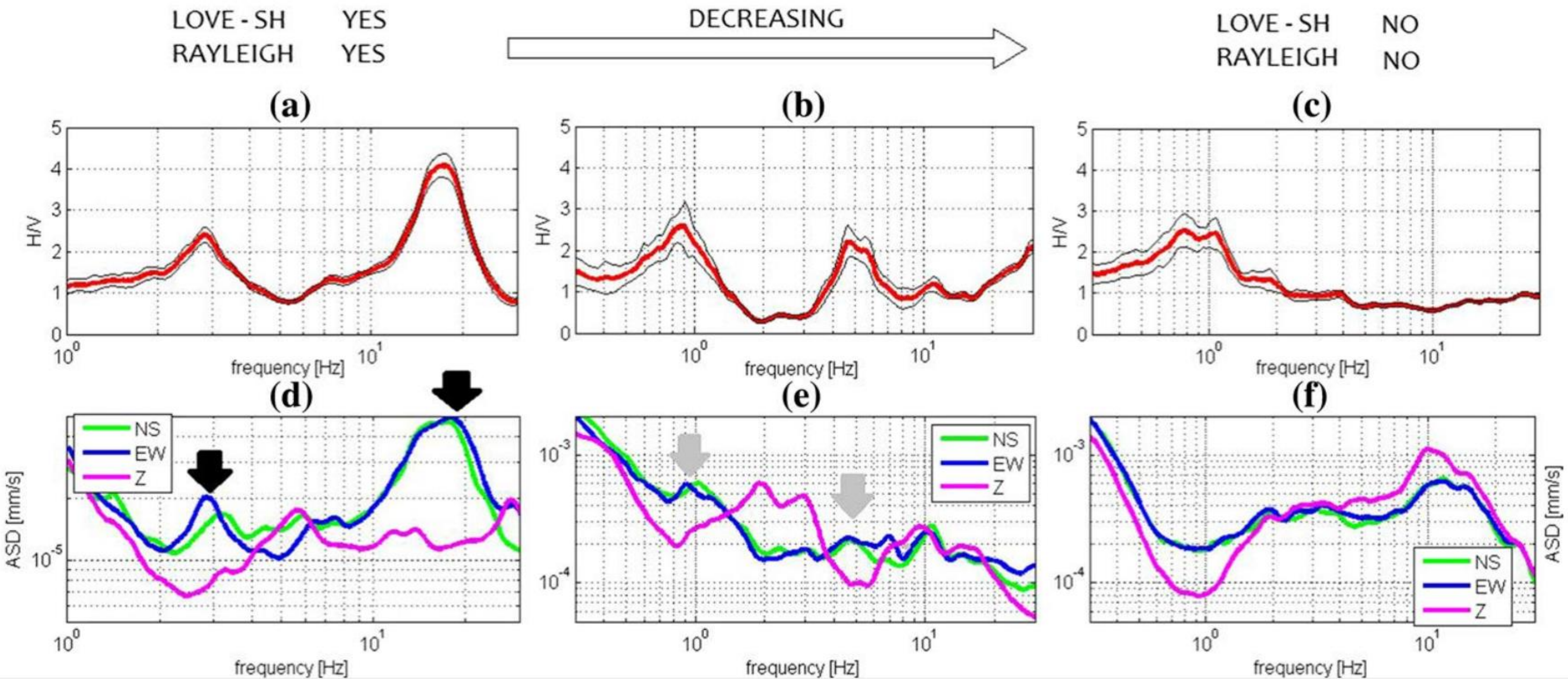
Hypothesis 2: $H/V = H_{surface}/V_{surface}$



From Konno and Omachi, *2008*, *BSSA*

Single Station measurement: H/V technique (HVSR) – Nakamura (1984)

From Molnar et al, 2018, Surveys in Geophys.



Single Station measurement: H/V technique (HVSR) – Nakamura (1984)

Take home message

$$\frac{H}{V} = \frac{H_{body} + H_{Love} + H_{Rayleigh}}{V_{body} + V_{Rayleigh}}$$

Body waves   Surface waves

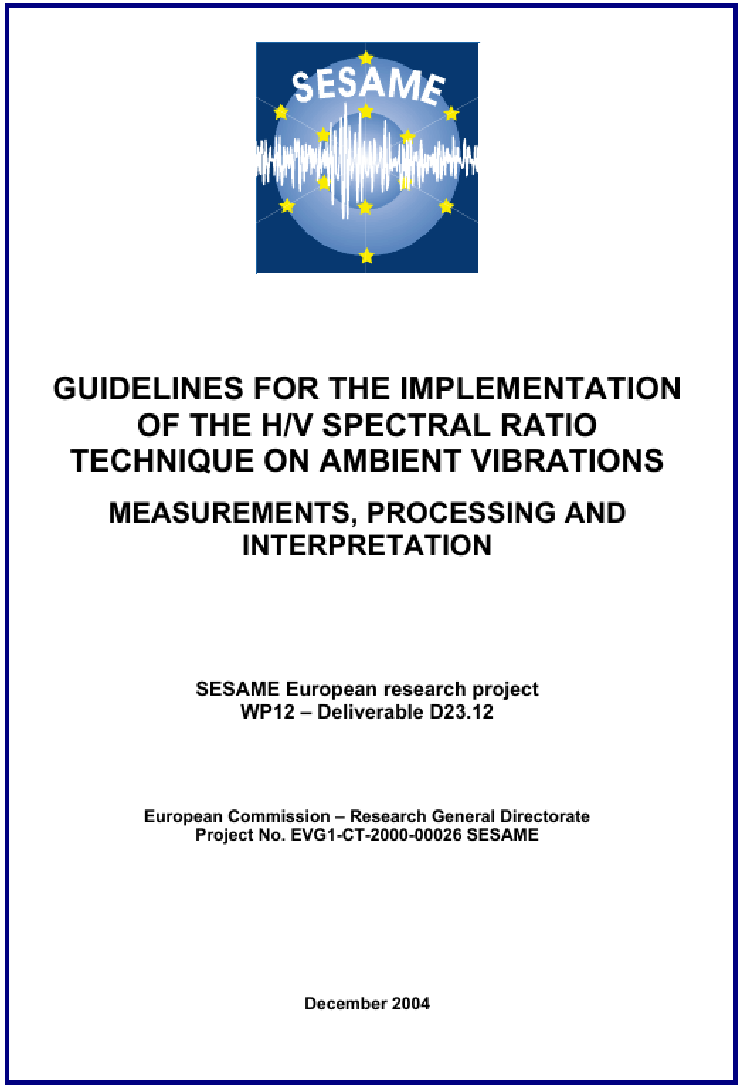
The peak frequency of H/V curve provides a reasonable estimation of f_0 whatever the origin of th H/V peak

Single Station measurement: H/V technique (HVSR) – Nakamura (1984)

Summary

S waves	**- Resonance frequency (f_0=Vs/4H)**
Rayleigh waves	**- Fell is close to f_0 (especially for large impedence contrasts)** **- Frequency dependent ellipticity is related to Vs structure and poisson ratio**
Love Waves	**- F_{airy} is close to f_0**

Single Station measurement: H/V technique (HVSR) – Nakamura (1984)



GUIDELINES FOR THE IMPLEMENTATION OF THE H/V SPECTRAL RATIO TECHNIQUE ON AMBIENT VIBRATIONS

MEASUREMENTS, PROCESSING AND INTERPRETATION

SESAME European research project
WP12 – Deliverable D23.12

European Commission – Research General Directorate
Project No. EVG1-CT-2000-00026 SESAME

December 2004

SESAME Project (Site Effects aSsessment using AMbient Excitations)

Recommandations for
- H/V measurements (duration, soil sensor coupling ...)
- H/V computation
- Interpretation of H/V measurements

Single Station measurement: H/V technique (HVSR) – Nakamura (1984)

Low frequency effects

Recording on grass during windy periods is not recommended
(low frequencies sites)

Transients such as cars, trains, pedestrians, may influence the results

Single Station measurement: **H/V** technique (**HVSR**) – Nakamura (1984)

H/V measurement and processing

Seismic noise recording (20 minutes)

Time windowing

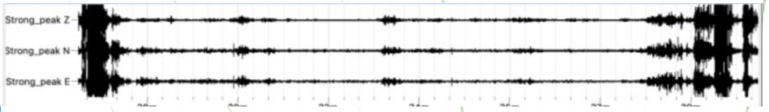
Time series windowing (demean, detrend, tapering, FFT, smoothing)

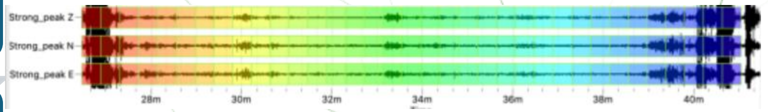
Squared or geometric average of the spectral amplitude horizontal components

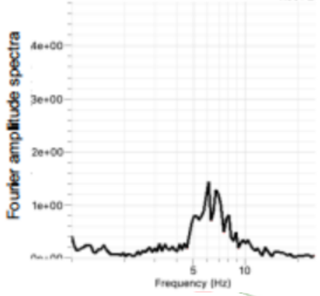
H/V computation

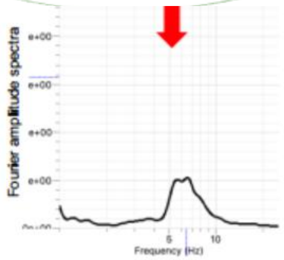
Konno – Ohmachi smoothing function

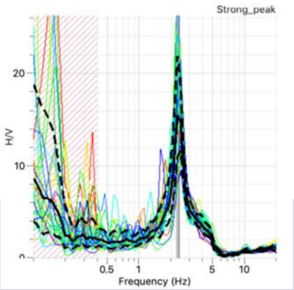
$$\frac{\sin\left(\left(\log_{10}\left(\frac{f}{fc}\right)\right)^{b}\right)}{\left(\left(\log_{10}\left(\frac{f}{fc}\right)\right)^{b}\right)^{4}}$$



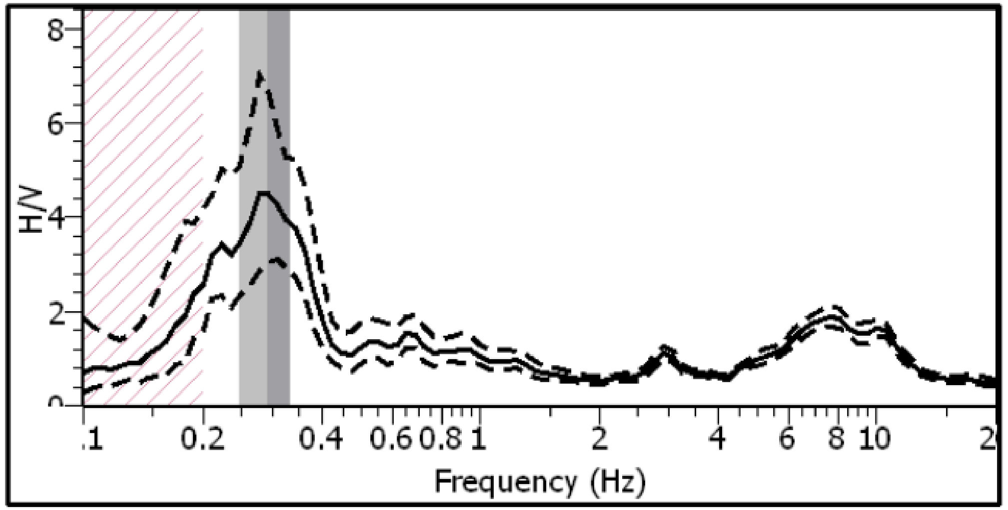




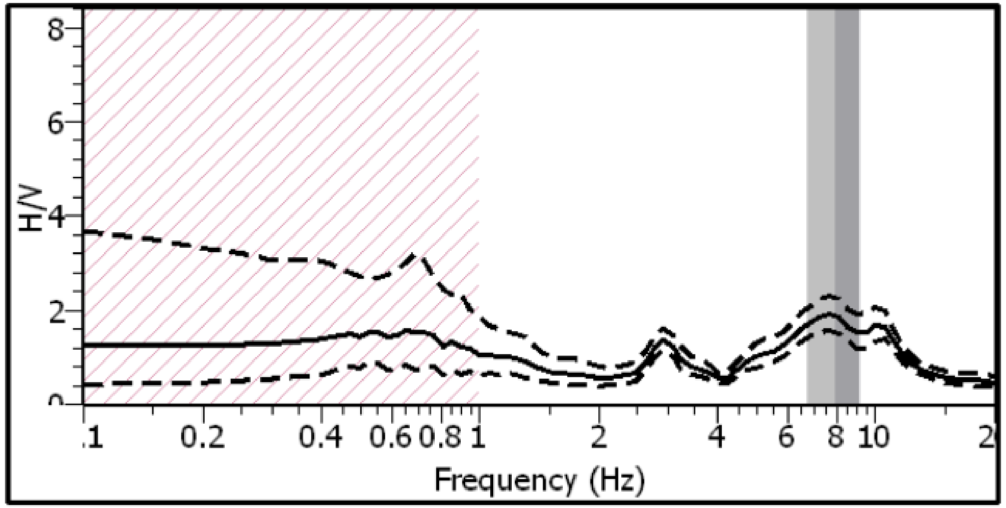




Single Station measurement: H/V technique (HVSR) – Time windowing effect

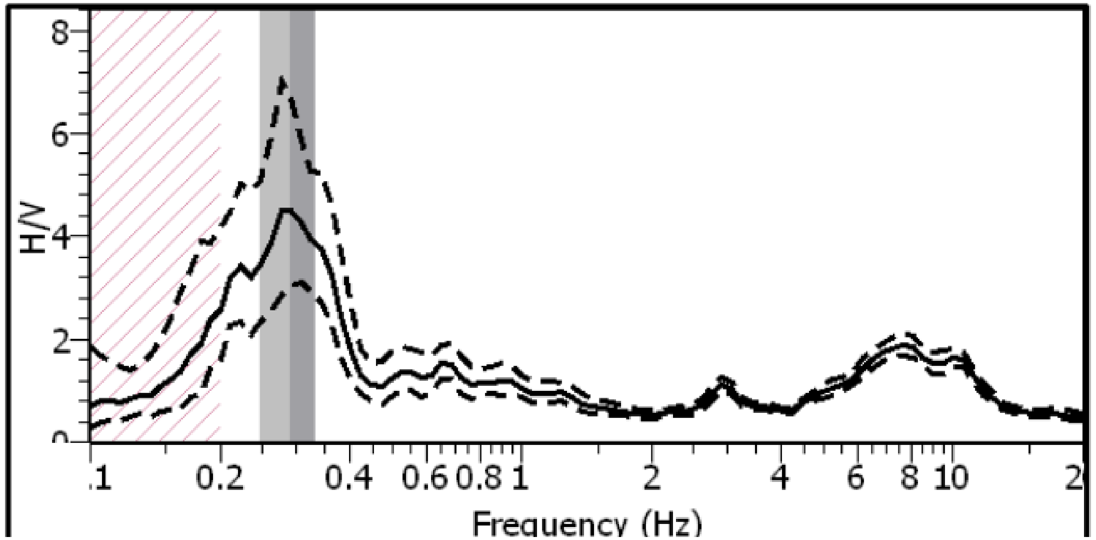


50 s window
Clear peak at 0.3 Hz

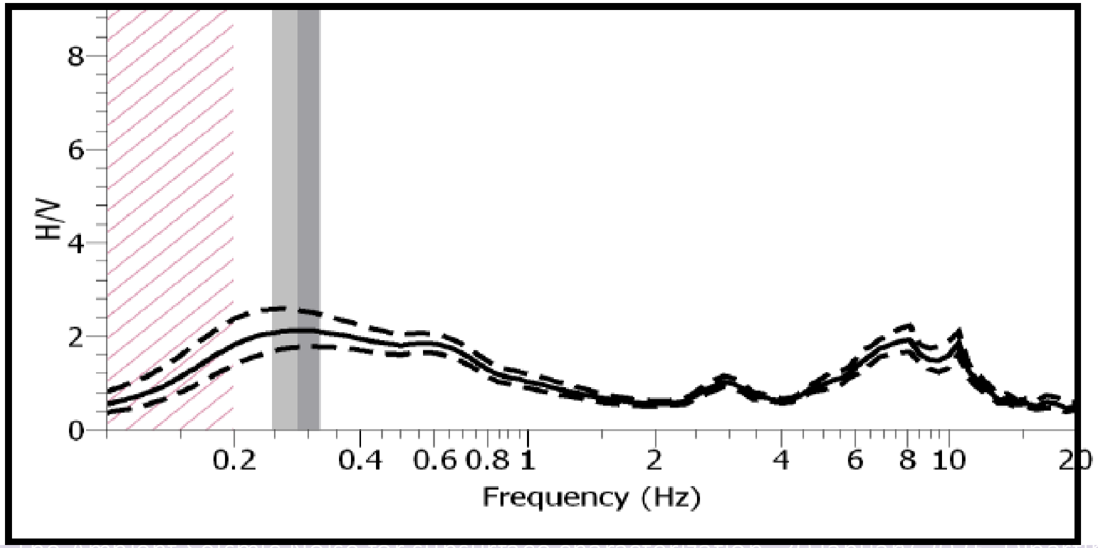


10 s window
No Clear peak;
Lack of resolution at low frequency

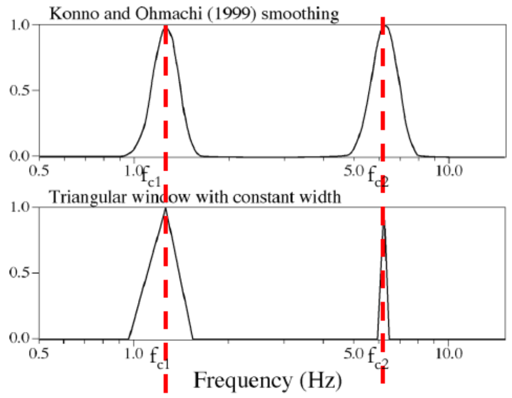
Single Station measurement: H/V technique (HVSR) – smoothing influence



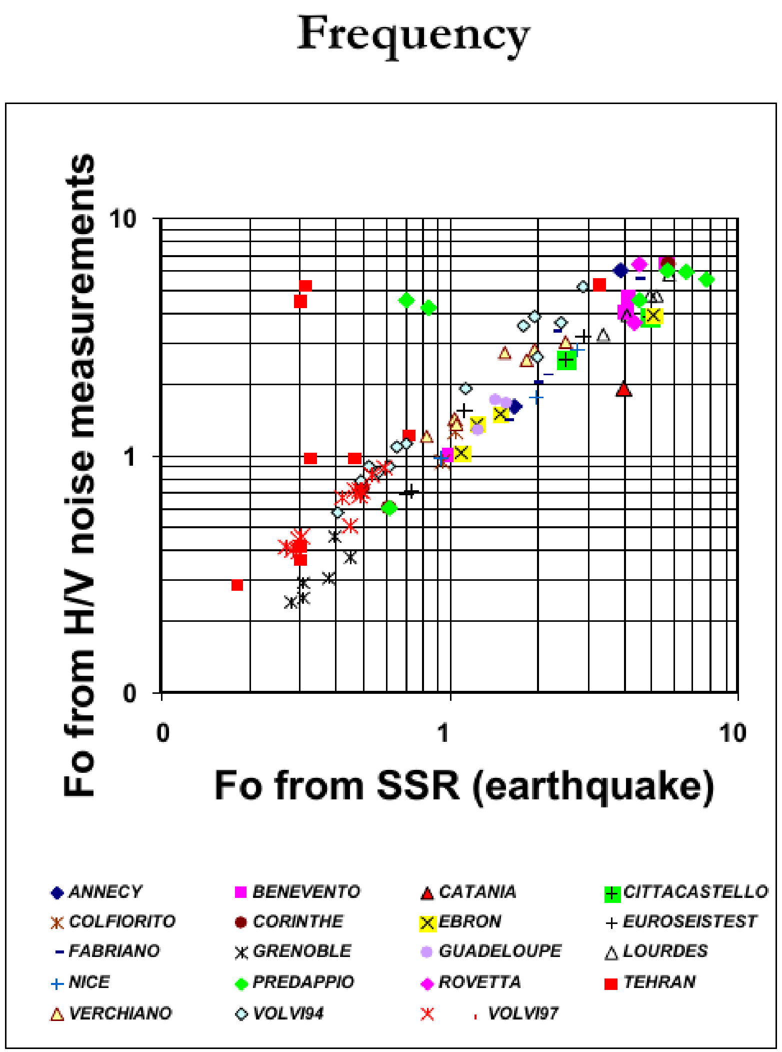
50 s window
Konno – Ohmachi smoothing
b=40

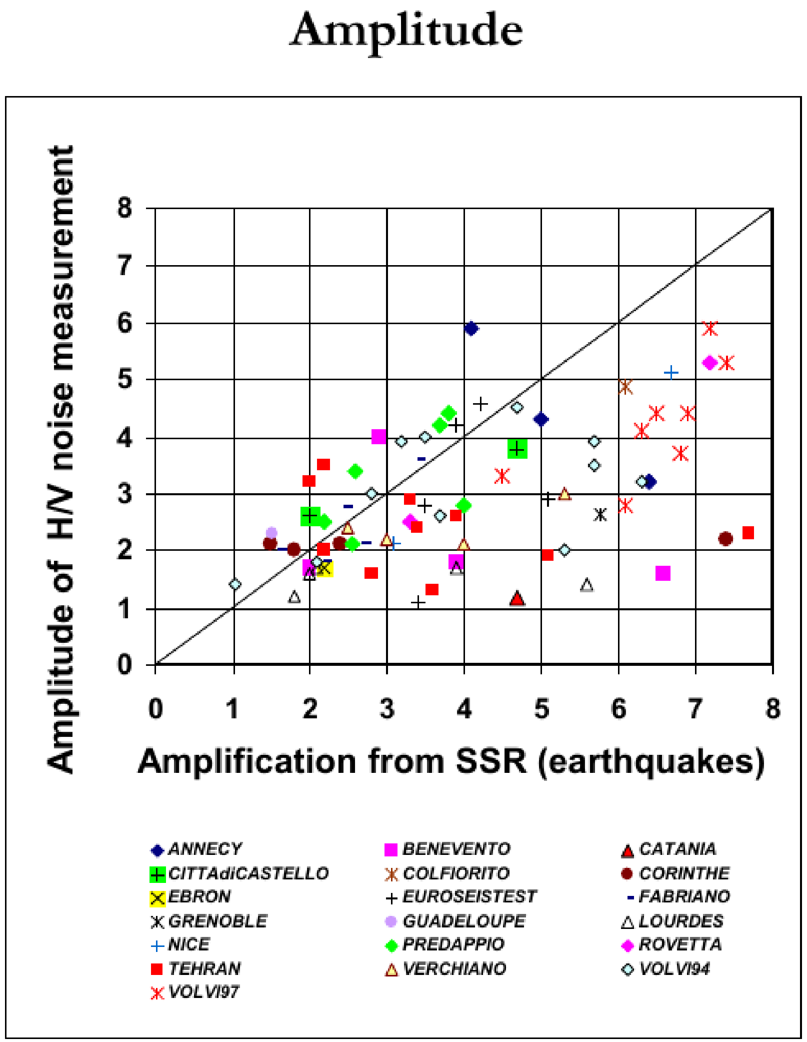


50 s window
Constant smoothing
Band-width = 1 Hz



Single Station measurement: H/V technique (HVSR) – 1D interpretation





From Haghshenas et al., 2008.
Bull. Earth. Eng

Single Station measurement: H/V technique (HVSR) – Criteria for a reliable H/V curve

ITINERIS

Criteria for a reliable H/V curve

i) $f_0 > 10 / l_w$

and

ii) $n_c (f_0) > 200$

and

iii) $\sigma_A(f)<2$ for $0.5f_0<f<2f_0$ if $f0>0.5Hz$

or $\sigma_A(f)<3$ for $0.5f_0<f<2f_0$ if $f0<0.5Hz$

Criteria for a clear H/V peak

(at least 5 out of 6 criteria fulfilled)

i) $\exists f^- \in [f_0/4, f_0] \mid A_{H/V}(f^-) < A_0/2$

ii) $\exists f^+ \in [f_0, 4f_0] \mid A_{H/V}(f^+) < A_0/2$

iii) $A_0 > 2$

iv) $f_{peak}[A_{H/V}(f) \pm \sigma_A(f)] = f_0 \pm 5\%$

v) $\sigma_f < \varepsilon(f_0)$

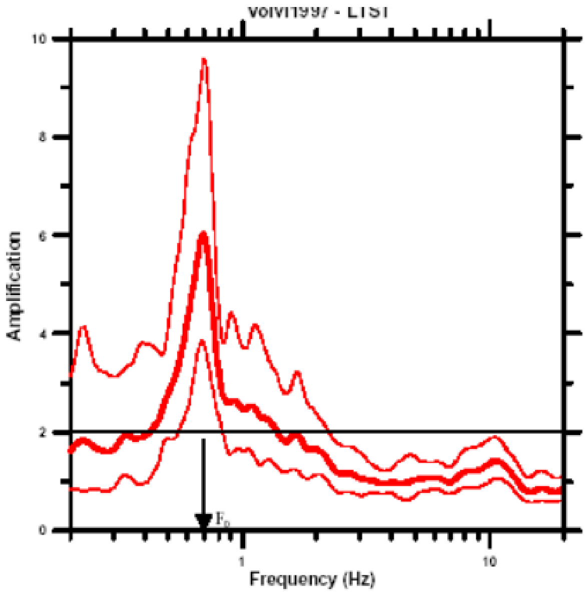
vi) $\sigma_A(f_0) < \theta (f_0)$

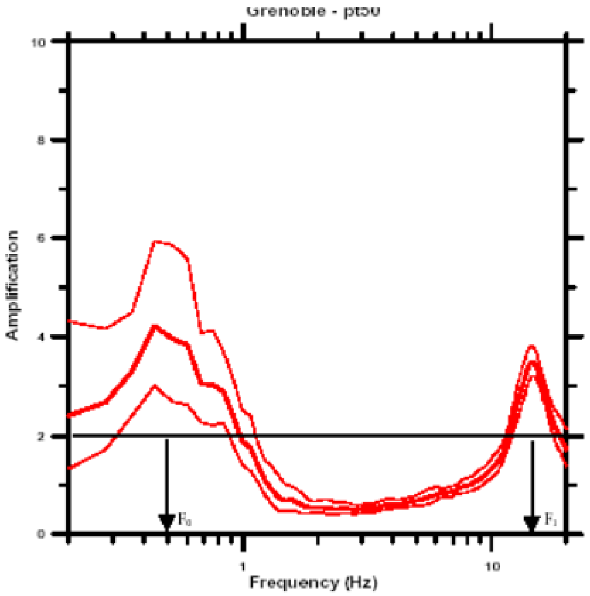
- l_w = window length
- n_w = number of windows selected for the average H/V curve
- $n_c = l_w \cdot n_w \cdot f_0$ = number of significant cycles
- f = current frequency
- f_{sensor} = sensor cut-off frequency
- f_0 = H/V peak frequency
- σ_f = standard deviation of H/V peak frequency ($f_0 \pm \sigma_f$)
- $\varepsilon (f_0)$ = threshold value for the stability condition $\sigma_f < \varepsilon(f_0)$
- A_0 = H/V peak amplitude at frequency f_0
- $A_{H/V} (f)$ = H/V curve amplitude at frequency f
- f^- = frequency between $f_0/4$ and f_0 for which $A_{H/V}(f^-) < A_0/2$
- f^+ = frequency between f_0 and $4f_0$ for which $A_{H/V}(f^+) < A_0/2$
- $\sigma_A (f)$ = "standard deviation" of $A_{H/V} (f)$, $\sigma_A (f)$ is the factor by which the mean $A_{H/V}(f)$ curve should be multiplied or divided
- $\sigma_{logH/V} (f)$ = standard deviation of the $logA_{H/V}(f)$ curve, $\sigma_{logH/V} (f)$ is an absolute value which should be added to or subtracted from the mean $logA_{H/V}(f)$ curve
- $\theta (f_0)$ = threshold value for the stability condition $\sigma_A(f) < \theta(f_0)$
- $V_{s,av}$ = average S-wave velocity of the total deposits
- $V_{s,surf}$ = S-wave velocity of the surface layer
- h = depth to bedrock
- h_{min} = lower-bound estimate of h

Sesame recommandations

Single Station measurement: H/V technique (HVSR) – Interpretation of curves: summary

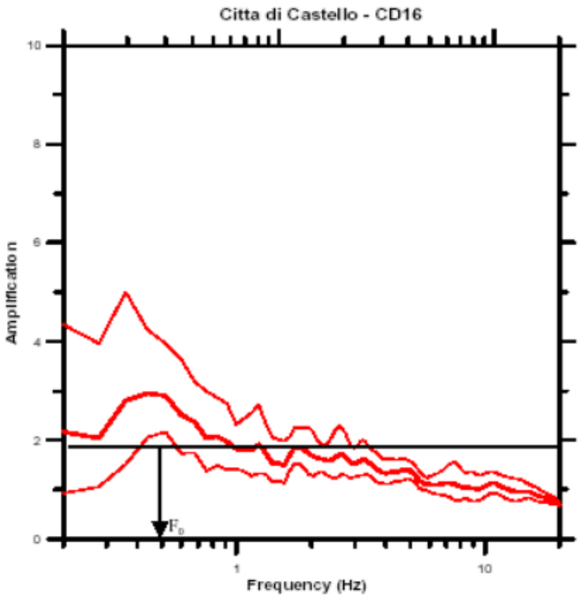
Easy case

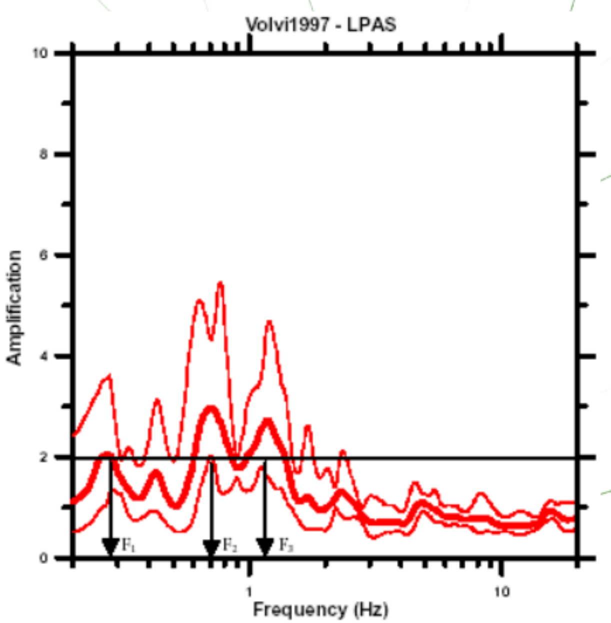




- quantitative information
- Vs,average
- Hmin

Difficult case

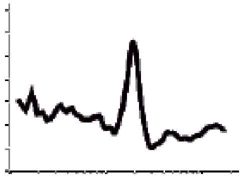




- Not recommanded to extract quantitative information
- Check the geology (stiff sediments, low contrast,basin-edge, ...)
- Use earthquakes recordings

How Ambient Noise can help us in deriving information on site conditions?

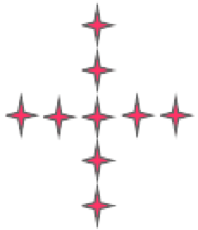
Single station



H/V method

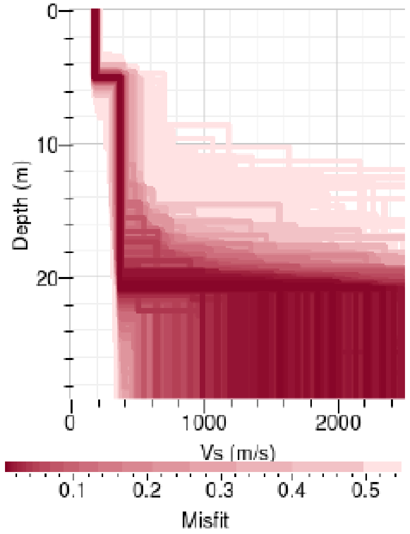
Output: site resonance frequency

Array of stations (with synchroneous records)

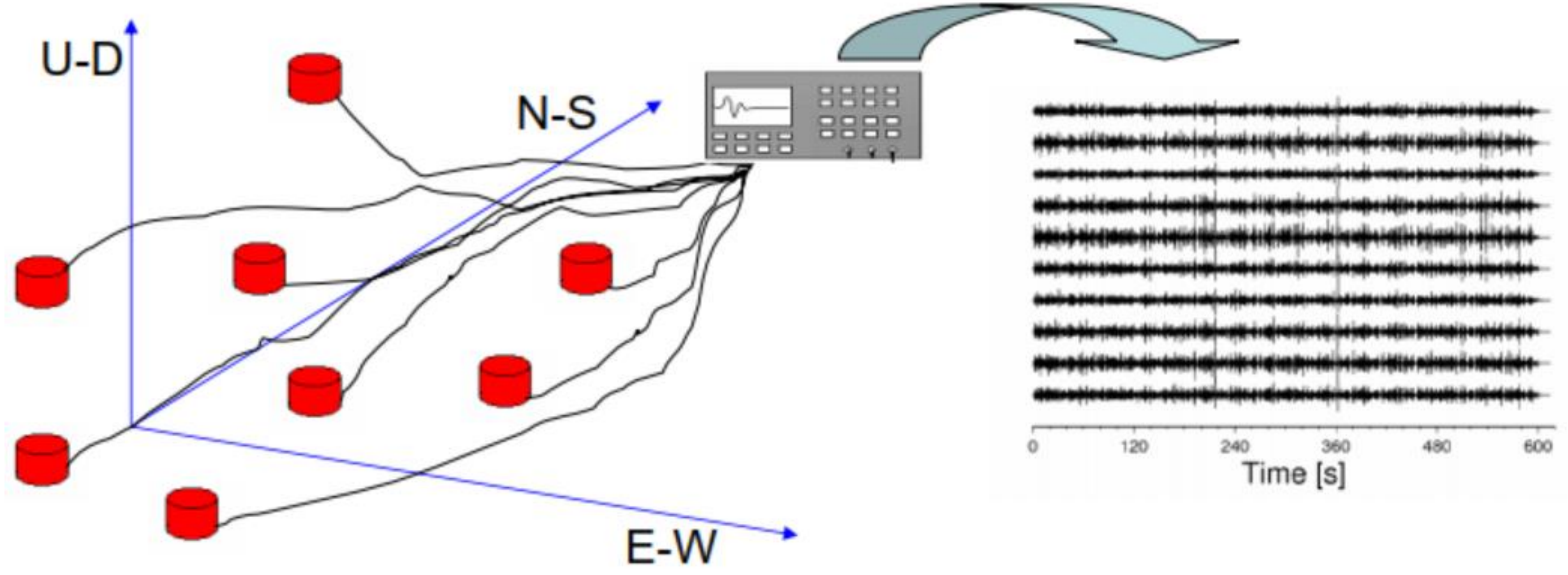


Study wave propagation between motion sensors

Output: shear wave velocity vs. depth



SEISMIC ARRAYS BASED METHODS



What is a «seismic array»?

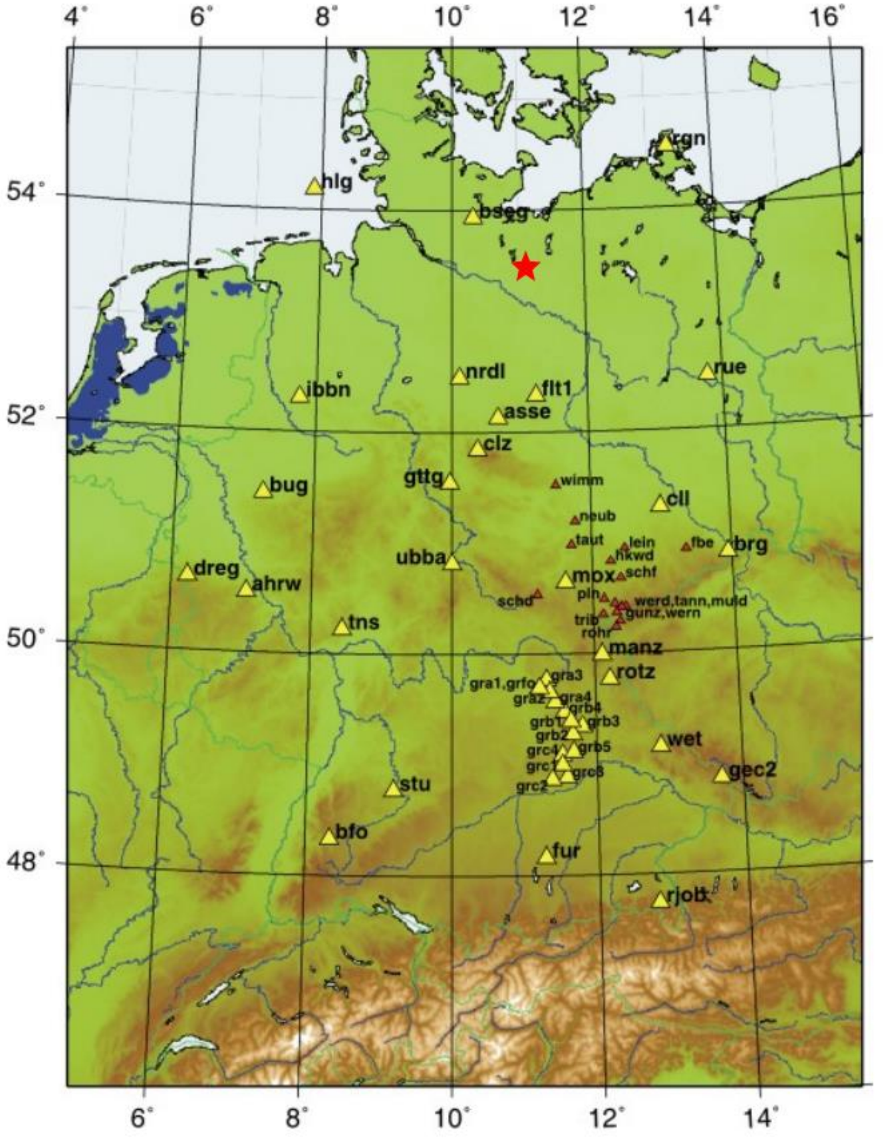
SEISMIC NETWORK { Set of seismograph stations with common base time

AND

Sensors located closely enough in space so that arriving seismic signal waveforms can be correlated between adjacent sensors

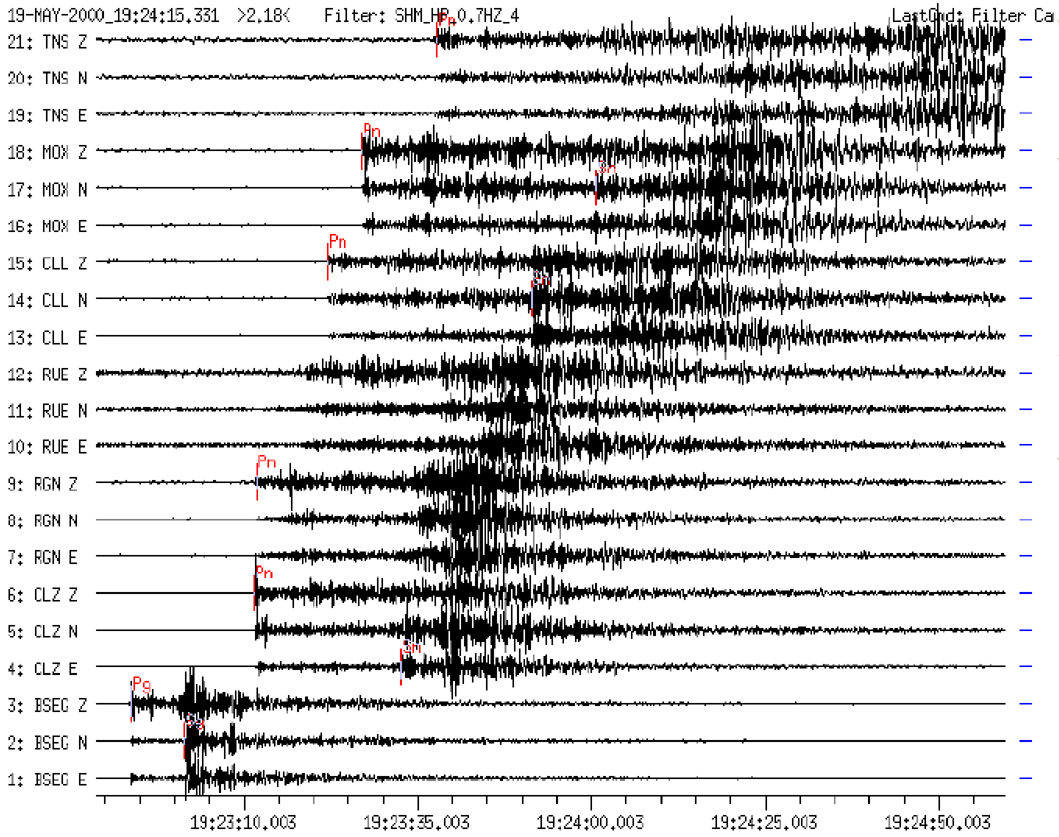
NETWORKS OR ARRAYS?

ITINERIS



Example for NETWORK operations

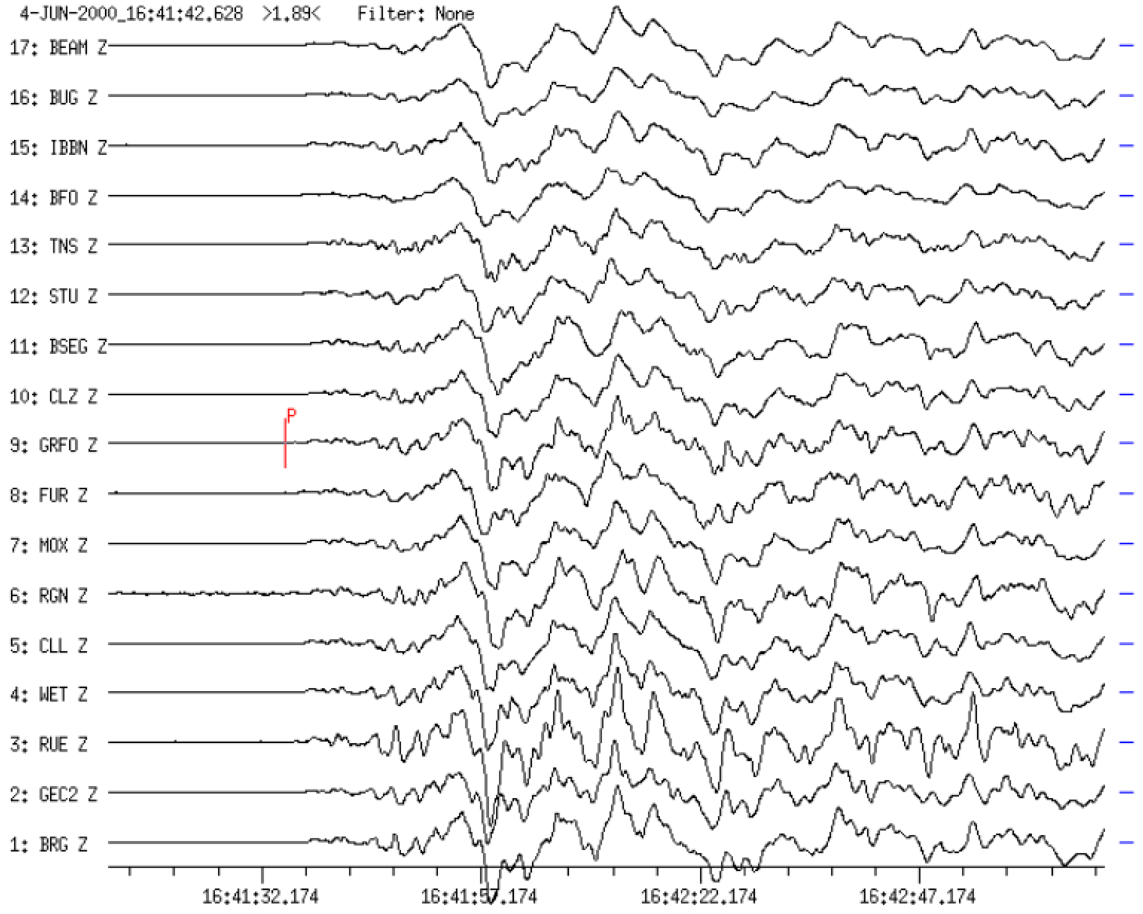
Local earthquake recorded at seven 3C seismic stations belonging to The German Regional Seismic Network



NETWORKS OR ARRAYS?

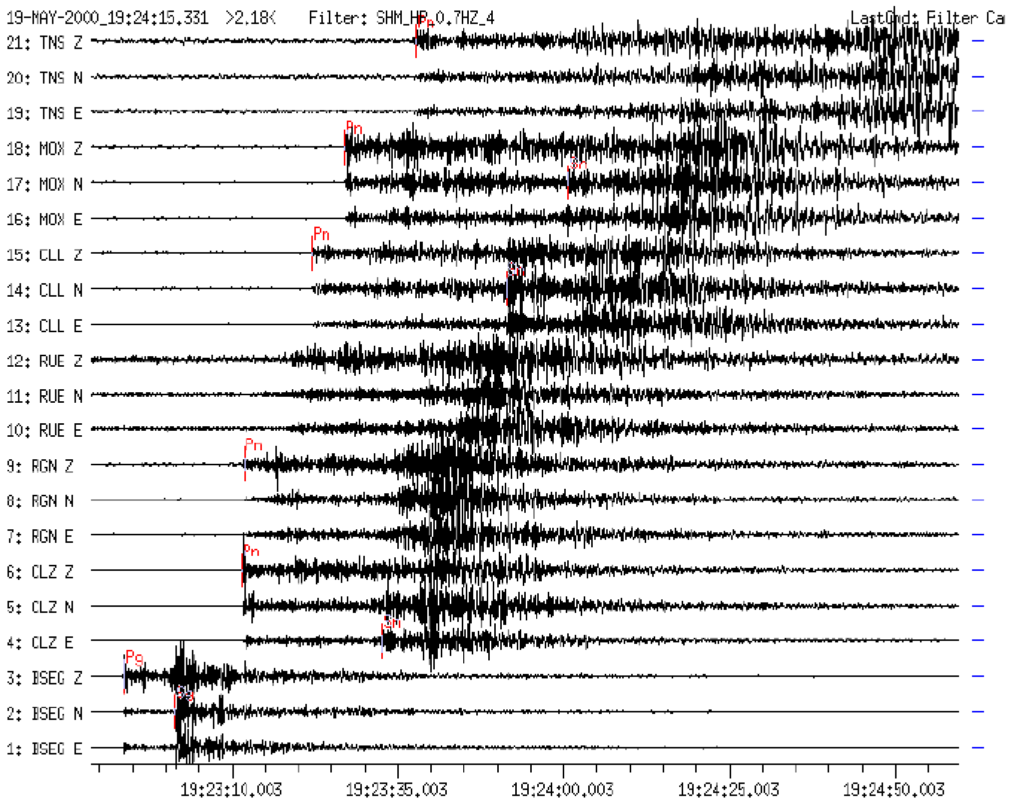
Example for Array operations

Teleseismic earthquake occurred in Southern Sumatra Region



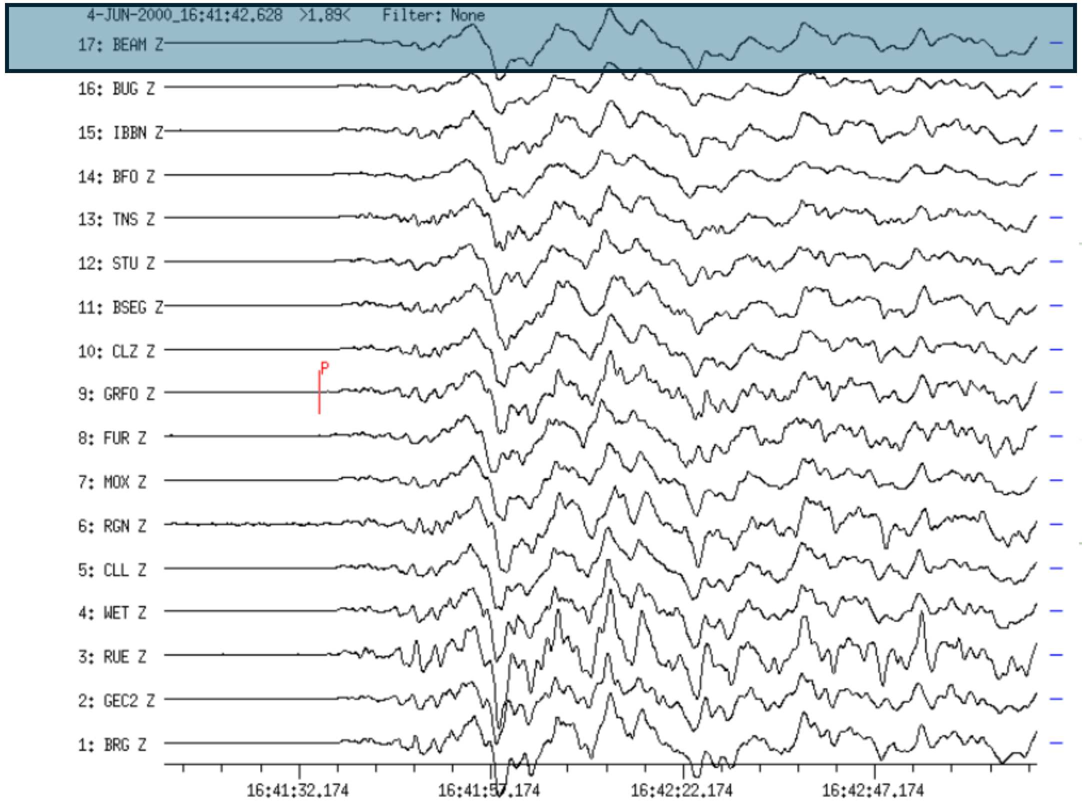
NETWORKS OR ARRAYS?

Example for NETWORK operations



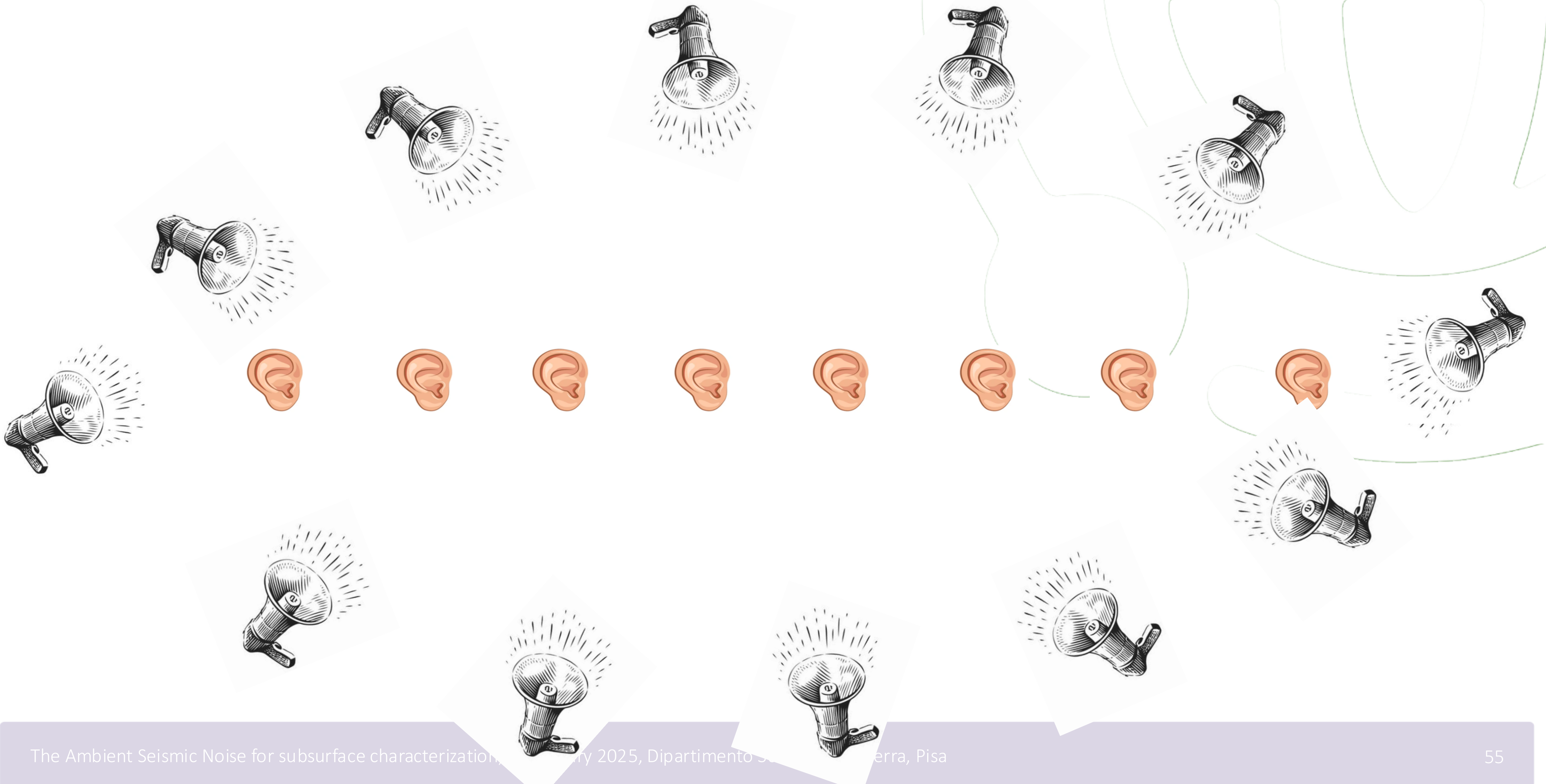
Example for Array operations

Teleseismic earthquake occurred in Southern Sumatra Region

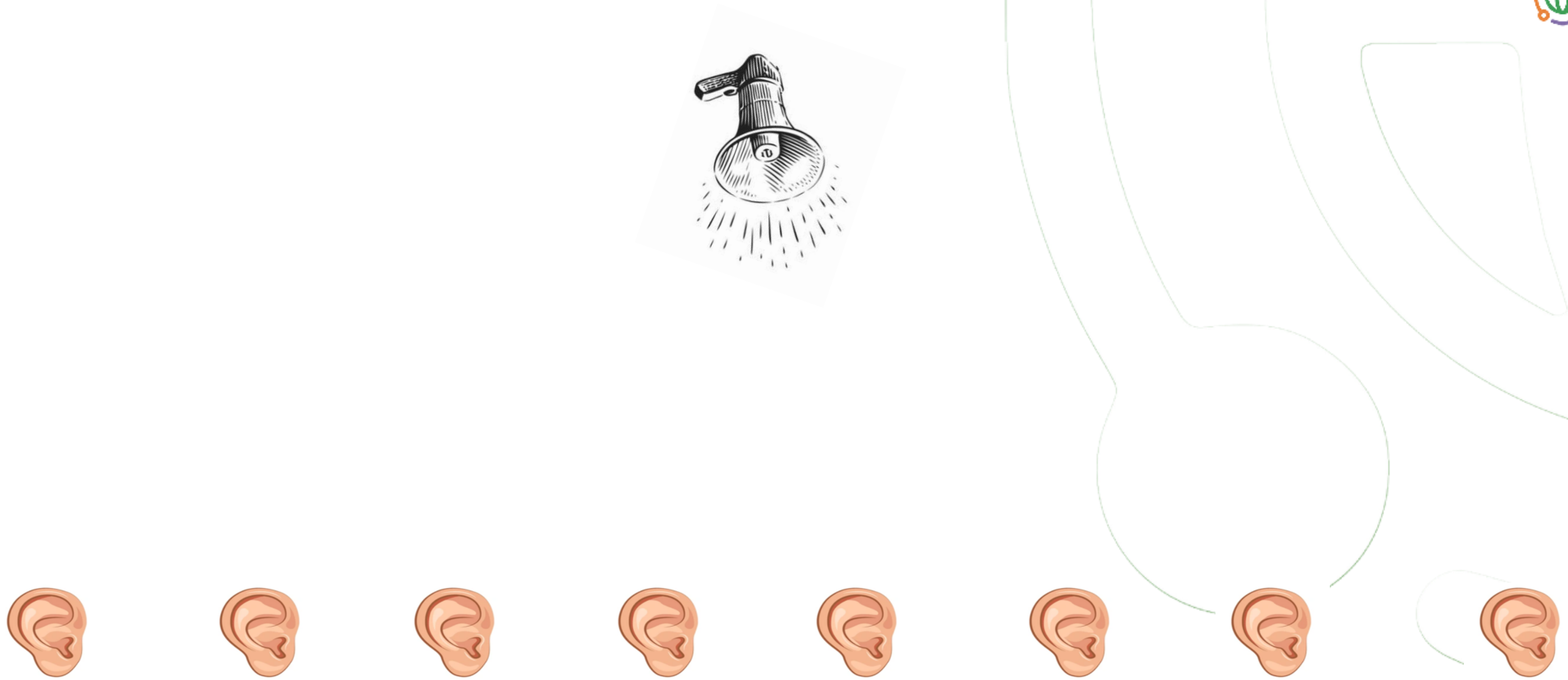


NOTE THE DIFFERENCE: WAVEFORM SIMILARITY → **Function of array dimension and signal wavelength**

SEISMIC ARRAYS BASED METHODS



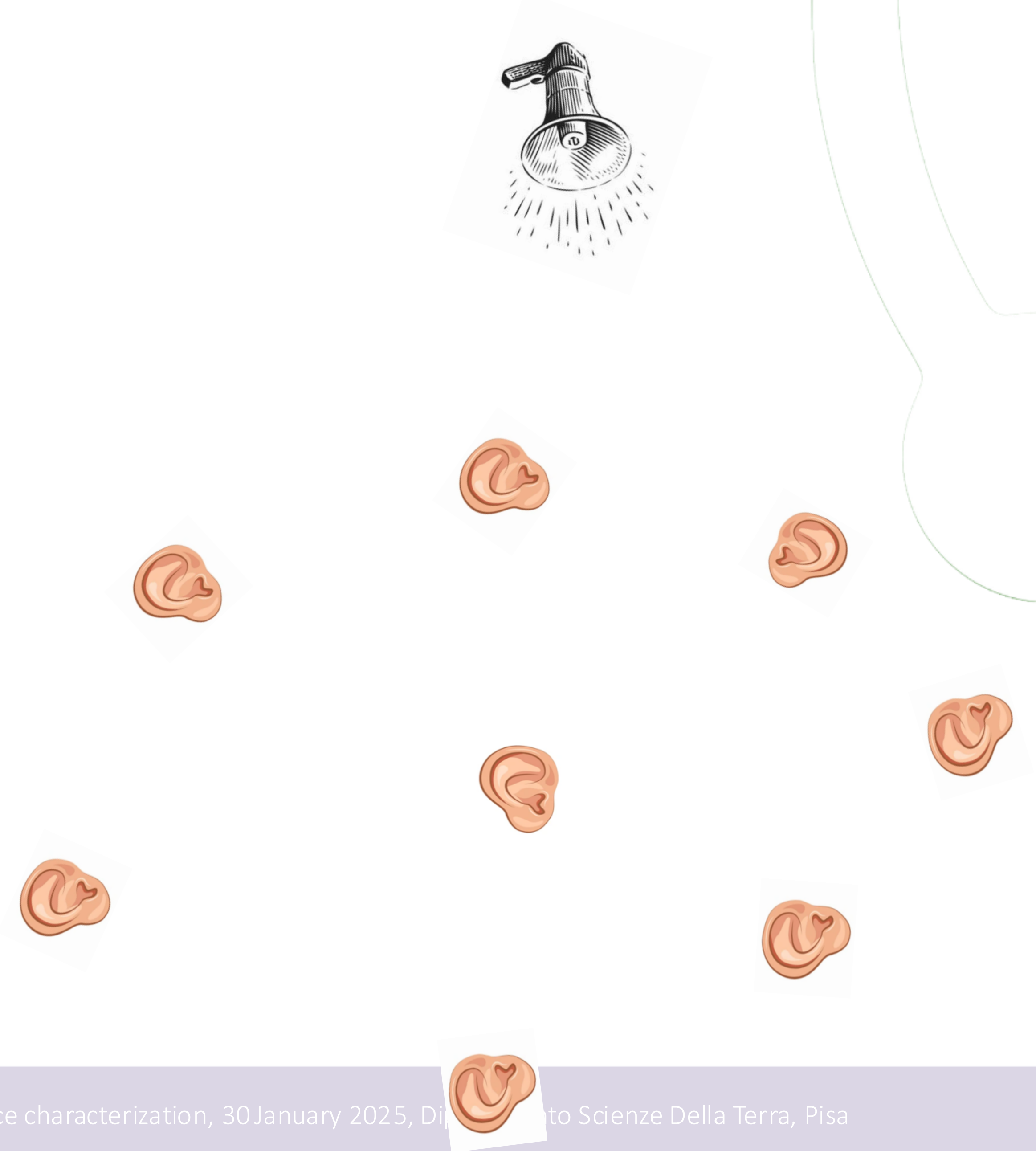
SEISMIC ARRAYS BASED METHODS



SOME INFORMATION CAN BE MISSED

SEISMIC ARRAYS BASED METHODS

ITINERIS



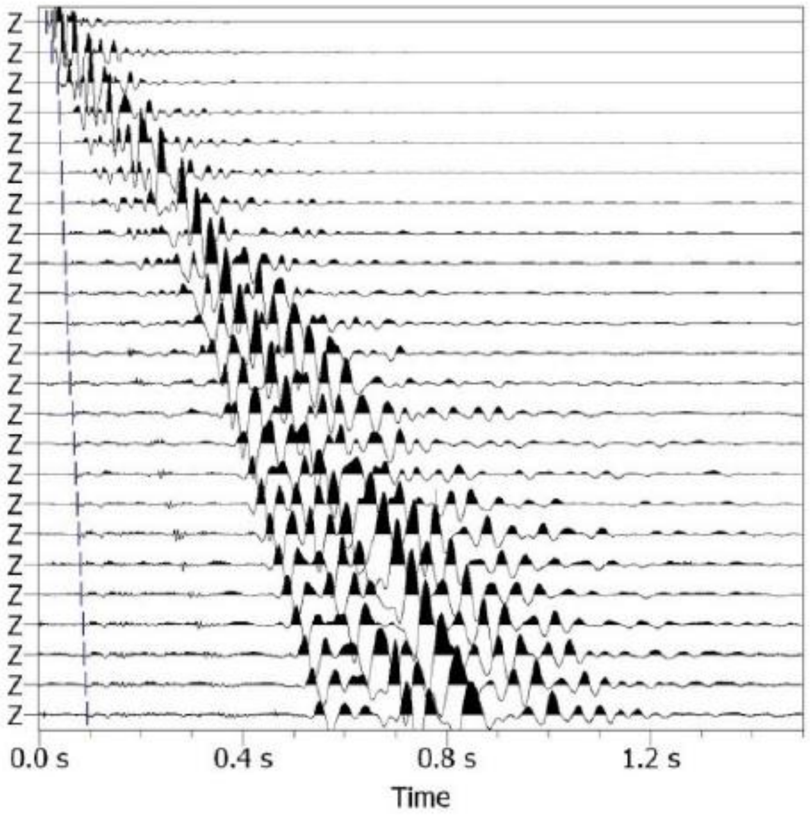
SEISMIC ARRAYS BASED METHODS

SEISMIC ARRAYS BASED METHODS

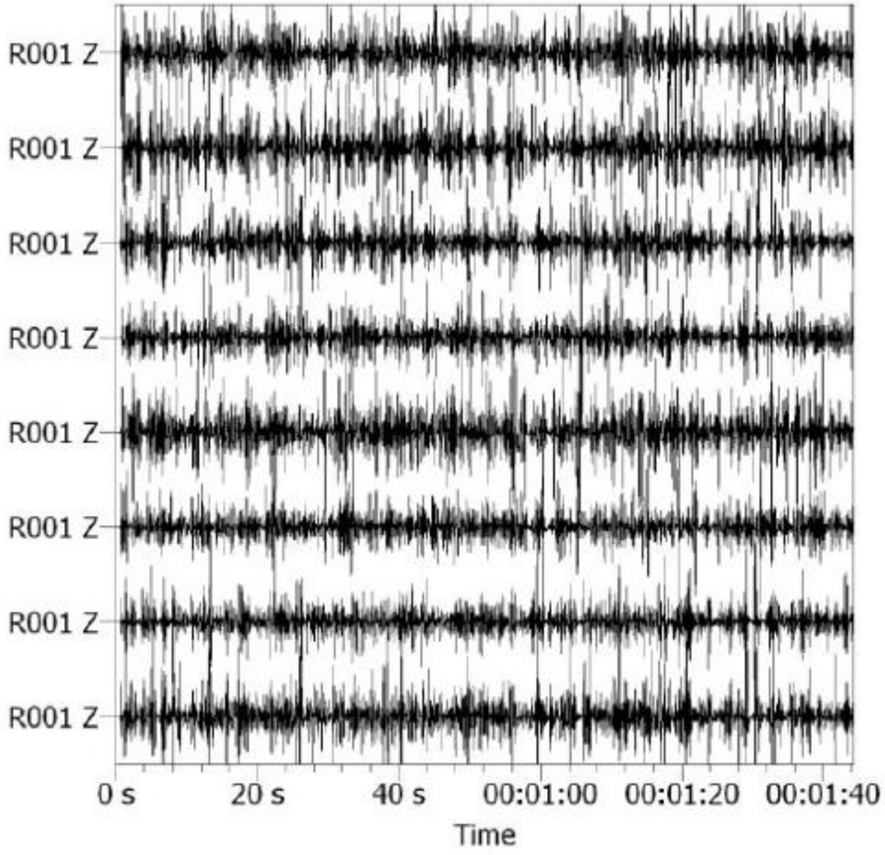
Each speaker a different signal

Basic assumption for array processing: the need for a wave propagation model

Seismograms
(active seismics)



Noise records



Basic assumption for array processing: the need for a wave propagation model

Simple model and therefore appealing:

$$D(\vec{x},t) = A\exp(i(\omega t \pm \vec{k}\vec{x}))$$

Harmonic plane wave representation

PHASE

Particular solution to the homogeneous wave equation:

$$\frac{\partial^2 D}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 D}{\partial t^2}$$

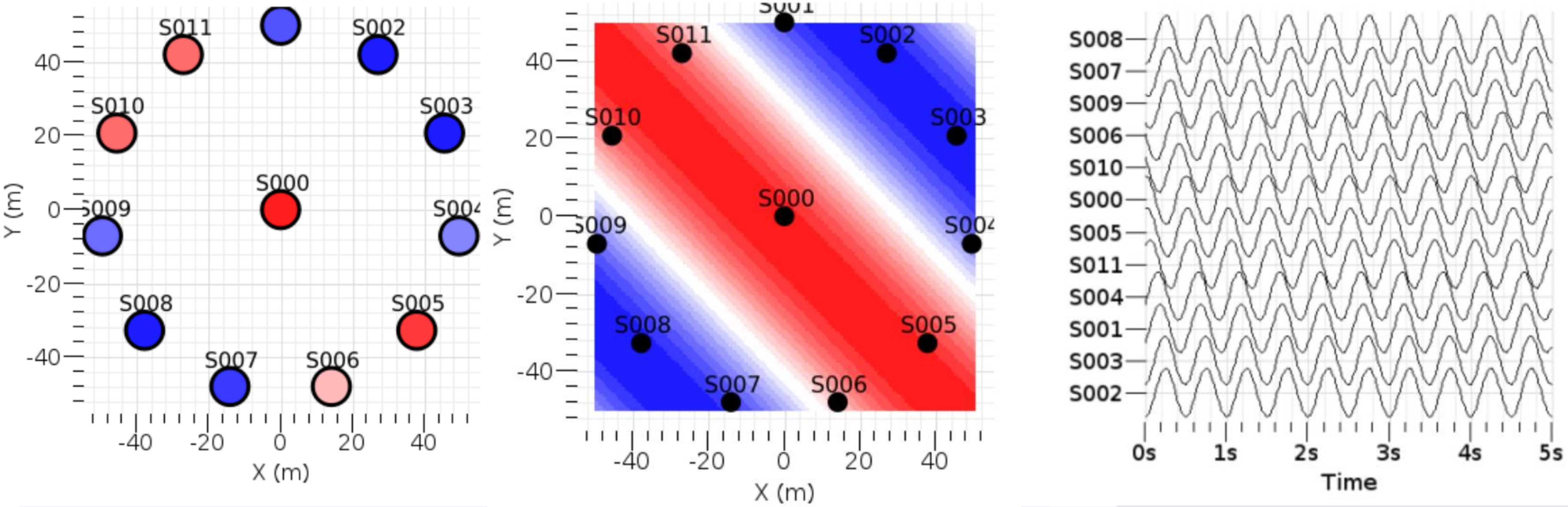
Basic assumption for array processing: the need for a wave propagation model

PHASE

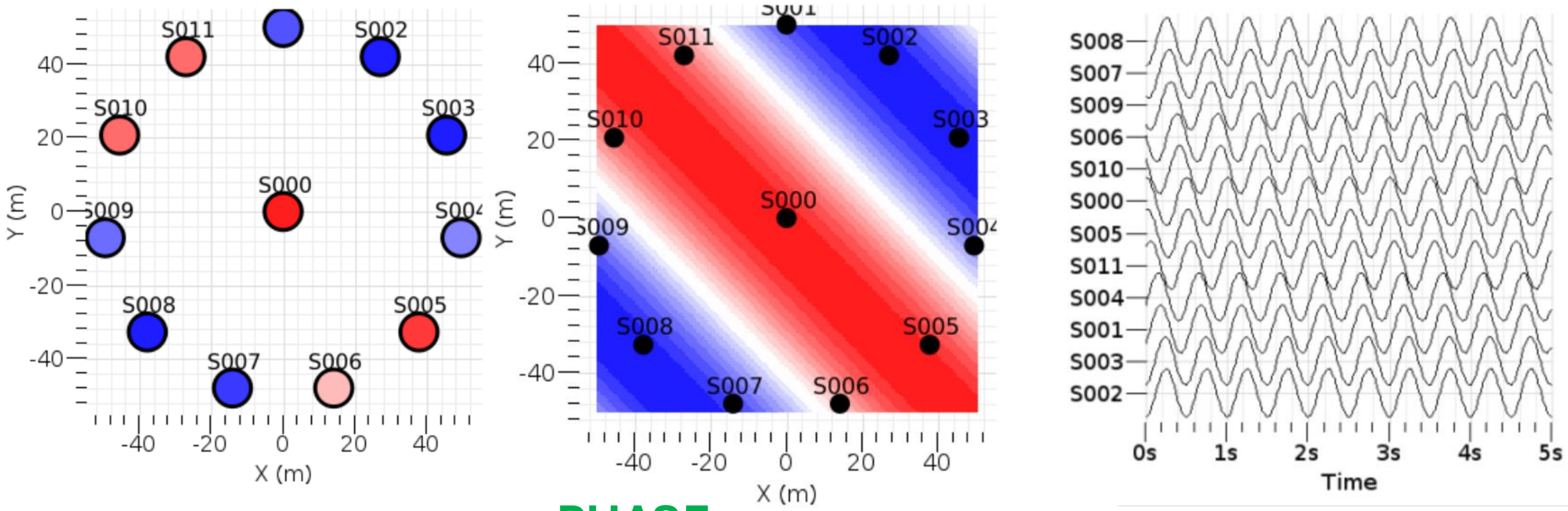
$$D(\vec{x},t) = A\exp(i(\omega t \pm \vec{k}\vec{x}))$$

Harmonic plane wave representation

At any instant of time t_0, the value of $D(x,y,z,t_0)$ is the same at all points lying in a plane given by $k_x x+k_y y+k_z z=CONST$



Basic assumption for array processing: the need for a wave propagation model

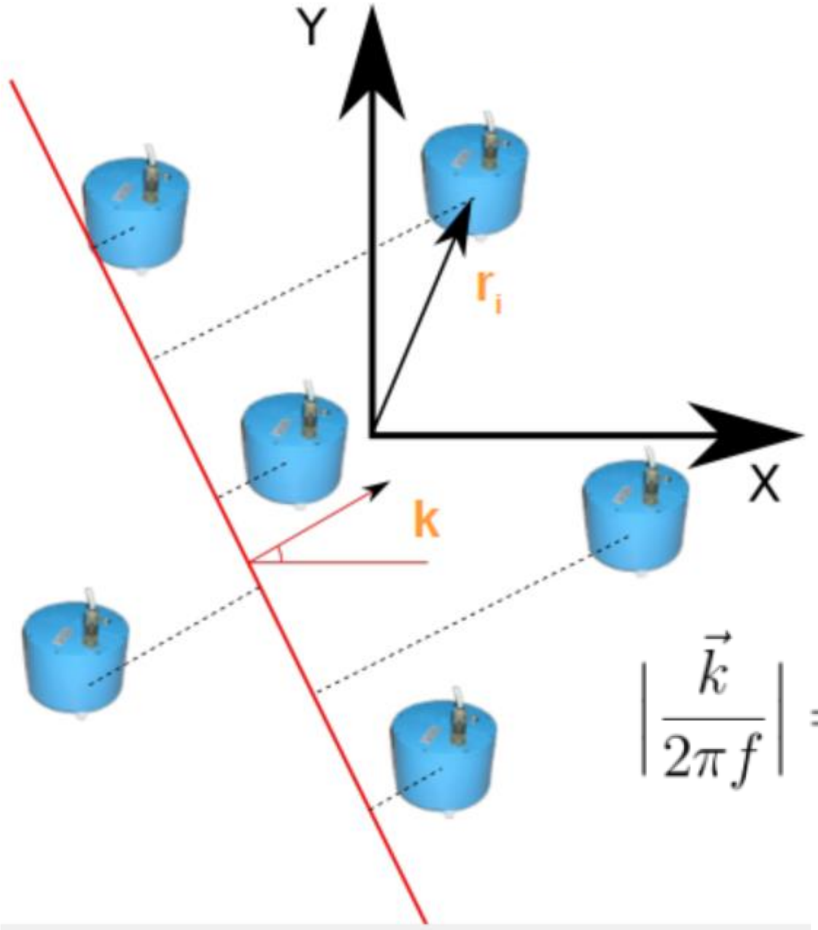


PHASE

$$D(\vec{x},t) = A\exp(i(\omega t \pm \vec{k}\vec{x}))$$

$\vec{k}\vec{x} = const$ Wavefront: the set (locus) of all points having the same phase.

Plane wave propagation model: Observation of particular waveform s(t) at array sensors



Plane wave description at a single sensor

s(t)= 

$$x_i(t) = s\left(t - \frac{\vec{k}\vec{r}_i}{2\pi f}\right) + \eta_i$$

Relative time shift depend on
- Station position (r_i);
- Velocity (slowness)

$$x_i(t) = S(t) + \eta(t)$$

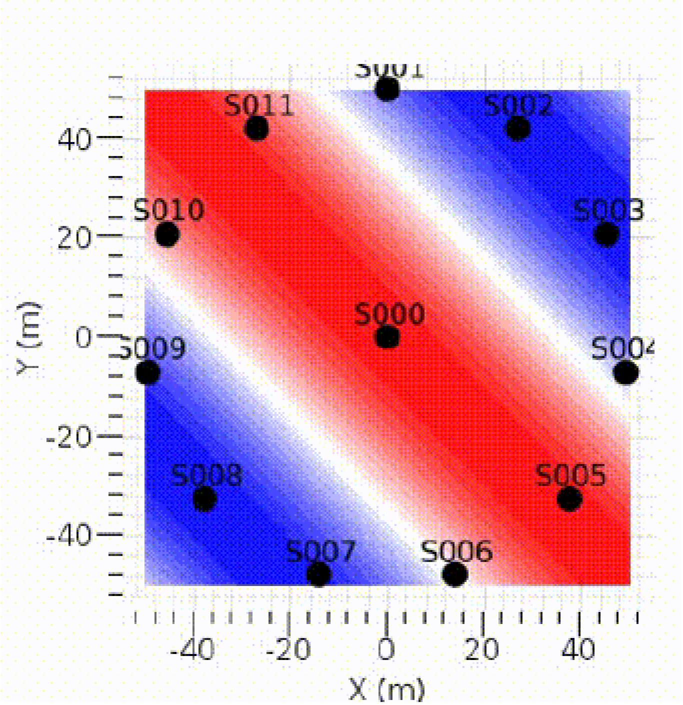
SIGNAL NOISE

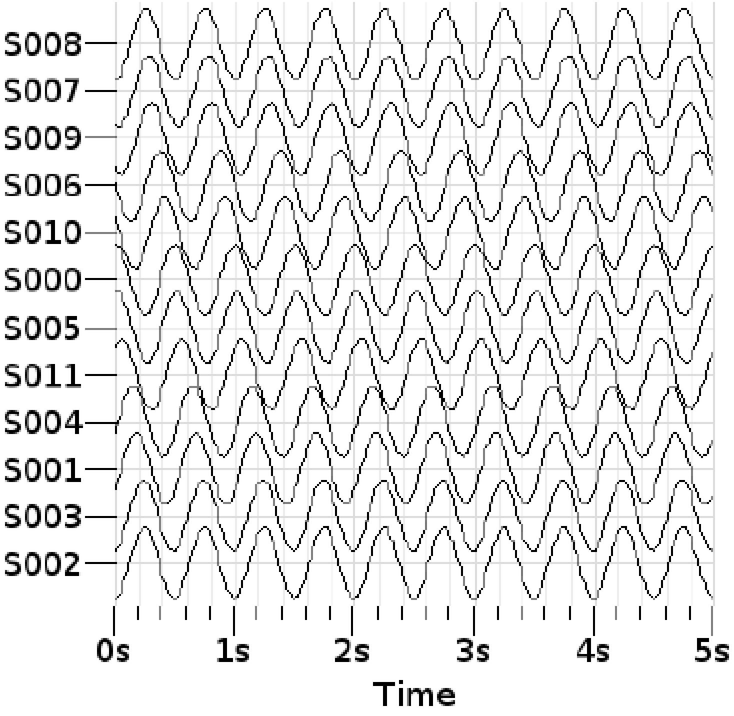
$$\left|\frac{\vec{k}}{2\pi f}\right| = \frac{1}{v} \qquad v = \frac{1}{|\vec{u}|}$$

$\vec{u}$: slowness

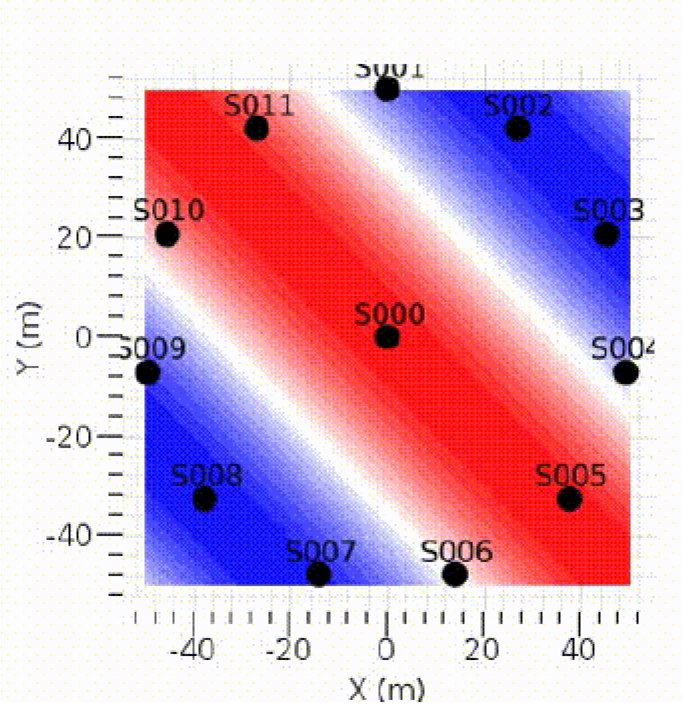
SIGNAL: the component of observations common to all sensor outputs

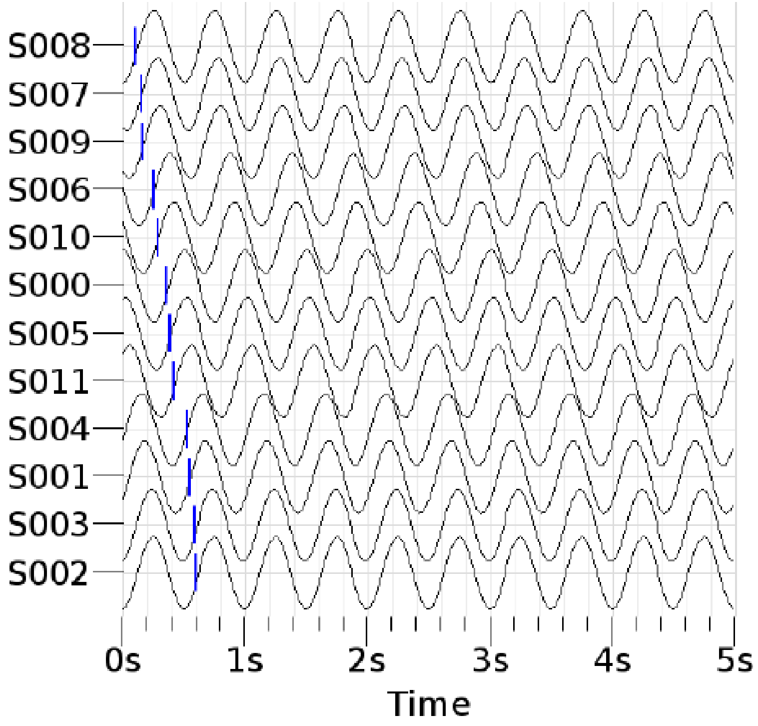
Plane wave propagation model: Observation of particular waveform s(t) at array sensors





Plane wave parameter determination I: Arrival picking at N stations





Arrival time at the *i-th* sensor

$$t_i = t_0 + \frac{\vec{k}\vec{r}_i}{2\pi f} = t_0 + \vec{u}\vec{r}_i$$

For a plane wave model

$$\begin{bmatrix} t_1 - t_o \\ t_2 - t_o \\ \vdots \\ t_N - t_o \end{bmatrix} = \begin{bmatrix} r_{1x} & r_{1y} \\ r_{2x} & r_{2y} \\ \vdots & \vdots \\ r_{Nx} & r_{Ny} \end{bmatrix} \begin{bmatrix} u_x \\ u_y \end{bmatrix}$$

$$\vec{t} = \boldsymbol{R}\vec{u}$$

$$\vec{u} = \boldsymbol{R}^{-1}\vec{t}$$

$$\theta = atan(u_x/u_y)$$

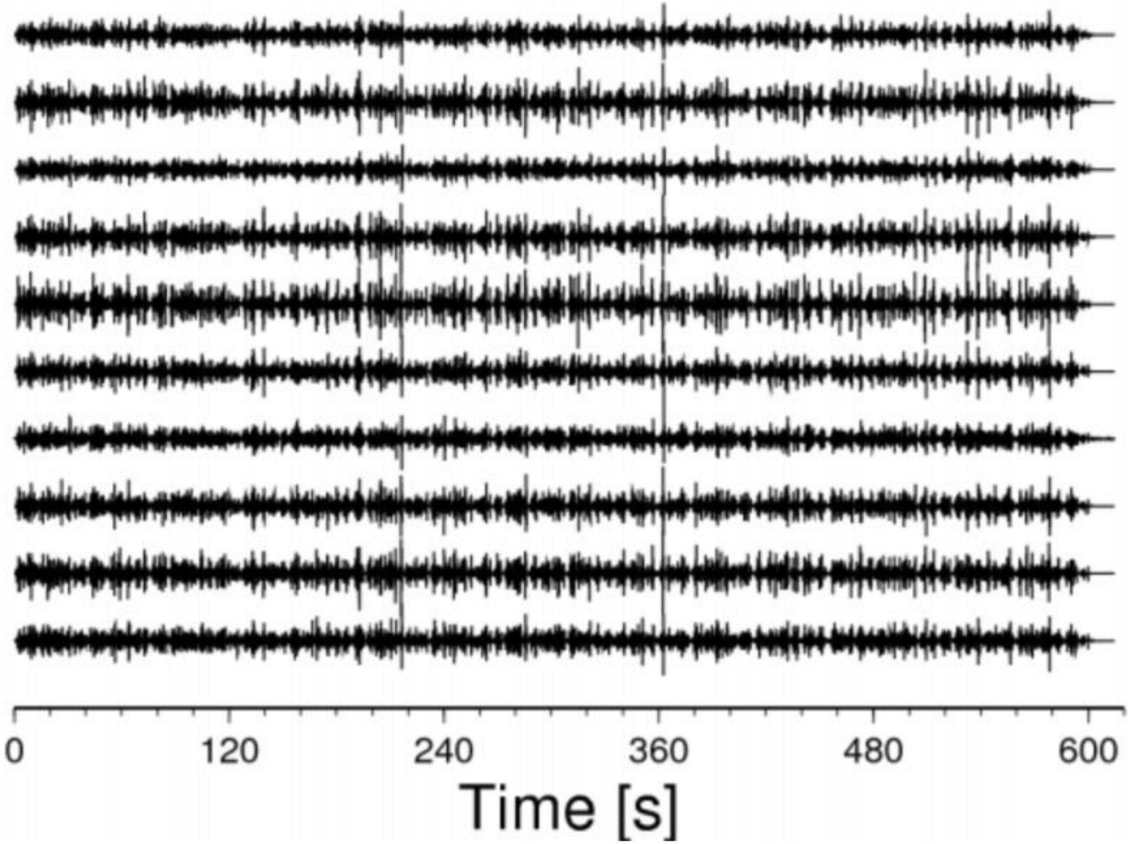
$$\left|\frac{\vec{k}}{2\pi f}\right| = \frac{1}{v} \qquad v = \frac{1}{|\vec{u}|}$$

$\vec{u}$: slowness

Plane wave parameter determination II: enhancing signals for specific parameters

Real case

Is there a signal with parameters θ_0 and u_0?



Original observations

$$x_i(t) = s(t - \vec{r}_i \cdot \vec{u}_0) + \eta_i(t)$$

SIGNAL

NOISE

Delayed observations

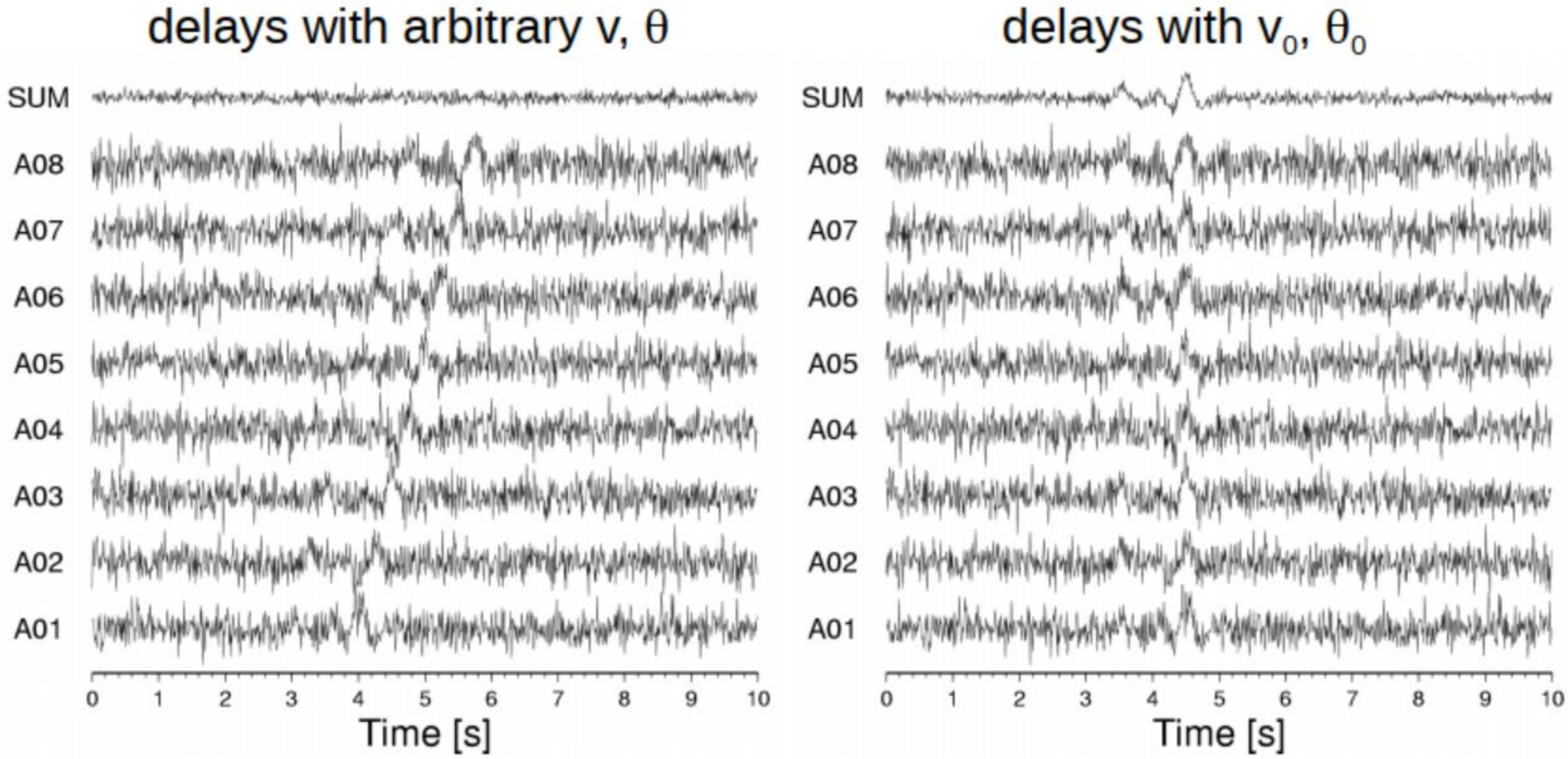
$$\tilde{x}_i(t, \vec{u}) = s(t + \vec{r}_i \cdot (\vec{u} - \vec{u}_0)) + \eta_i(t + \vec{r}_i \cdot \vec{u})$$

Sum (beam)

$$b(t, \vec{u}_0) = \frac{1}{N} \sum_{i=1}^{N} \tilde{x}_i(t, \vec{u}_0) = s(t) + \frac{1}{N} \sum_{i=1}^{N} \eta_i(t + \vec{r}_i \cdot \vec{u}_0) \quad \geq b(t, \vec{u}) \ , \forall \vec{u} \neq \vec{u}_0$$

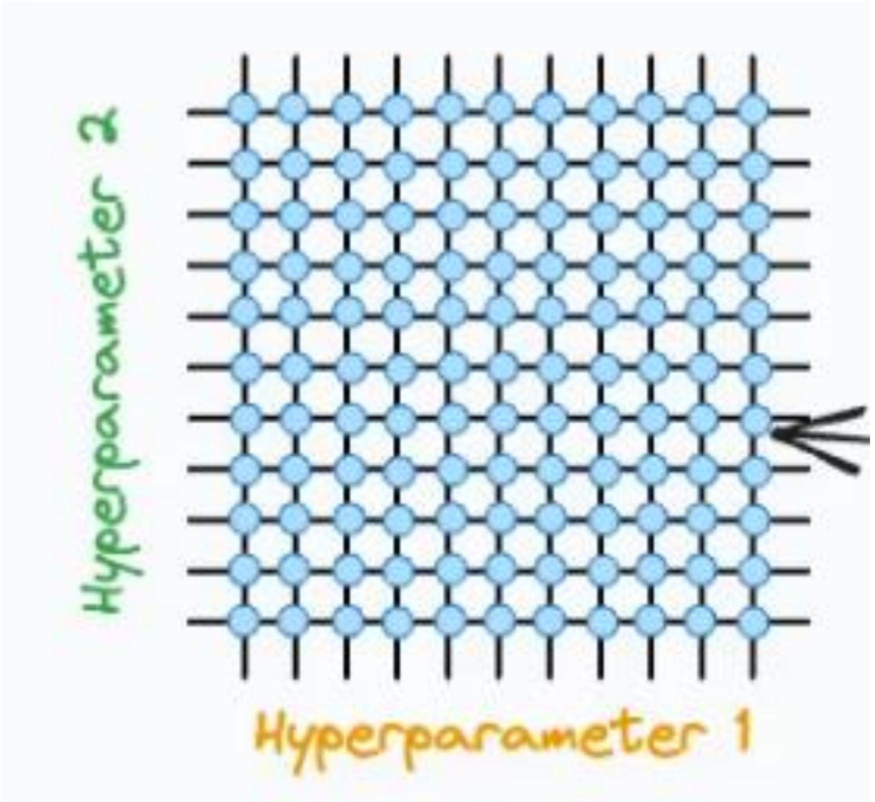
Sum is maximum for the right parameters (θ_0 and u_0); noise decreases by averaging over the N waveforms received by the sensors.

Plane wave parameter determination II: enhancing signals for specific parameters



Plane wave parameter determination III: any signal arriving with any possible parameter

Question: is there some signal with arbitrary parameter θ and u which we might be interested in? (e.g. Rayleigh waves?)



GRIDSEARCH TECHNIQUE

As quantitative measure of goodness of fit we can use beampower

Delay and sum beamforming → Beampower as function of θ and u.

Plane wave parameter determination IV: Beam forming: a different view by switching domains

$s(t)=$ 

$$x_i(t) = s(t - \vec{r_i}\,\vec{u_0})$$

NOISE FREE SIGNAL AT SENSOR i, BEING s(t) the original signal propagating with slowness vector u_0

$$x_i(t,\vec{u}) = s(t - \vec{r_i}\,\vec{u_0} + \vec{r_i}\vec{u}) \Rightarrow s\left(t + \vec{r_i}(\vec{u} - \vec{u_0})\right)$$

TIME SHIFTED TRACES, according to test slowness vector $\vec{u}$

$$b(t,\vec{u}) = \frac{1}{N}\sum_{i=1}^{n} s\left(t + \vec{r_i}(\vec{u} - \vec{u_0})\right)$$

Beam (sum of shifted traces)

The power of beam is function of the array configuration and difference between true and test slowness

Plane wave parameter determination IV: Beam forming: a different view by switching domains

$$b(t,\vec{u}) = \frac{1}{N}\sum_{i=1}^{n} s\left(t + \vec{r_i}(\vec{u} - \overrightarrow{u_0})\right)$$

Seismic energy of the **beam** of shifted traces

$$E(t) = \int_{-\infty}^{+\infty} b^2(t,\vec{u})dt = \int_{-\infty}^{+\infty} \left[\frac{1}{N}\sum_{i=1}^{n} s\left(t + \vec{r_i}(\vec{u} - \overrightarrow{u_0})\right)\right]^2 dt$$

Parseval theorem $\int_{-\infty}^{\infty} b^2(t)dt = \int_{-\infty}^{+\infty} |B^2(\omega)|d\omega$

Time domain ←→ frequency domain: Fourier transform

Shifting theorem of FT: $x(t - t_0) \Leftrightarrow X(f)exp(-2\pi j f t_0)$

Plane wave parameter determination IV: Beam forming: a different view by switching domains

Parseval theorem $\int_{-\infty}^{\infty} b^2(t)dt = \int_{-\infty}^{+\infty} |B^2(\omega)|d\omega$

$$\int_{-\infty}^{\infty} b^2(t)dt = \int_{-\infty}^{+\infty} |B^2(\omega)|d\omega$$

$$E(t) = \int_{-\infty}^{+\infty} b^2(t,\vec{u})dt = \int_{-\infty}^{+\infty} \left[\frac{1}{N}\sum_{i=1}^{n} s\left(t + \vec{r_i}(\vec{u} - \overrightarrow{u_0})\right)\right]^2 dt$$

$$E(\omega, \vec{u} - \overrightarrow{u_0}) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} |S(\omega)|^2 \left|\frac{1}{N}\sum_{i=1}^{n} e^{j\omega\,\vec{r_i}(\vec{u} - \overrightarrow{u_0})}\right|^2 d\omega$$

But, since $\boldsymbol{\omega}\,\boldsymbol{u_0} = \boldsymbol{k_0}$

$$E(\omega, \vec{k} - \overrightarrow{k_0}) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} |S(\omega)|^2 \left|\frac{1}{N}\sum_{i=1}^{n} e^{j\vec{r_i}(\vec{k} - \overrightarrow{k_0})}\right|^2 d\omega$$

Plane wave parameter determination IV: Beam forming: a different view by switching domains

$$E(\omega, \vec{k} - \overrightarrow{k_0}) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} |S(\omega)|^2 \left|C(\vec{k} - \overrightarrow{k_0})\right|^2 d\omega$$

Energy of the ARRAY BEAM for a plane wave with slowness s_0. F-K POWER SPECTRAL DENSITY

$$\left|C(\vec{k} - \overrightarrow{k_0})\right|^2 = \left|\frac{1}{N} \sum_{i=1}^{n} e^{j\vec{r}_i(\vec{k} - \overrightarrow{k_0})}\right|^2$$

ARRAY TRANSFER FUNCTION

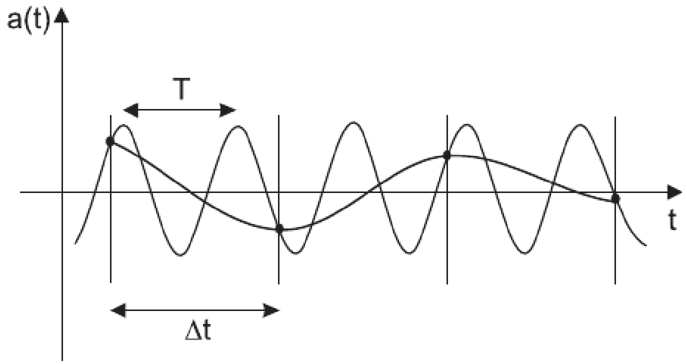
Array geometry and discrete sampling of a continuous wavefield

discrete spatial sampling of a continuous process consequences:

aliasing (sampling theorem) → at least 2 samples per period, wavelength

time domain $\Delta T < T_{min}/2$

spatial domain $\Delta x < \lambda^{\star}_{min}/2$

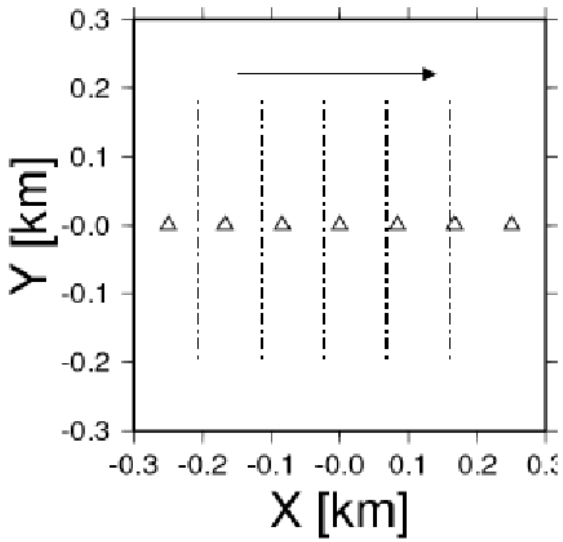


spectral resolution limit

time domain $\Delta\omega = 2\pi/((N-1)\Delta T)$

spatial domain $\Delta k = 2\pi/((N-1)d_{min}) = 2\pi/D_{max}$

Array response: starting simple 1D line of equidistantly space receivers



For the linear array example, we need only 2 parameters to describe array geometry:

- d_{min}: interstation distance;
- N: number of sensors → $(N-1)d_{min} = D_{max}$

D_{max} = Aperture

Station positions are then uniquely defined by $\vec{r_i} = i d_{min}$

$$\left|C(\vec{k} - \overrightarrow{k_0})\right|^2 = \left|C(\overrightarrow{k_x} - \overrightarrow{k_0})\right|^2$$

Array response: starting simple 1D line of equidistantly space receivers

$$\left|C(\vec{k}-\overrightarrow{k_0})\right|^2 = \left|\frac{1}{N}\sum_{i=1}^{n} e^{jid_{min}(\vec{k}_x-\overrightarrow{k_0})}\right|^2$$

The former expression is periodic in x-component, with period $2\pi/d_{min}$

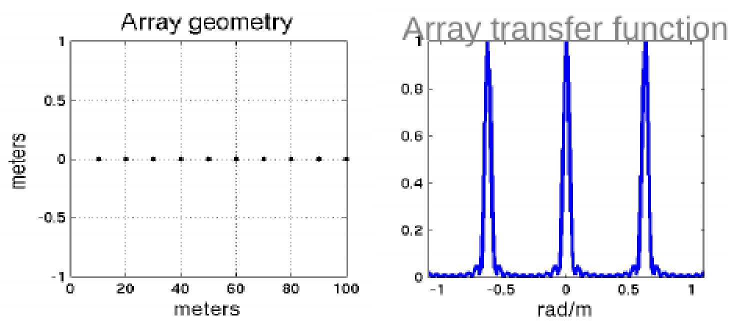
$$\left\{ \begin{array}{l} \exp\left(jid_{min}(\vec{k}_x-\overrightarrow{k_0})\right) = \exp\left(j(id_{min}(\vec{k}_x-\overrightarrow{k_0})+2\pi\right) \\ id_{min}(\vec{k}_x-\overrightarrow{k_0}) = id_{min}(\vec{k}_x-\overrightarrow{k_0})+2\pi \xrightarrow{\text{yields}} (\vec{k}_x-\overrightarrow{k_0}) = (\vec{k}_x-\overrightarrow{k_0})+2\pi/\,id_{min} \end{array} \right\}$$

K_{max}(aliasing)= $2\pi/d_{min}$ ⟶ $\mathbf{k_{sidelobe}}$

$K_{min} = 2\pi/D_{max}$ ⟶ **Width of the main lobe**

Array response: starting simple 1D line of equidistantly space receivers

L=100m dx=10m

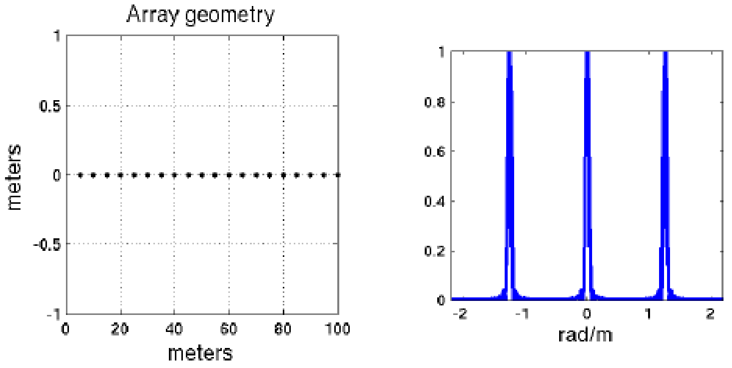


$$\left|C\left(\vec{k}-\vec{k_0}\right)\right|^2 = \left|\frac{1}{N}\sum_{i=1}^{n} e^{j i d_{min}\left(\vec{k}_x - \vec{k_0}\right)}\right|^2$$

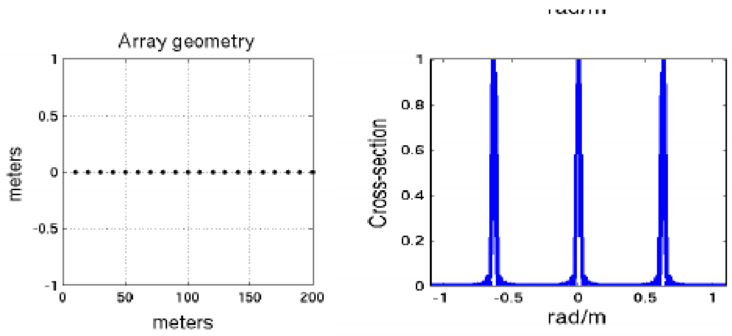
Kmax(aliasing)= $2\pi/d_{min}$

Kmin = $2\pi/D_{max}$

L=100m dx=5m



L=200m dx=10m

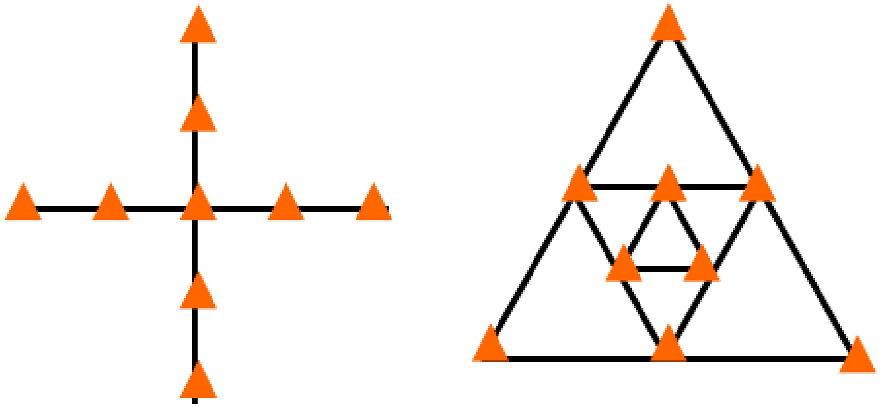


$K_{aliasing}$ pushed towards higher wavenumber

Narrow central lobe
=> resolution is improved

Array response: 2D situation
Planar arrays

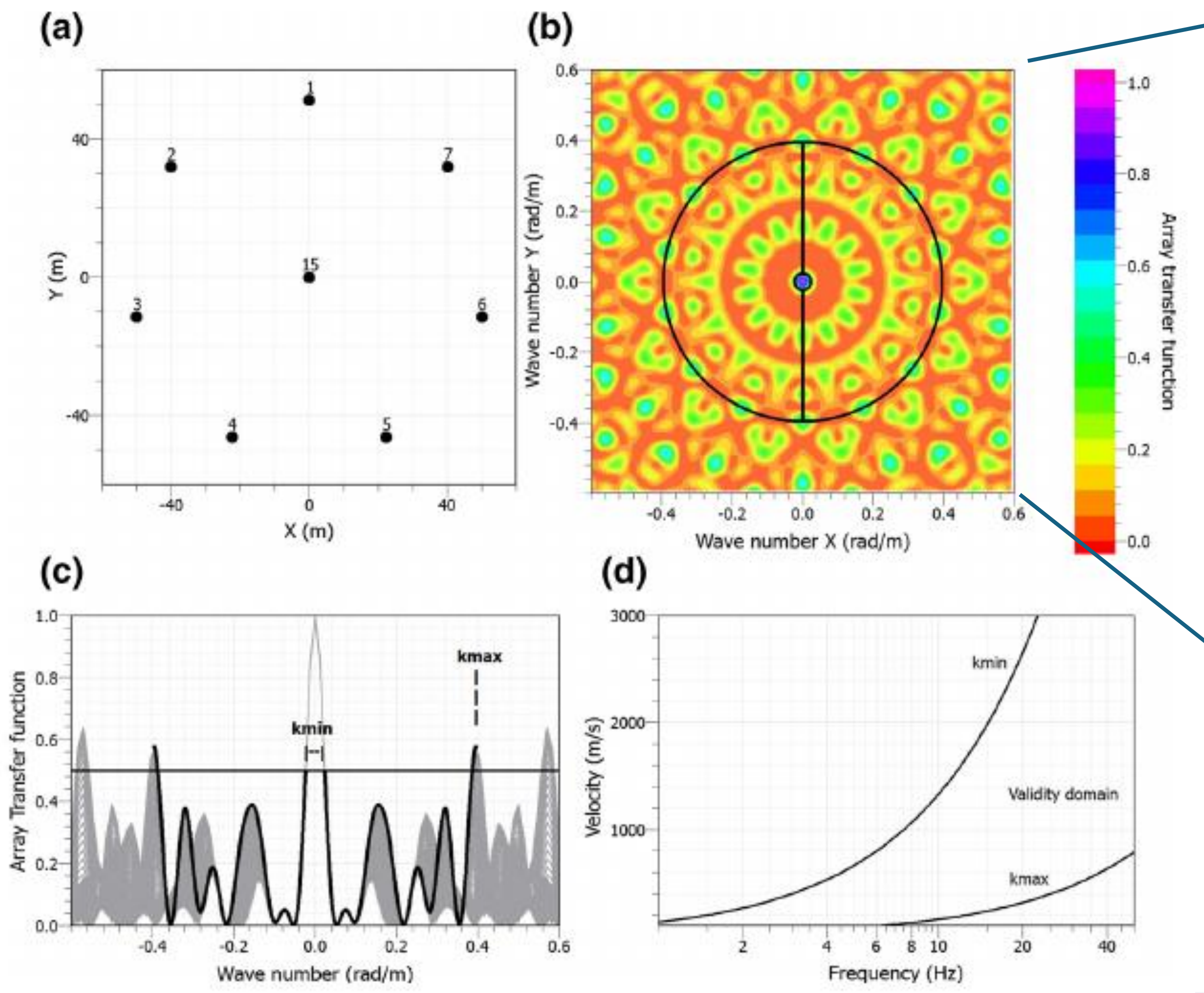
Parameter meaning less clear: how do d_{min}, N, D_{max} (aperture) relate to ARF?

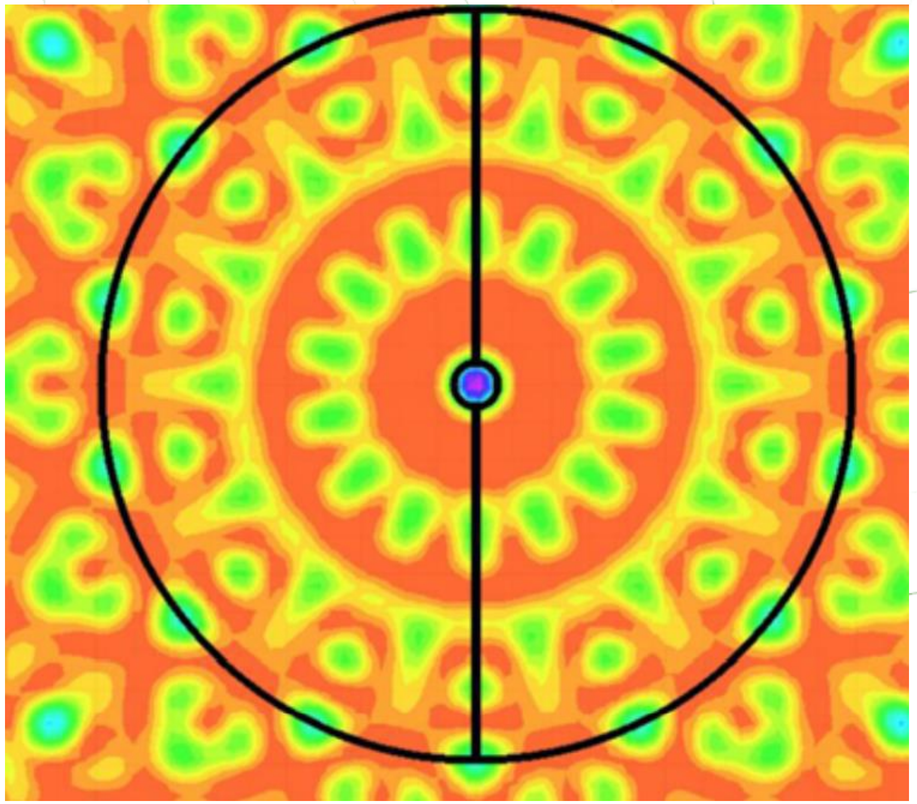


$$\left|C(\vec{k} - \vec{k_0})\right|^2 = \left|\frac{1}{N}\sum_{i=1}^{n} e^{jr_i(\vec{k} - \vec{k_0})}\right|^2$$

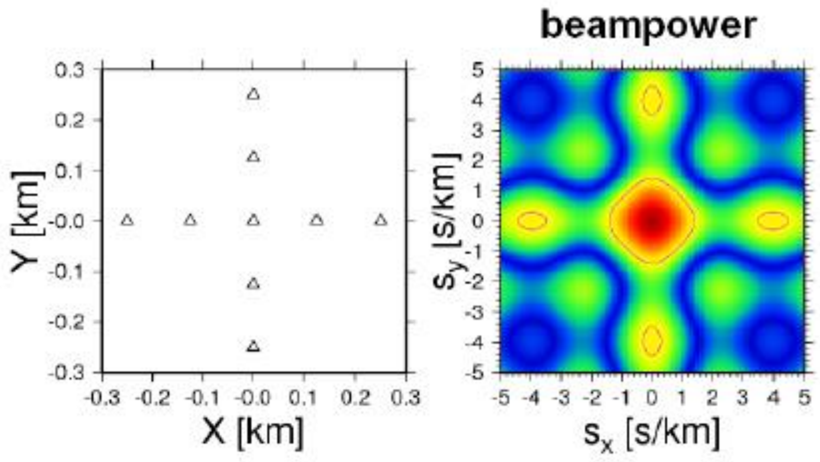
Array response: 2D situation
Planar arrays

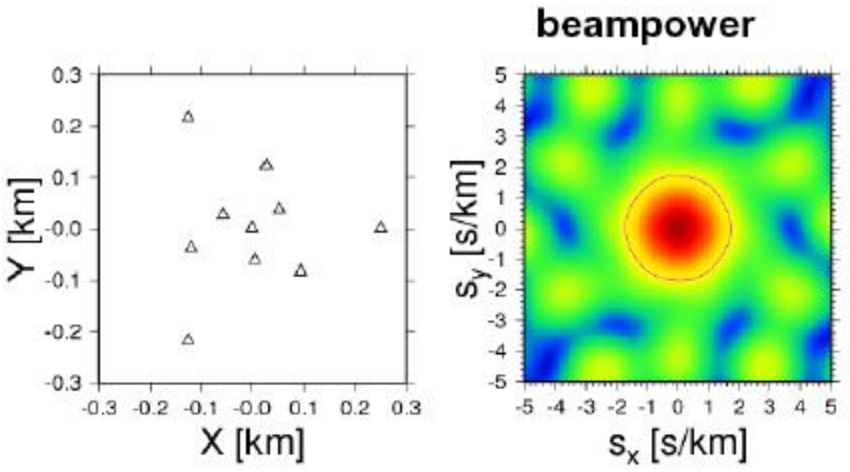
From **Foti et al.**, 2018, ***Bull. Earth. Eng***

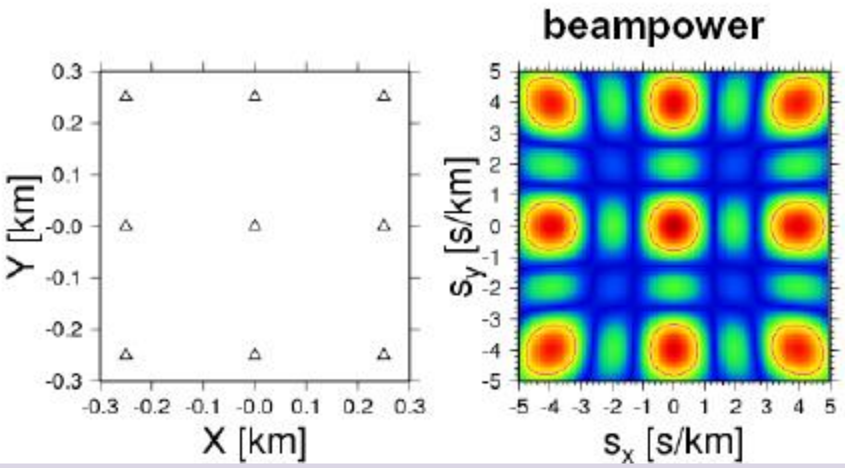


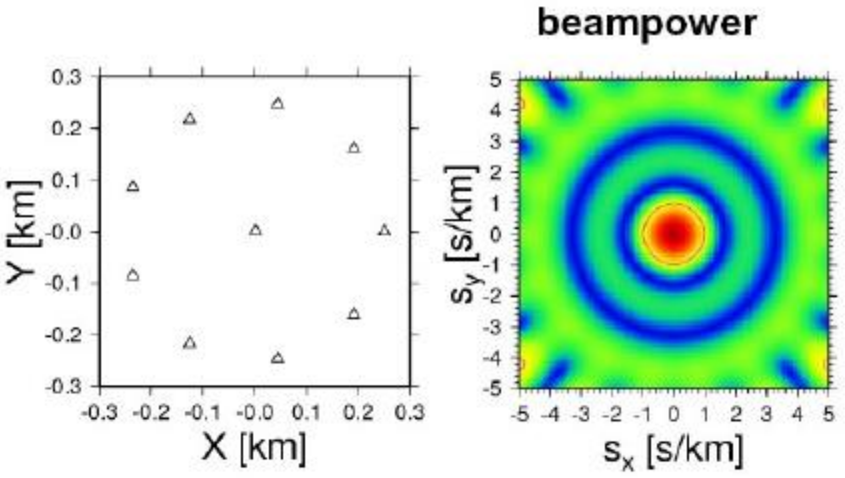


Array response: 2D situation
Planar arrays









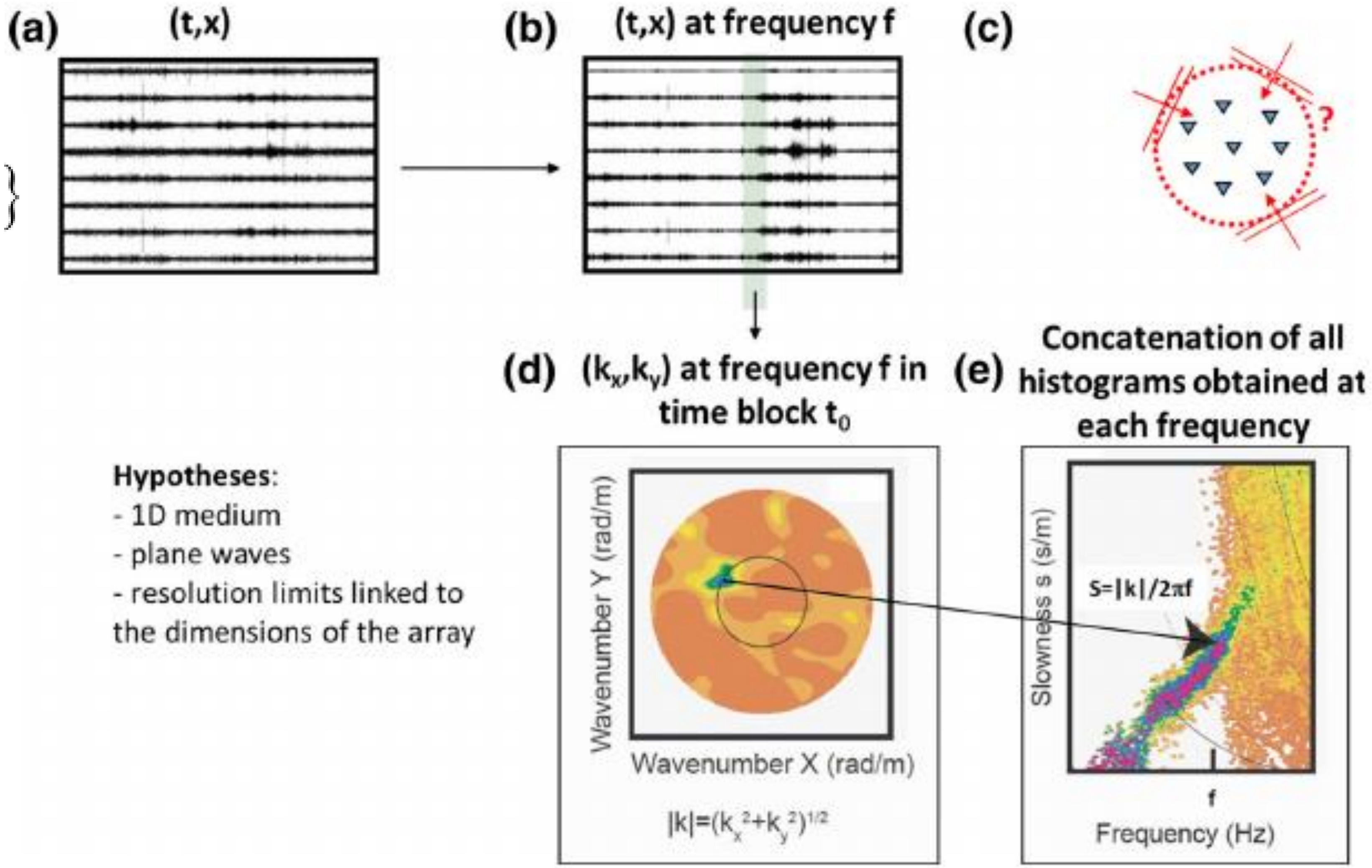
Array data processing: f-k beamforming

F-K SPECTRUM

$$P_b(f,k) = \sum_{l,m=1}^{n} \phi_{lm} \exp\{ik(X_l - X_m)\}$$

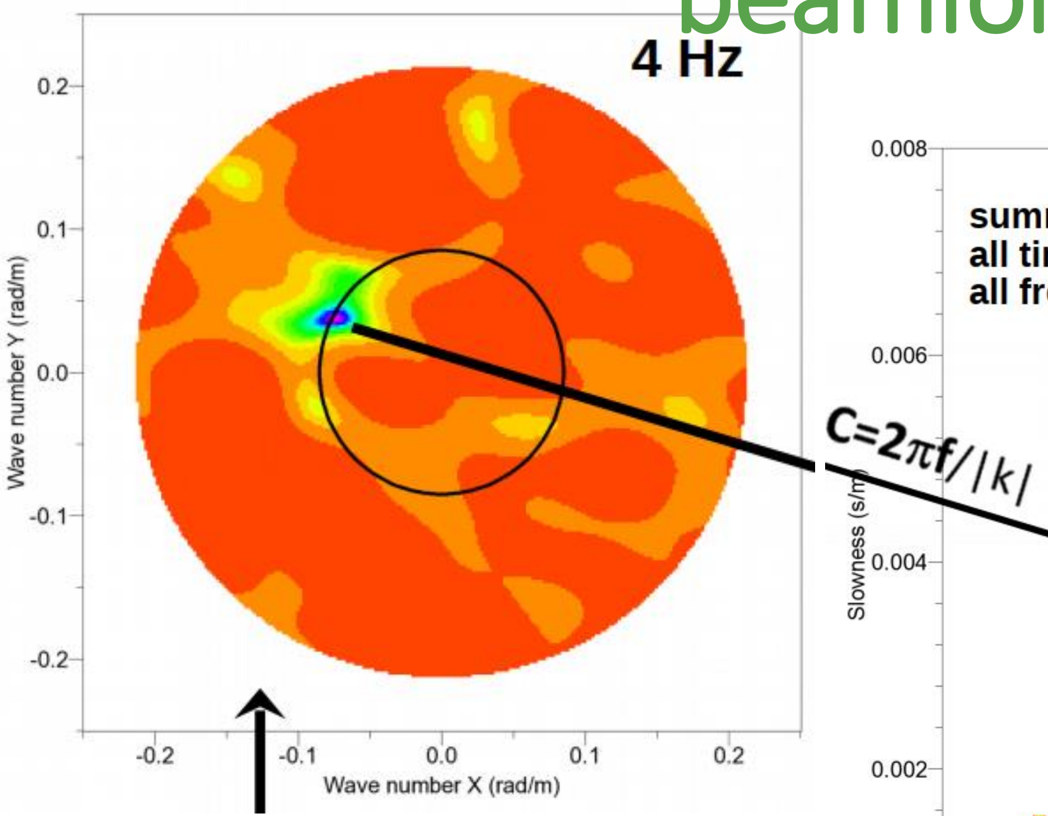
ϕ_{lm} CROSS POWER SPECTRUM BETWEEN RECORDINGS AT L AND M

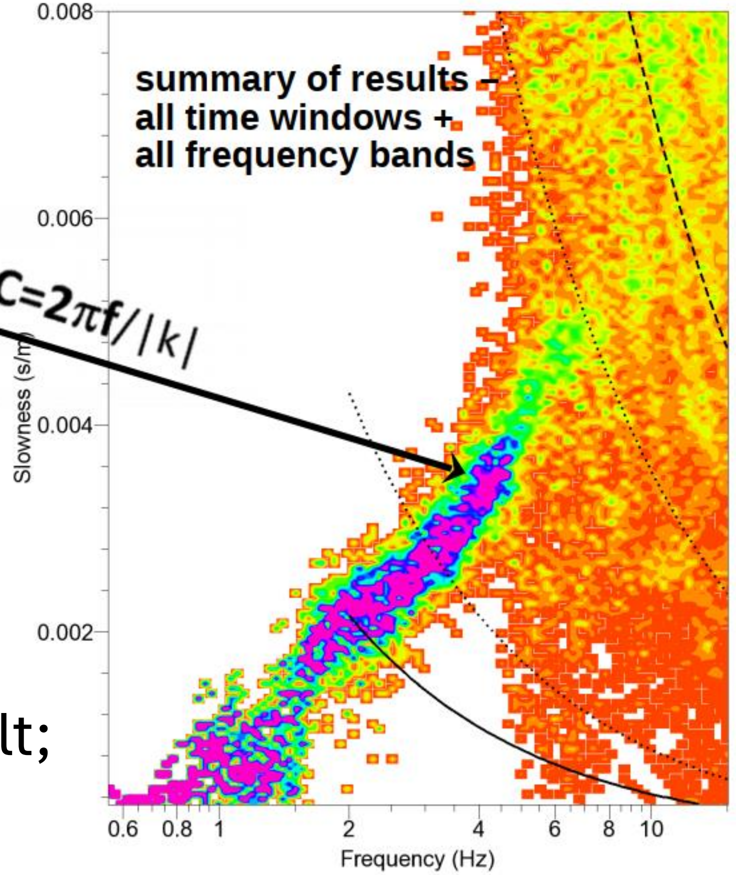
x_L, x_M COORDINATES



From **Foti et al.**, 2018, ***Bull. Earth. Eng***

Array data processing: f-k beamforming

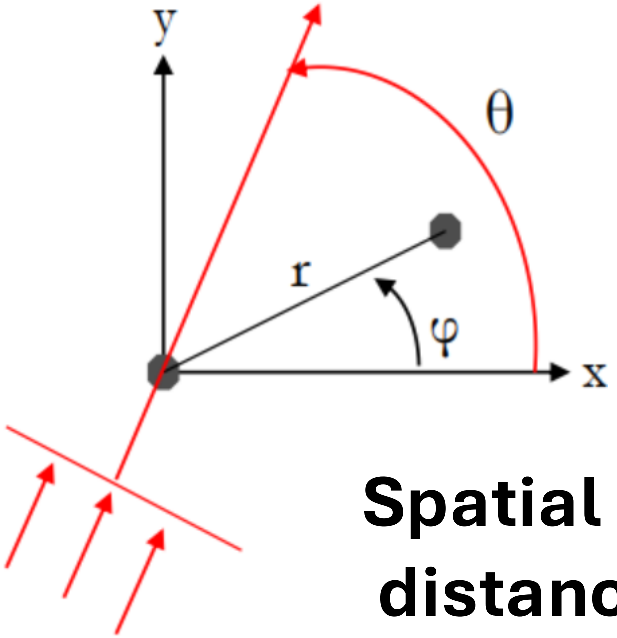




$$\theta = atan(u_x/u_y)$$

Single time window f-k analysis result;
center frequency 4Hz
bandwidth as fraction
of center frequency

Array data processing: SPAC
Spatial Autocorrelation (Aki, 1957)



Assumption: stochastic stationary wave field, both in space and in time

Spatial correlation function between two sensors located at distance r

$$\phi(r,\varphi) = \langle u(x,y,t) \cdot u(x + r\cos\varphi, y + r\sin\varphi, t) \rangle_t$$

$$\phi(r, \varphi) = \frac{1}{T} \int_0^T u(x,y,t)u^*(x + r\cos\varphi, y + r\sin\varphi, t)dt$$

Array data processing: SPAC
Spatial Autocorrelation (Aki, 1957)

$$\phi(r) = \frac{1}{\pi}\int_0^\infty \phi(\omega) J_0\left(\frac{\omega}{c(\omega)} r\right) d\omega,$$

J_0 Bessel function: the argument depends on the phase velocity at a given frequency and receiver spacing

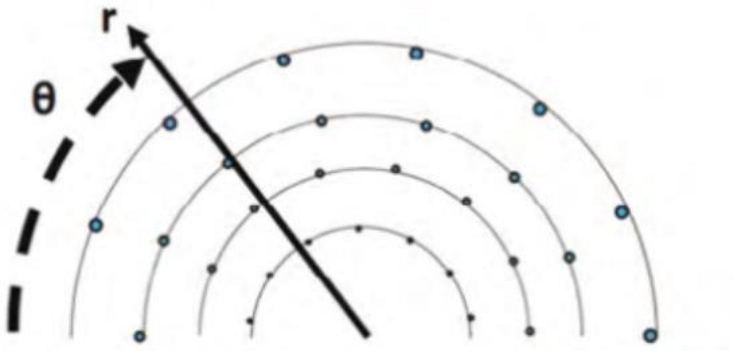
$\phi(\omega)$ Power spectrum, that is the spectrum of the temporal autocorrelation function $\phi(0,t)$

$$\phi(0,t) = \frac{1}{T}\int_0^T u(t')u^*(t'-t)dt'$$

$$\phi(r,\omega_o) = J_0\left(\frac{\omega_0}{c(\omega_0)} r\right)$$

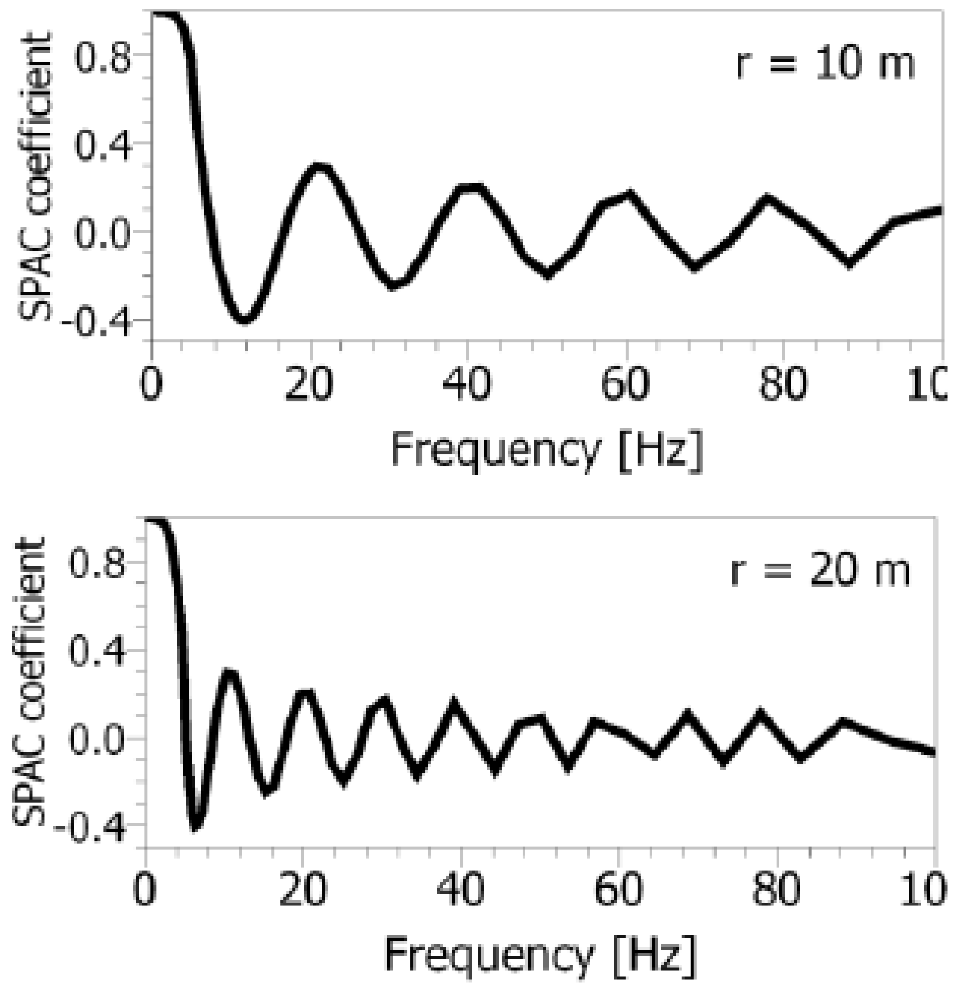
MEAN SPATIAL CORRELATION FUNCTION (normalized for the power spectrum) FOR AN ANGULAR FREQUENCY ω_0

Array data processing: SPAC
Spatial Autocorrelation (Aki, 1957)



$$\phi(r,\omega_o) = J_0\left(\frac{\omega_0}{c(\omega_0)} r\right)$$

By calculating the azimuth mean from the spatial correlation function (averaging for pairs of stations that have equal inter-station distances to each other but different azimuths), **directionally independent correlation coefficients** can be expressed using Bessel functions.



Array data processing: SPAC Spatial Autocorrelation (Aki, 1957)

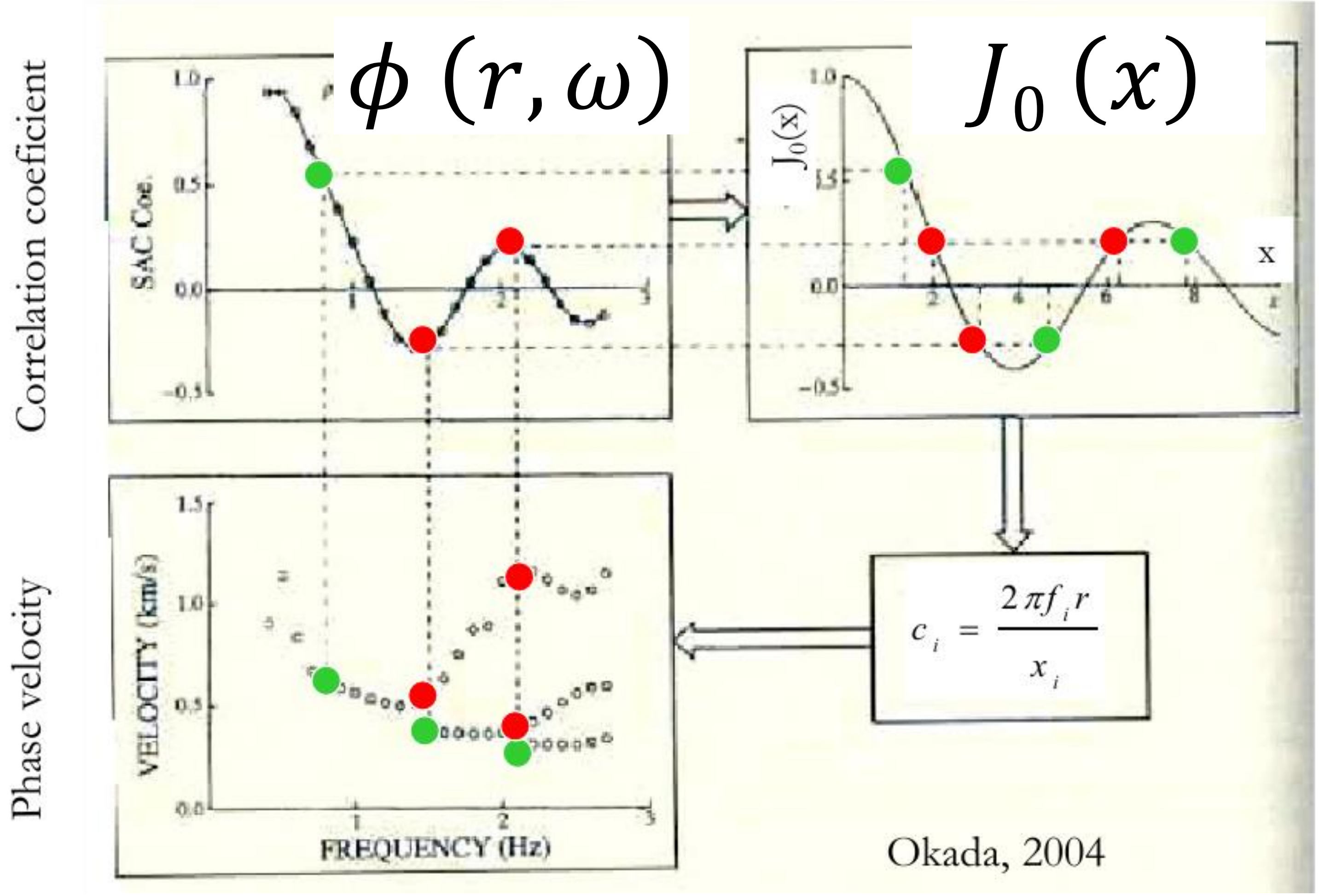
In the time domain

- Compute the Fourier transform of signals
- Narrow band-pass filter around w_0
- Inverse Fourier transform and computation of correlation
- Azimuthal averaging of the correlation coefficient

In the frequency domain

- Compute the cross-spectra normalized by the autospectra
- Azimuthal averaging on the real part of the cross-spectra

Array data processing: SPAC
Spatial Autocorrelation (Aki, 1957)



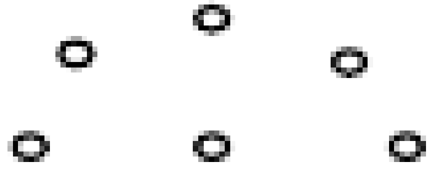
MEASURE

$\phi\,(r,\omega) = J_0\,(x)$

TARGET

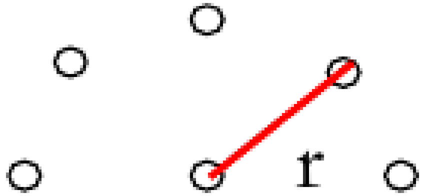
$$x = \frac{2\pi f}{c(f)}$$

Array data processing: SPAC
Spatial Autocorrelation (Aki, 1957)



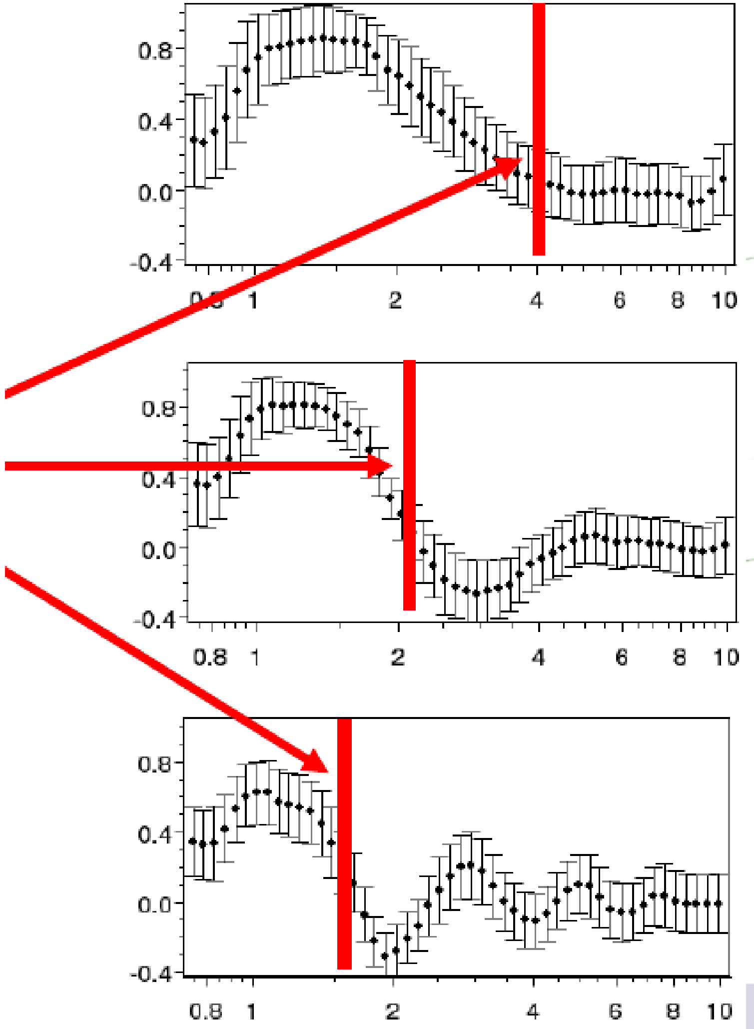
R=5 m

Non-uniqueness

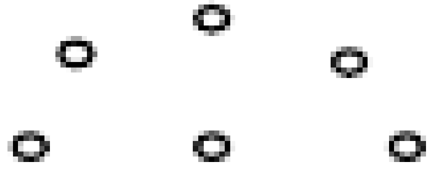


R=20 m

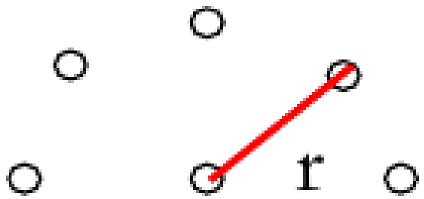
« real life »

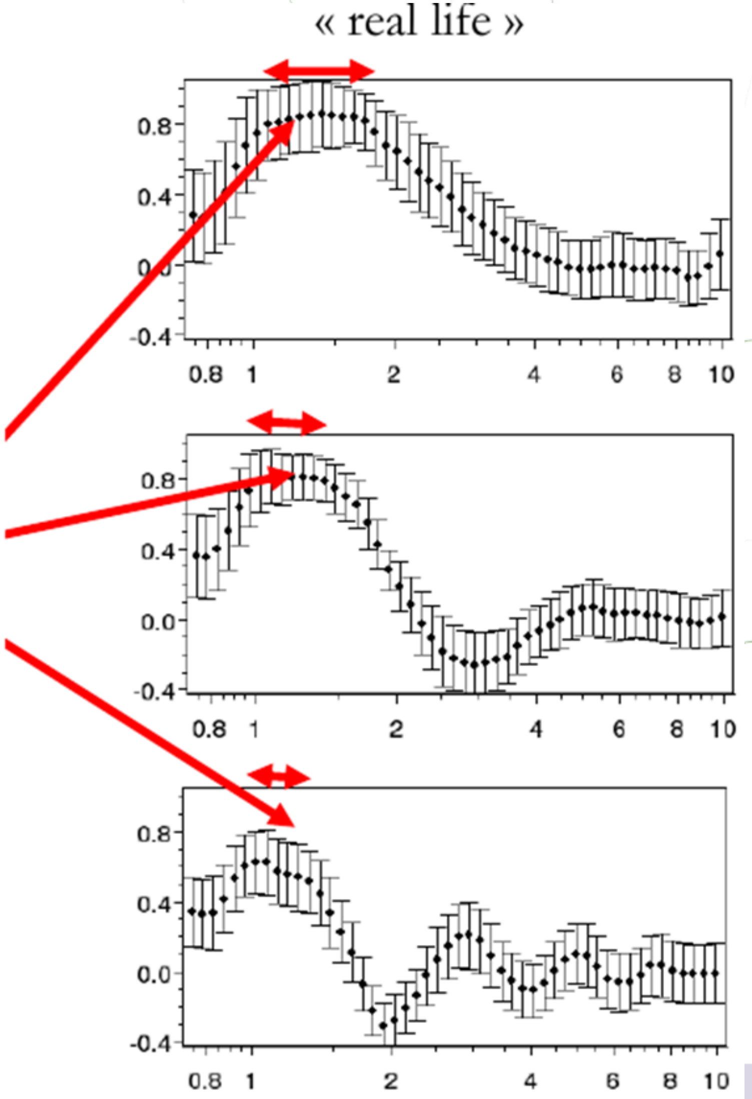


Array data processing: SPAC
Spatial Autocorrelation (Aki, 1957)

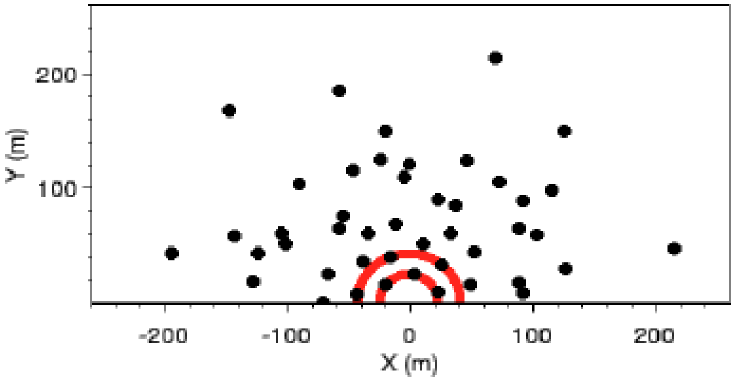


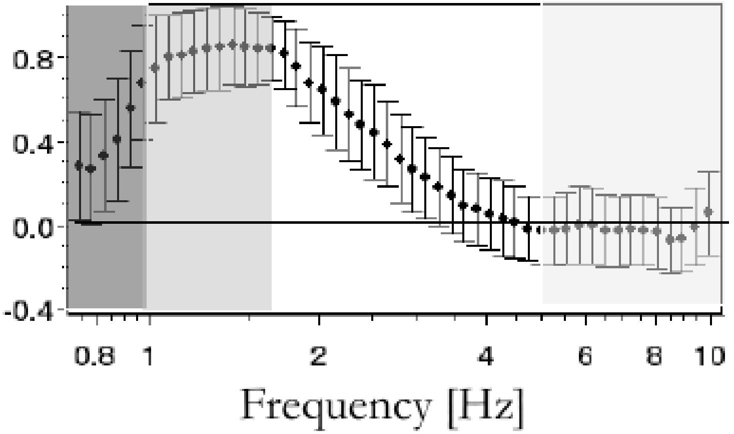
Lack of resolution





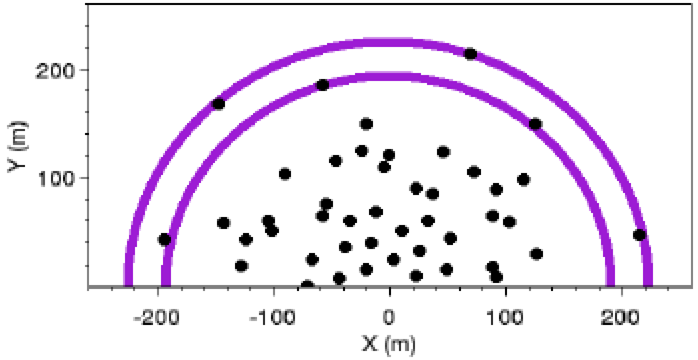
Array data processing: SPAC
Spatial Autocorrelation (Aki, 1957)

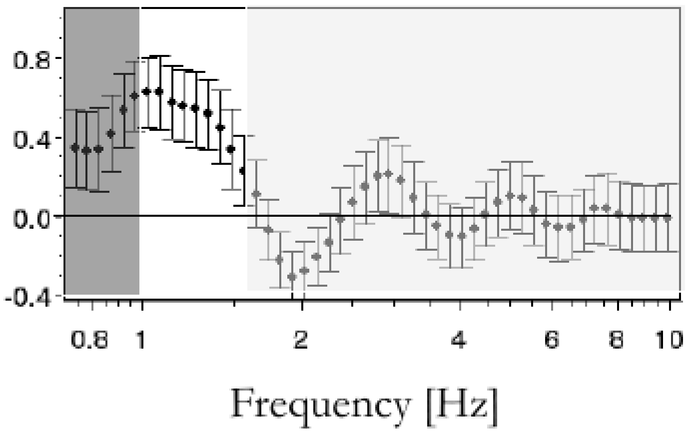




Smallest ring controls the non-uniqueness limit

⇔ location of f-k side lobes



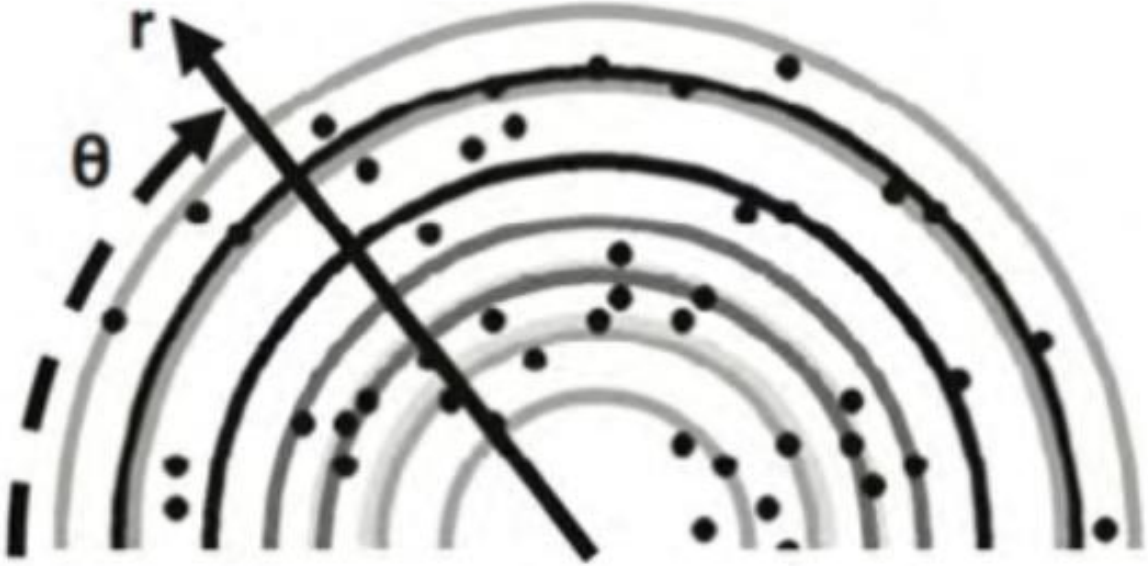


Largest ring controls the resolution

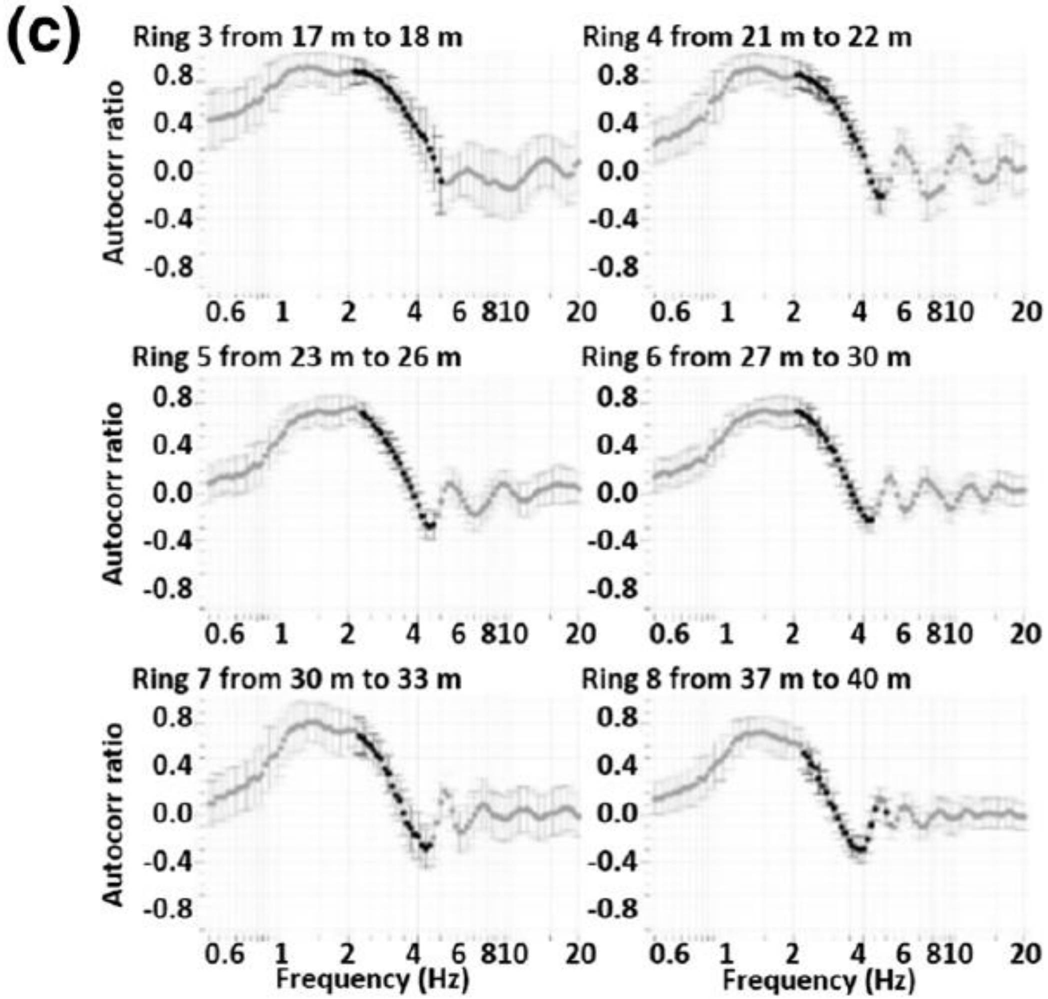
⇔ width of the f-k transfer function lobe

Array data processing: MSPAC
Modified Spatial Autocorrelation(Bettig et al., 2021)

From **Foti et al.,** 2018, ***Bull. Earth. Eng***

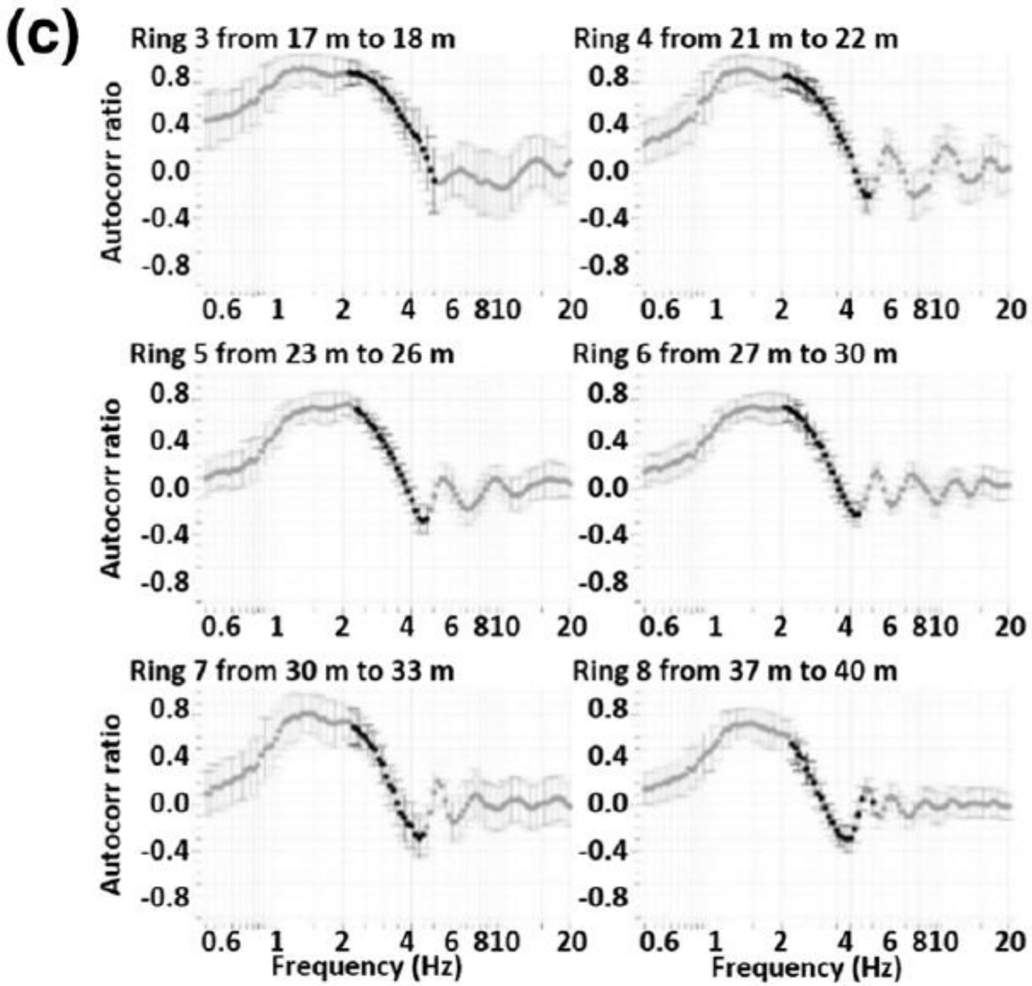


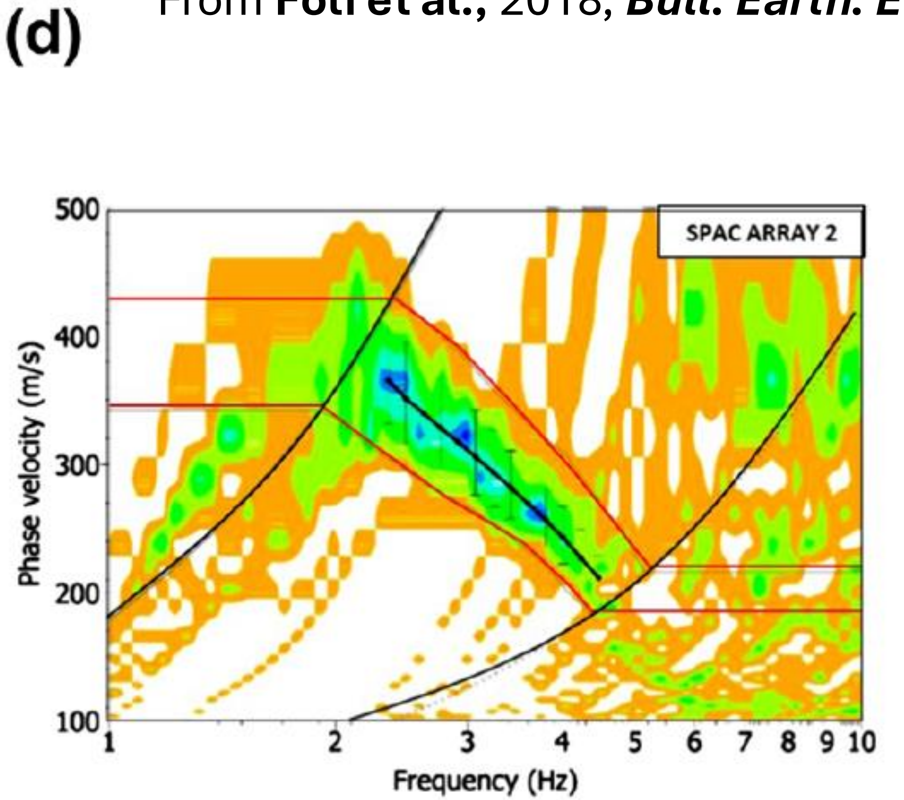
$$\phi(r,\omega_o) = J_0\left(\frac{\omega_0}{c(\omega_0)} r\right)$$



Array data processing: MSPAC
Modified Spatial Autocorrelation(Bettig et al., 2021)

From **Foti et al.,** 2018, ***Bull. Earth. Eng***





MSPAC vs SPAC

Advantages

- in urban areas: easier arrays realisation
- analysis of data sets suitable/optimized for FK
- broader frequency/wavelength range than SPAC (only 1 ring)

Disavantages

- less « precise » estimation than SPAC, especially for large thickness rings
- poor performance at high frequencies

Array data processing: ESAC
Extended Spatial Autocorrelation (Okada, 2003)

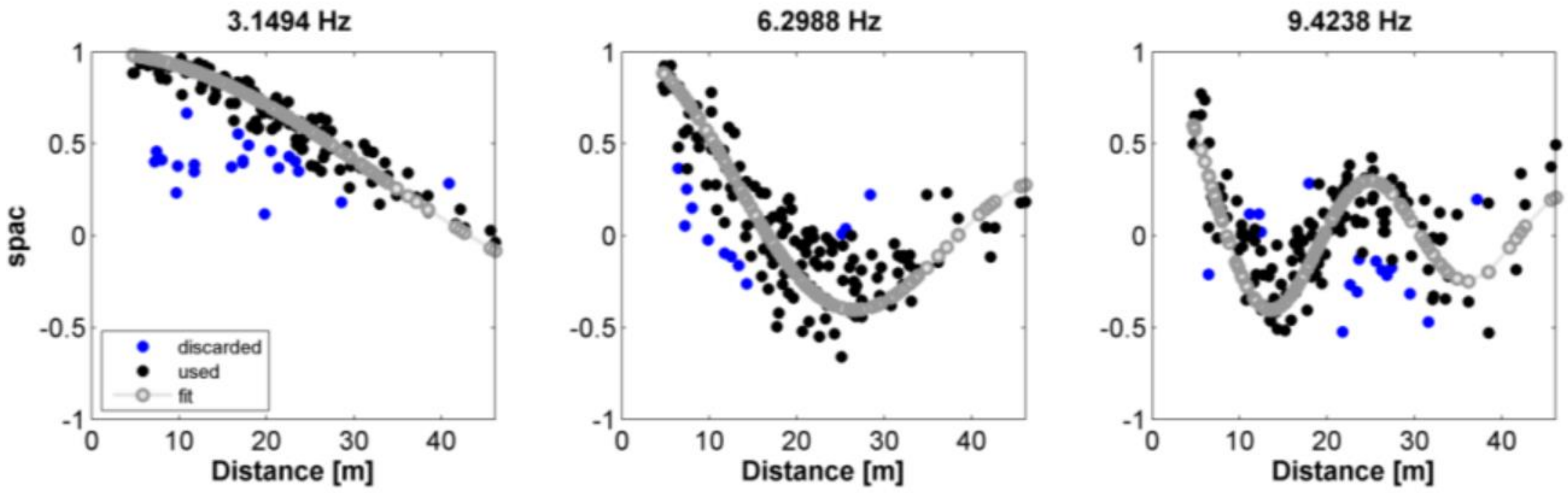
For each couple of stations:

$$\phi(\omega) = \frac{\frac{1}{M}\sum_{m=1}^{M} \mathrm{Re}\left({}_m S_{jn}(\omega)\right)}{\sqrt{\frac{1}{M}\sum_{m=1}^{M} {}_m S_{jj}(\omega) \sum_{m=1}^{M} {}_m S_{nn}(\omega)}}$$

MEASURE | TARGET

$$\phi(r,\omega_o) = J_0\left(\frac{\omega_0}{c(\omega_0)} r\right)$$

The signal is divided into M time segments. S_{jn} is the cross-power spectrum between station *j* and station *n*. M is the total number of segments used. S_{jj} and S_{nn} represent the power spectra at the two stations.



Main differences between FK and SPAC/MSPAC/ESAC

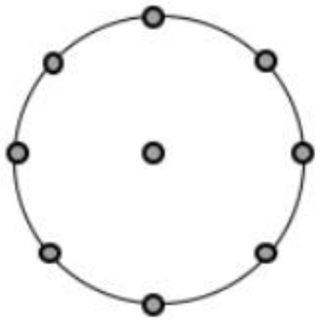
FK

- plane wave propagation
- one single source (or few uncorrelated sources)
- direct measure of phase delay

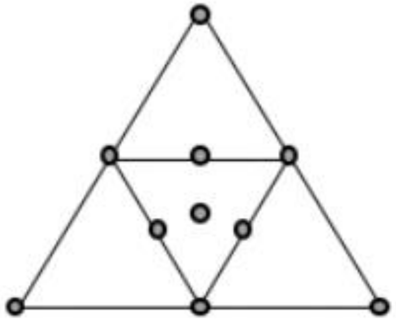
SPAC

- plane wave propagation
- large number of uncorrelated sources spatially and temporally randomly distributed
- measure of spatial (de-)coherency of waveforms

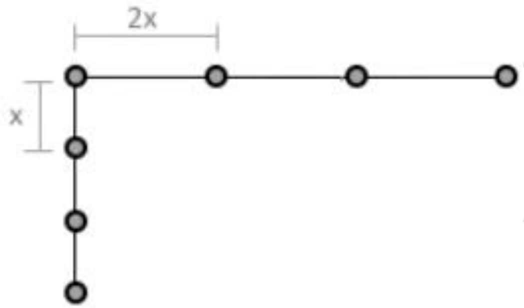
Practical indications: possible array geometries



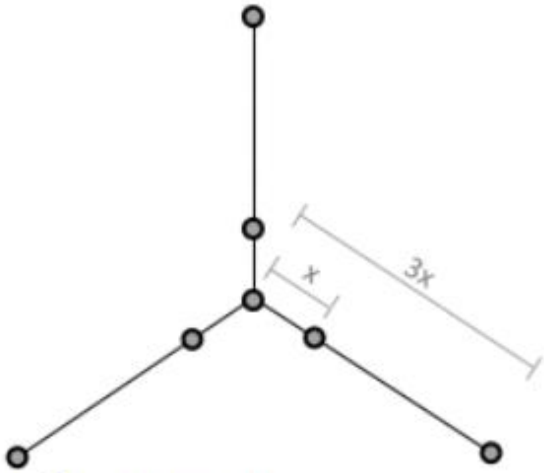
Circular shape



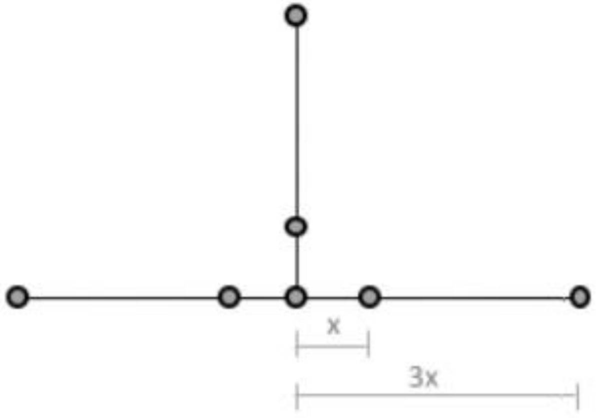
Nested triangles



L- shape



Sparse Nested triangles



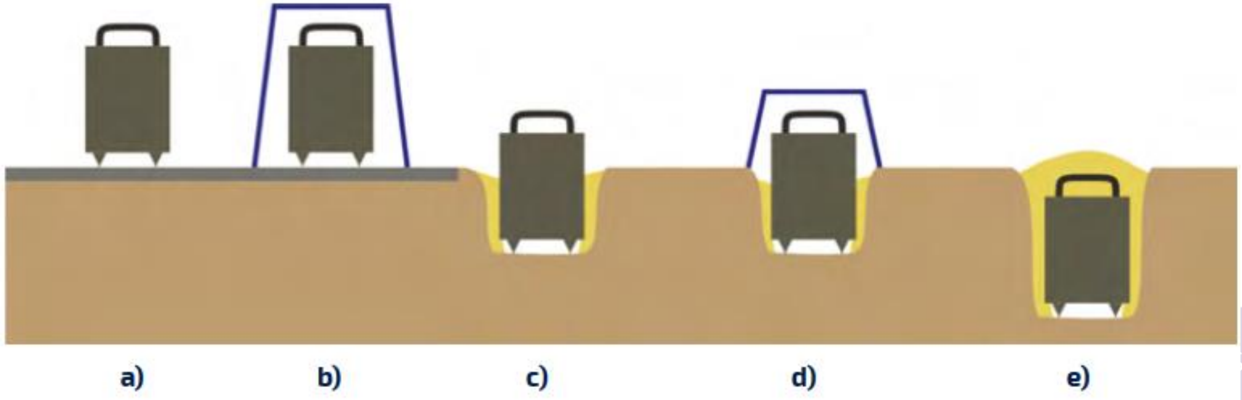
T- shape

Practical indications: which sensors and where

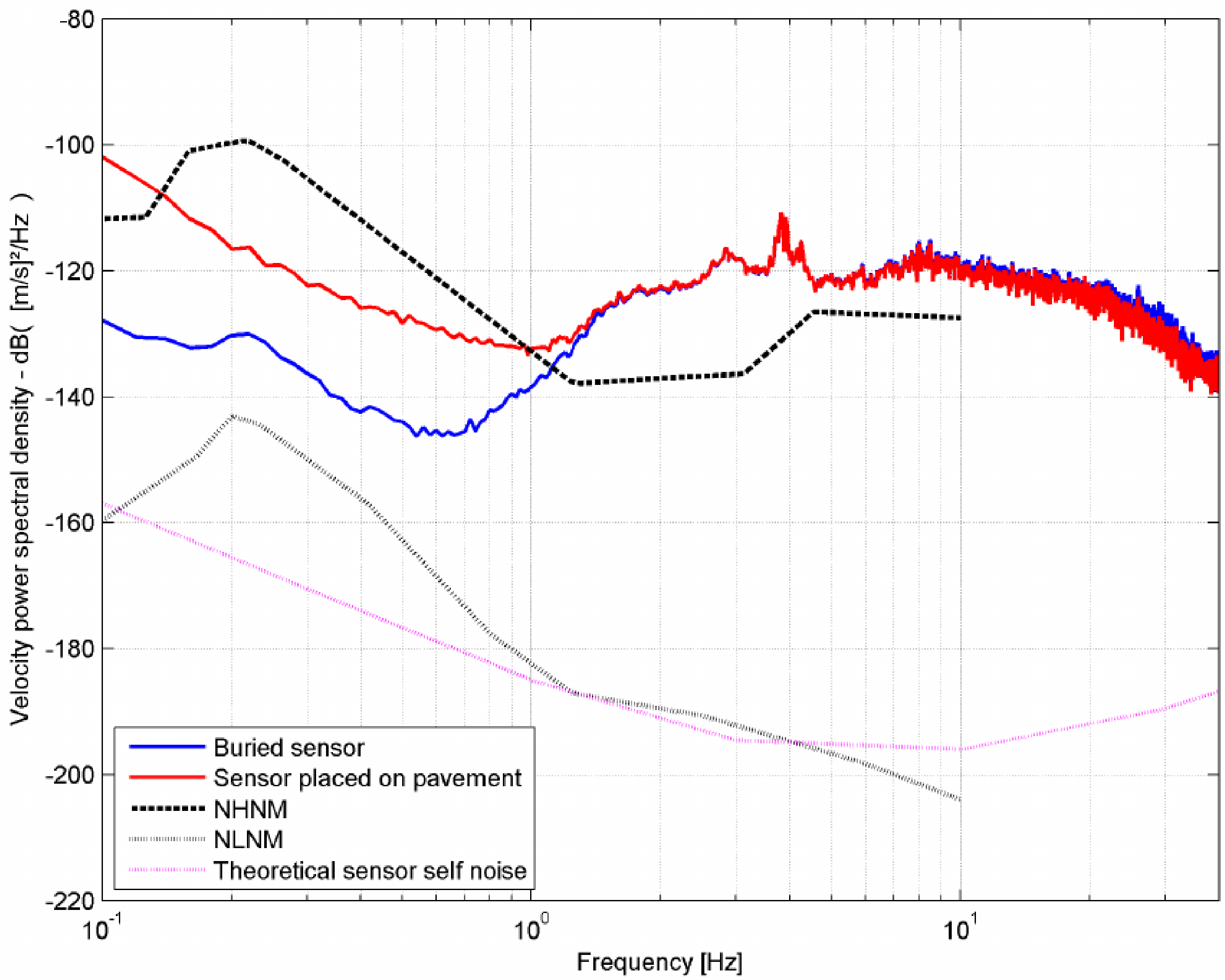
30 s seismometer (on the left)

4.5 Hz vertical geophone (on the right)

Number: the higher, the better



Practical indications: which sensors and where



Practical indications: acquisition parameters

Sampling frequency

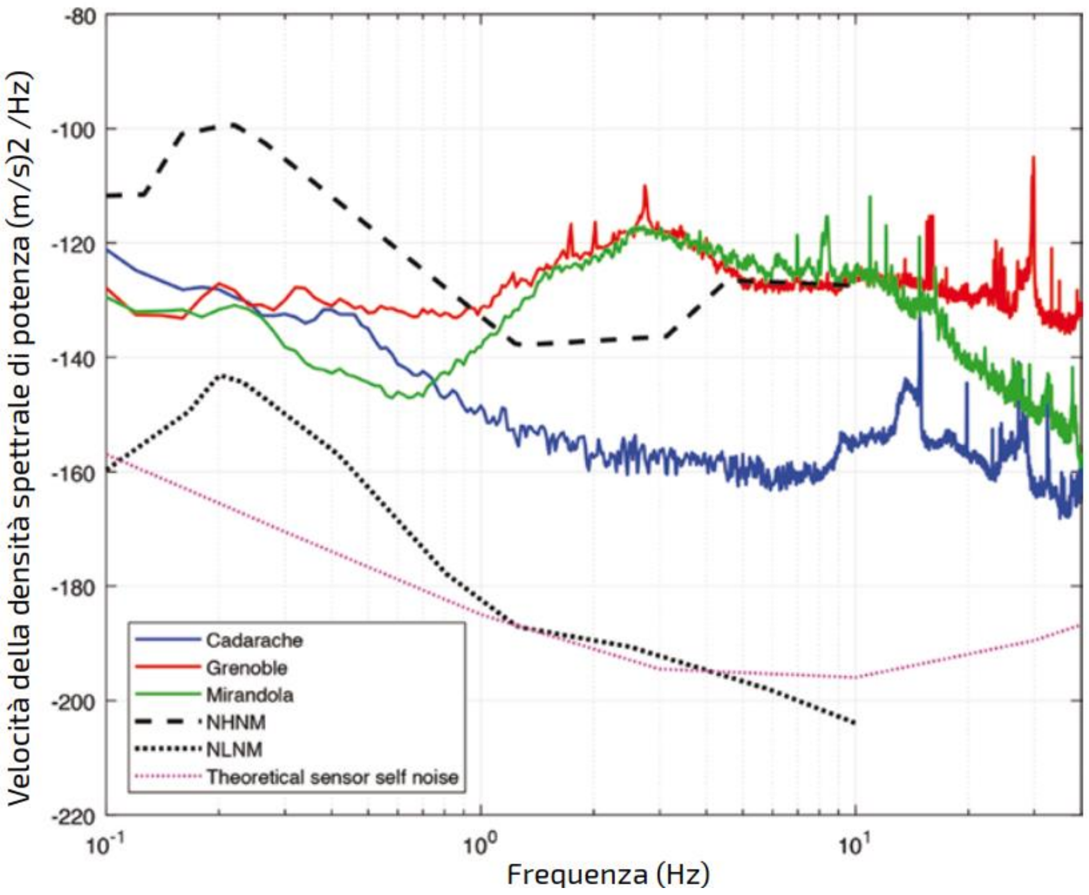
- 100 Hz - 200 Hz (Nyquist 50 Hz – 100 Hz)

Temporal windows

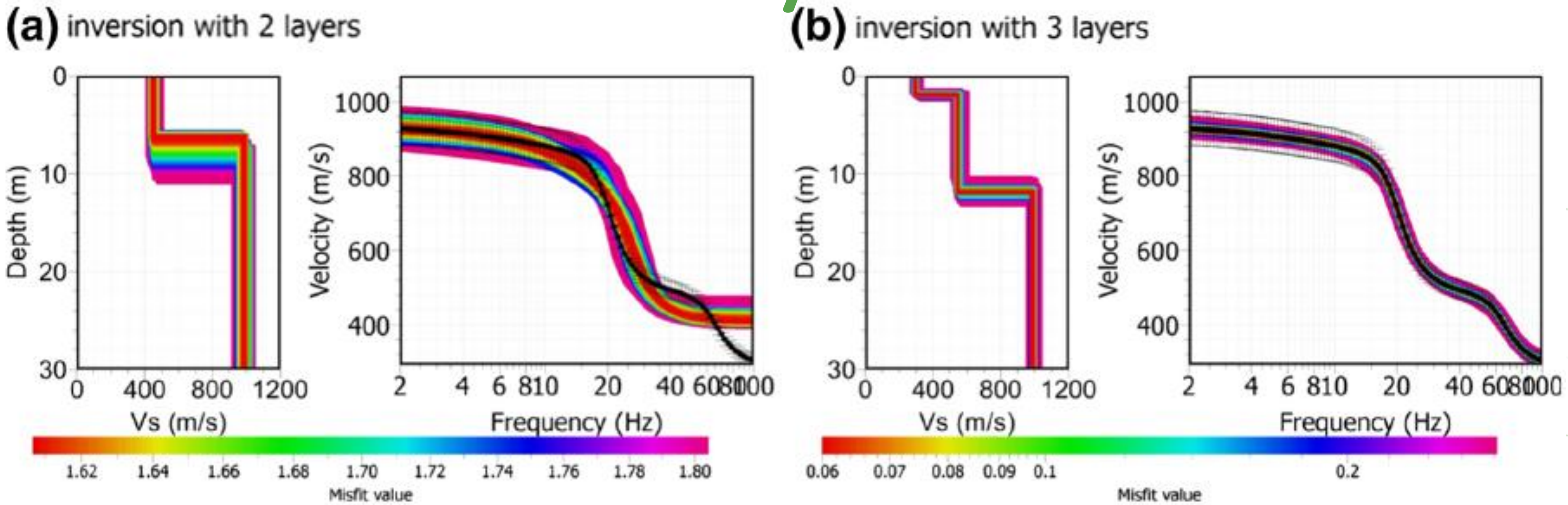
- Long duration recordings (30-120 minutes) are collected and then splitted into shorter ones (1-5 minutes) for data analyses

Practical indications: general tips

1)Avoid measurements near strong vibration sources;
2) Verify, preliminarily, the power spectral density of the signal, compared to instrumental noise



From dispersion curve to 1-D velocity model

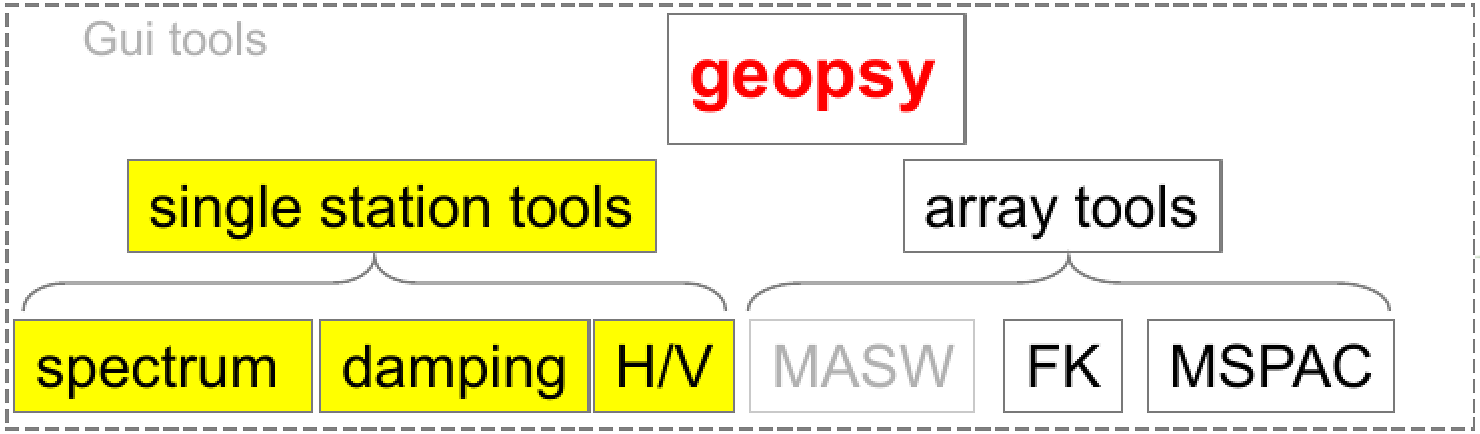


$$V_{S,30} = V_{R,[40-45]}$$

$$V_{S,30} = \frac{30m}{\sum_{i=1}^{N} \frac{H_i}{V_{S_i}}}$$

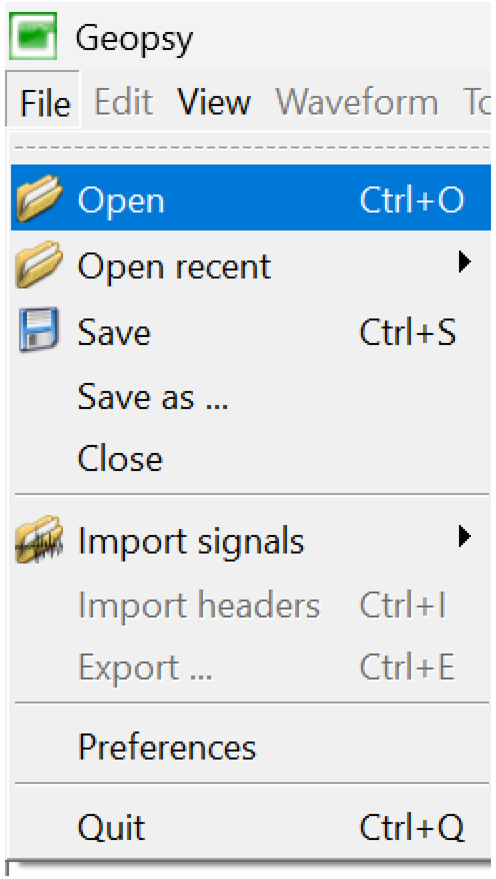
Relations between $V_{S,30}$ and phase velocity of fundamental mode of Rayleigh wave for λ between 40 m e 45 m.

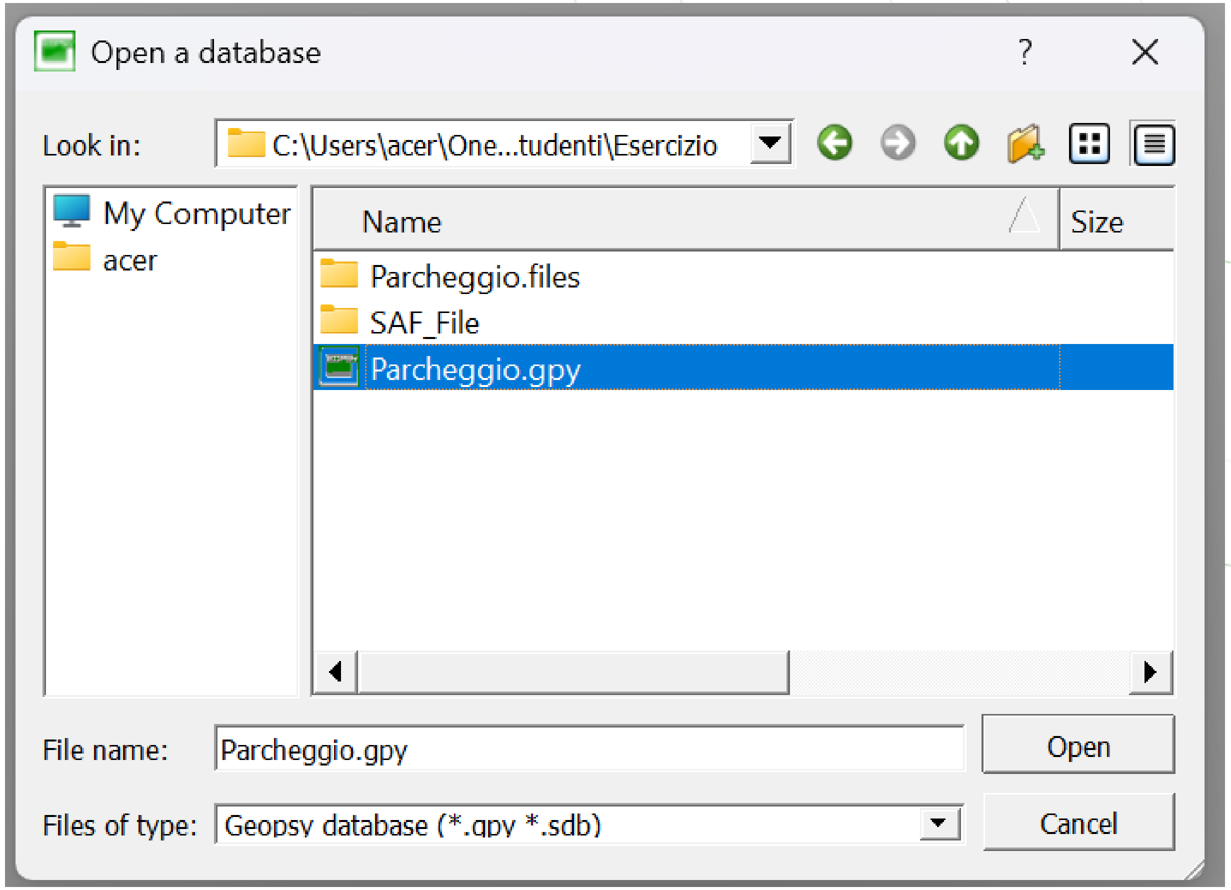
Practicing with GEOPSY and HV analysis



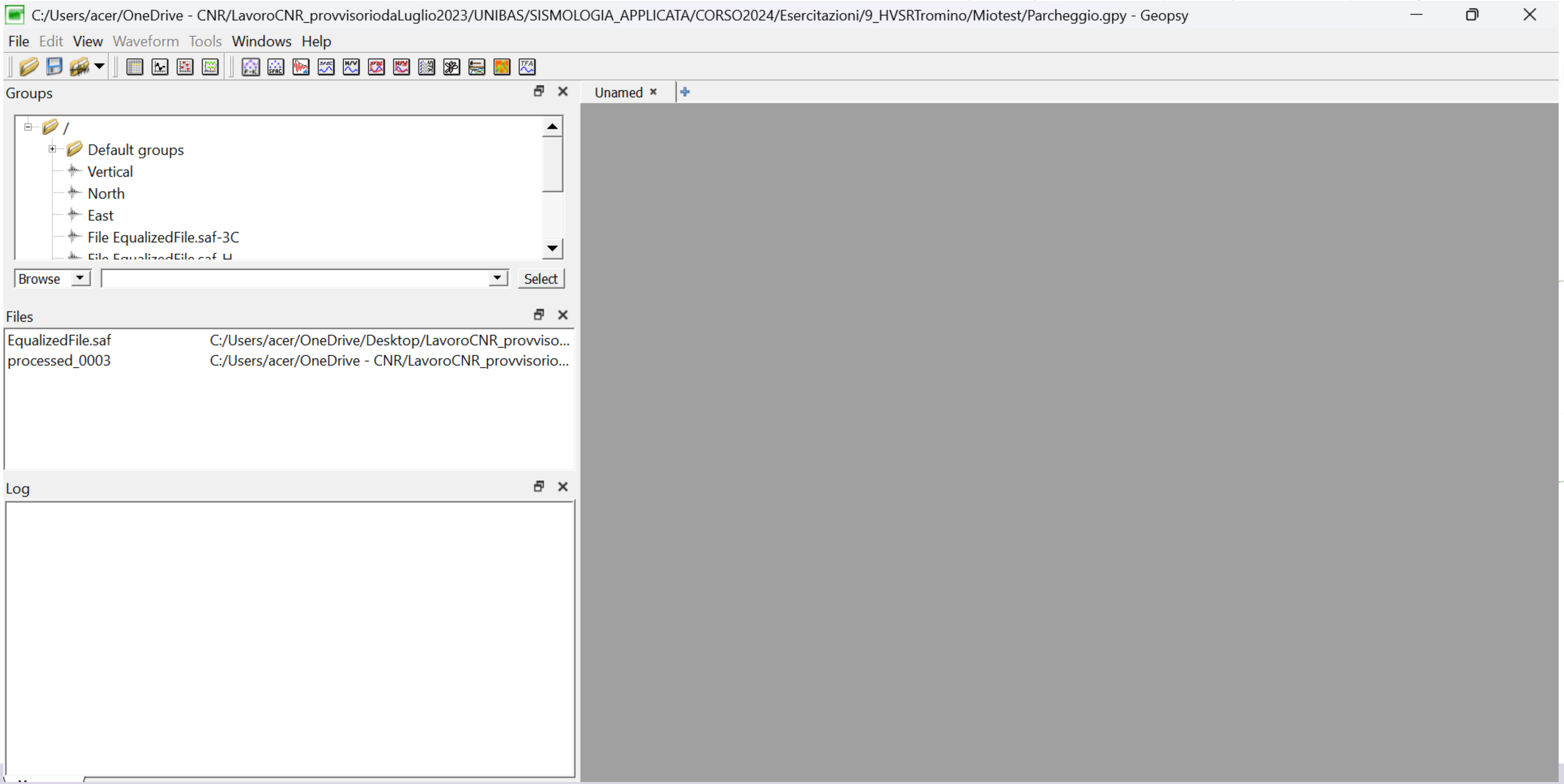
Geopsy is a graphical user interface for organising, viewing, and processing geophysical signals

Opening a database

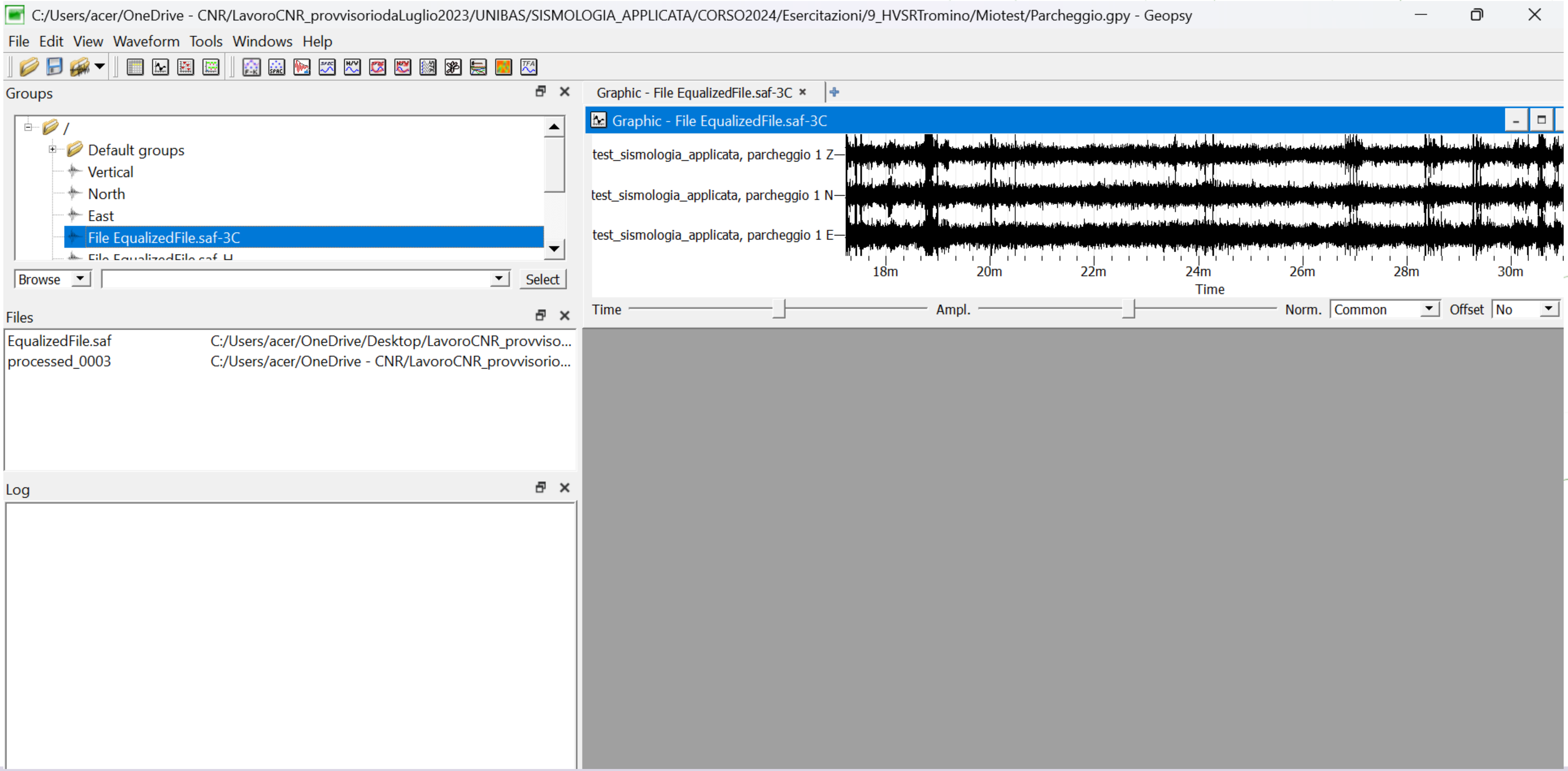




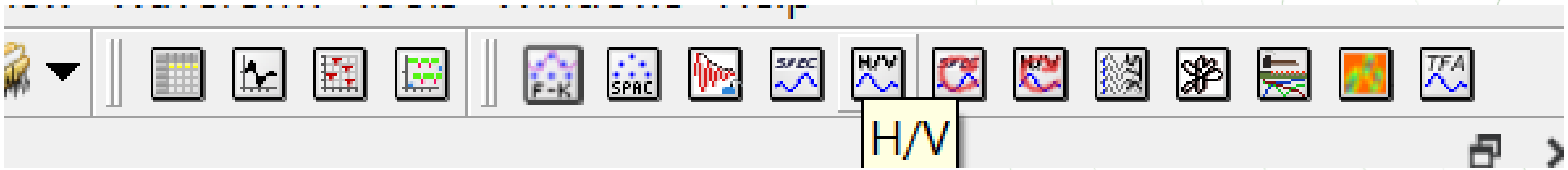
Opening a database

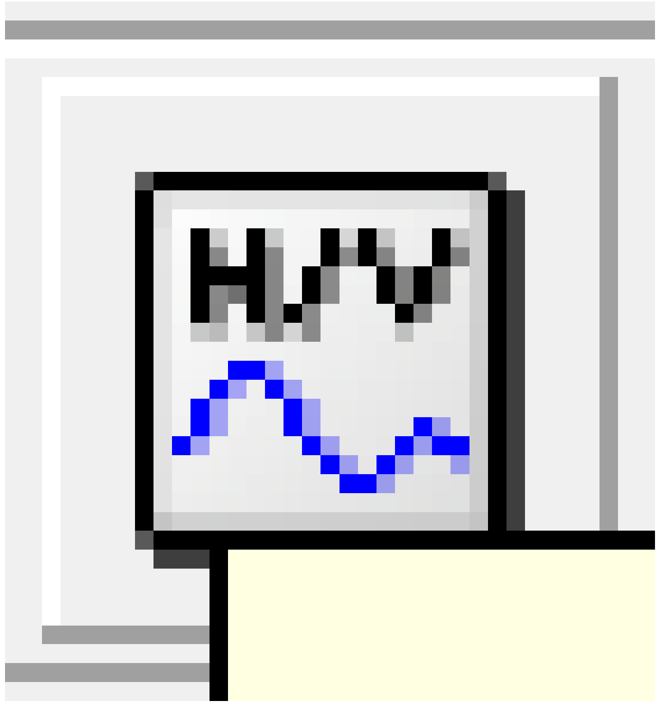


Moving in the graphic interface



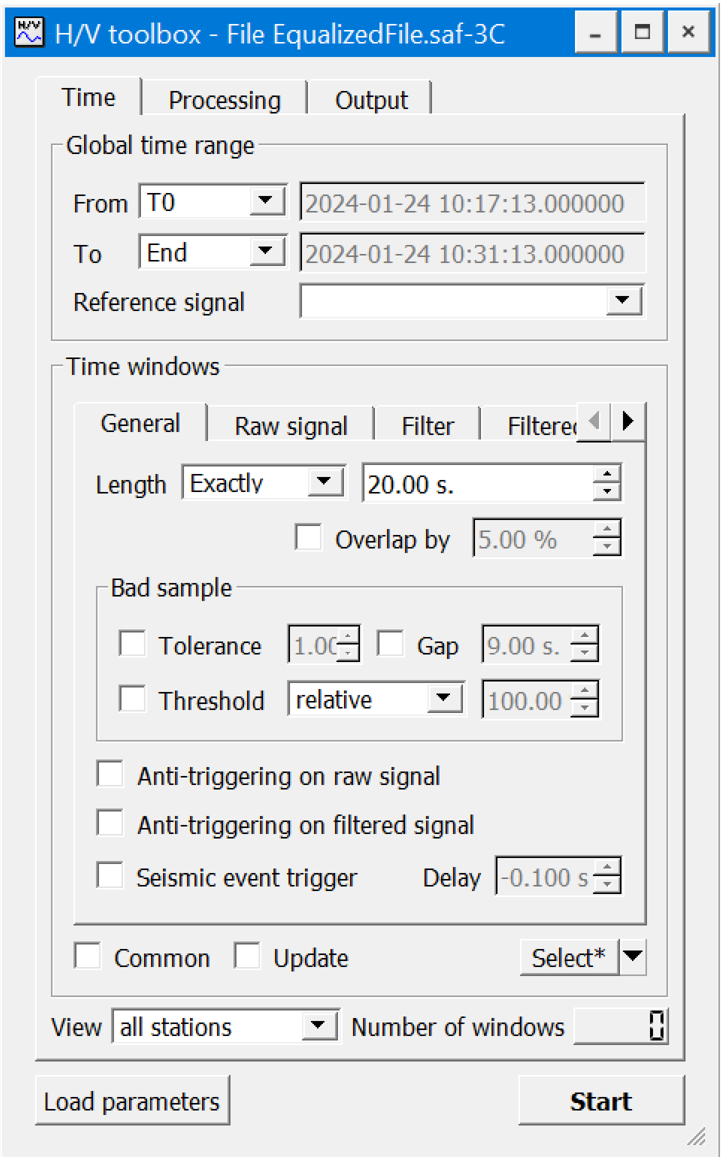
HV processing toolbox

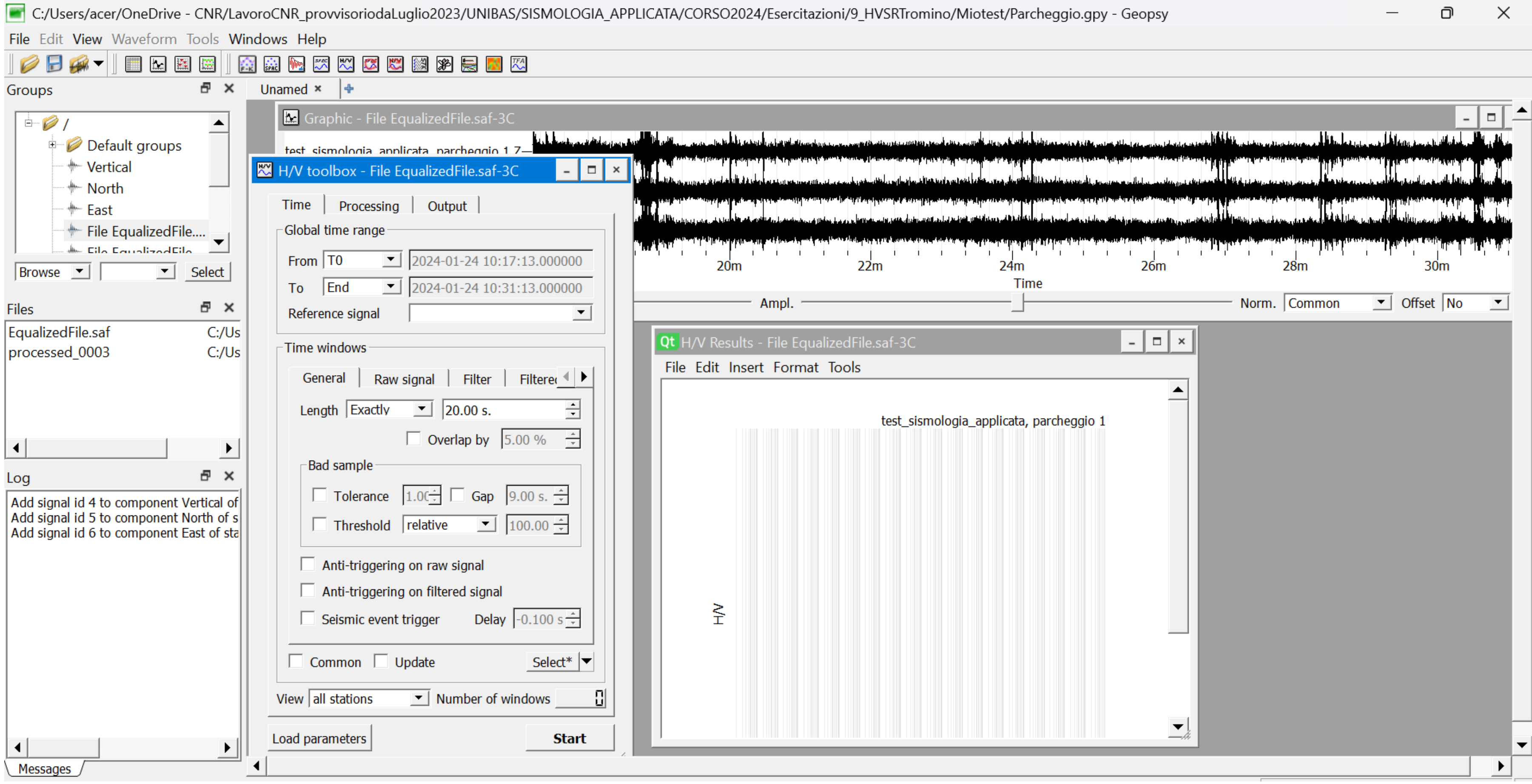




H/V tool

HV processing toolbox





Processing HV curve

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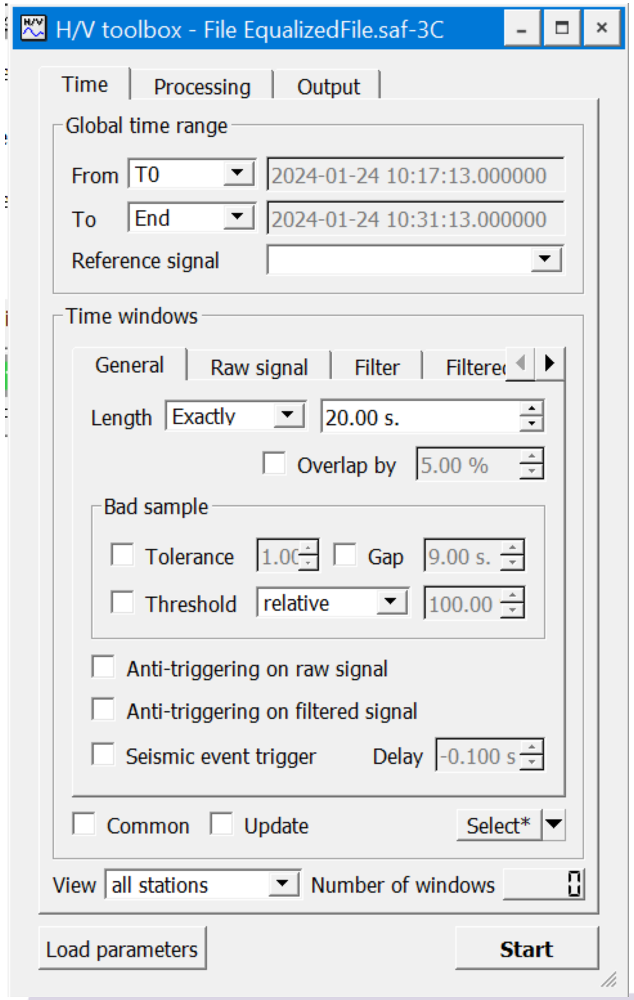
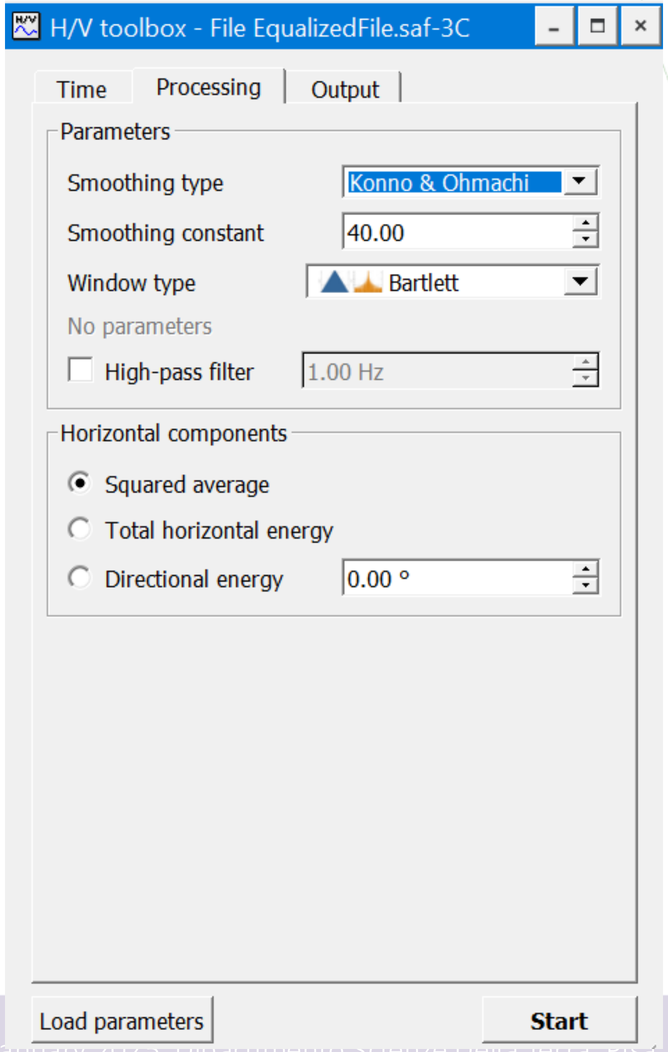
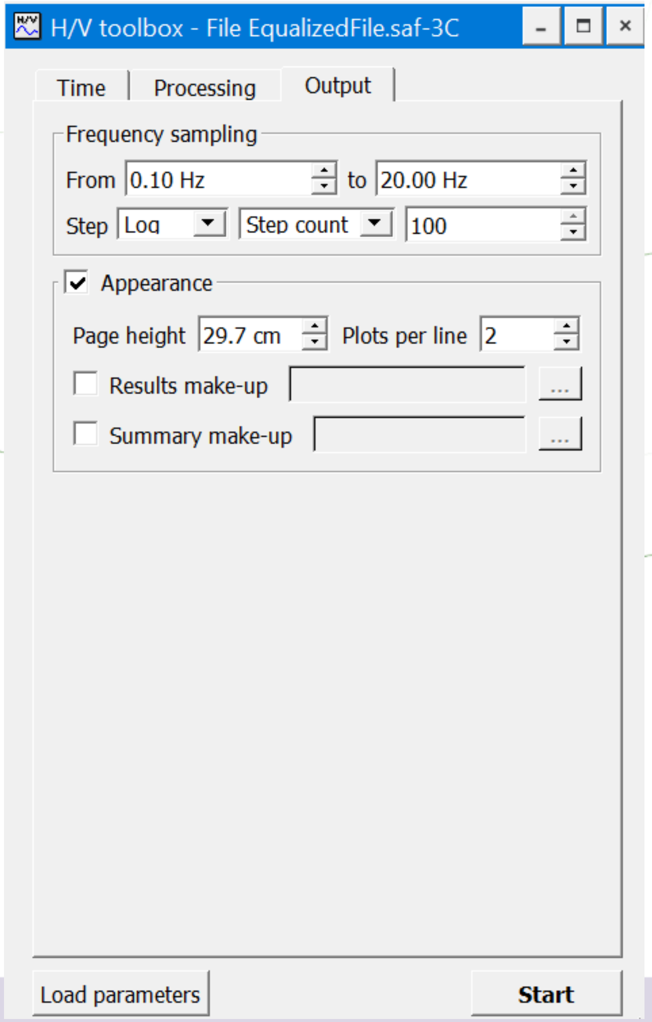
ON « Time » PANEL



ON « Processing » PANEL



ON « Output » PANEL

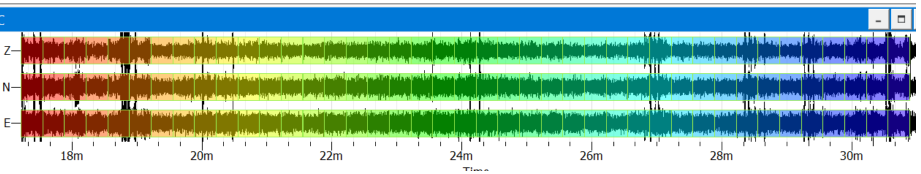


Processing HV curve

Black plain line: averaged H/V curve

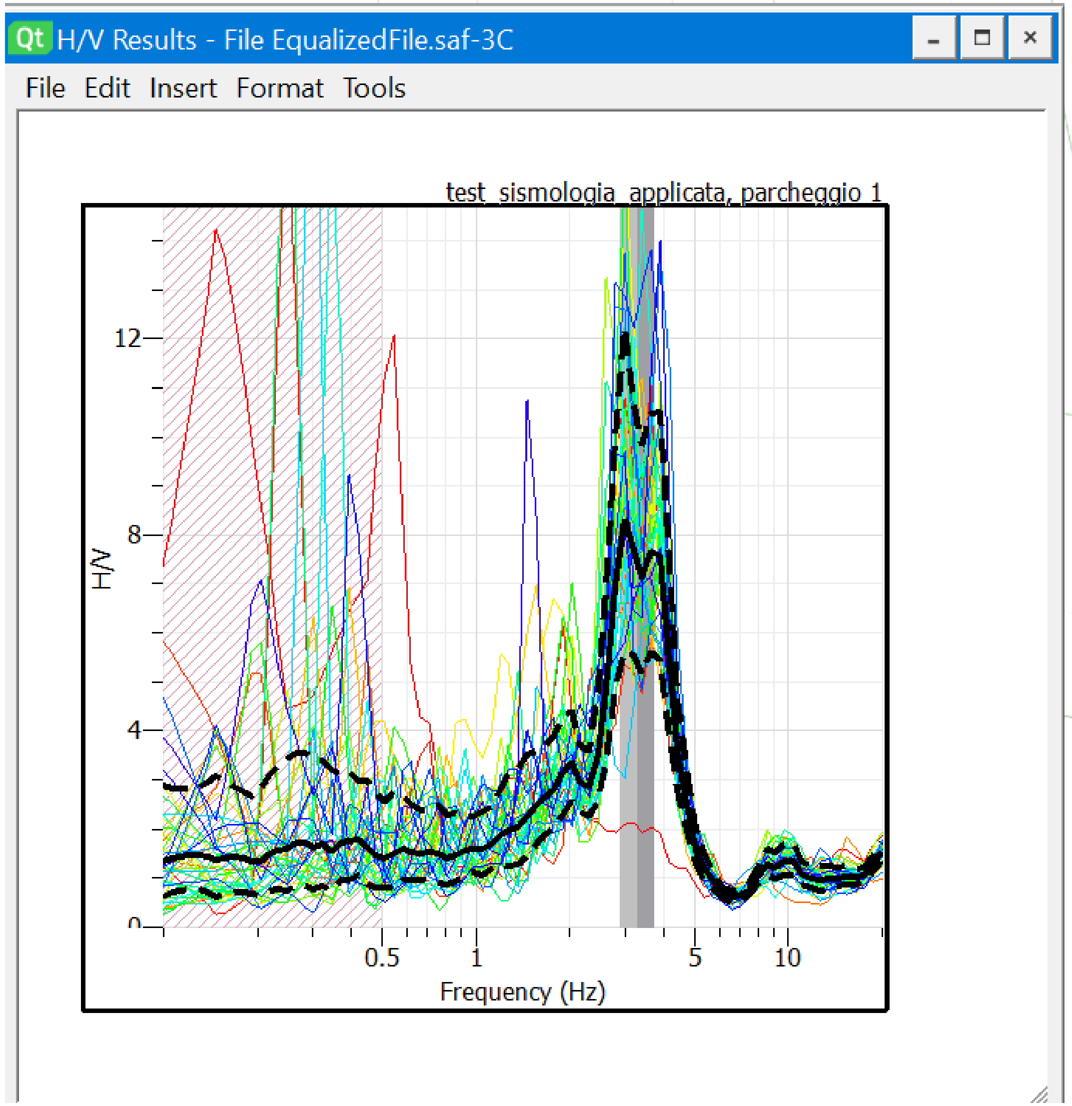
Black dashed lines: min/max H/V

Colored lines: individual H/V curves
Color scale similar as in the signal graph

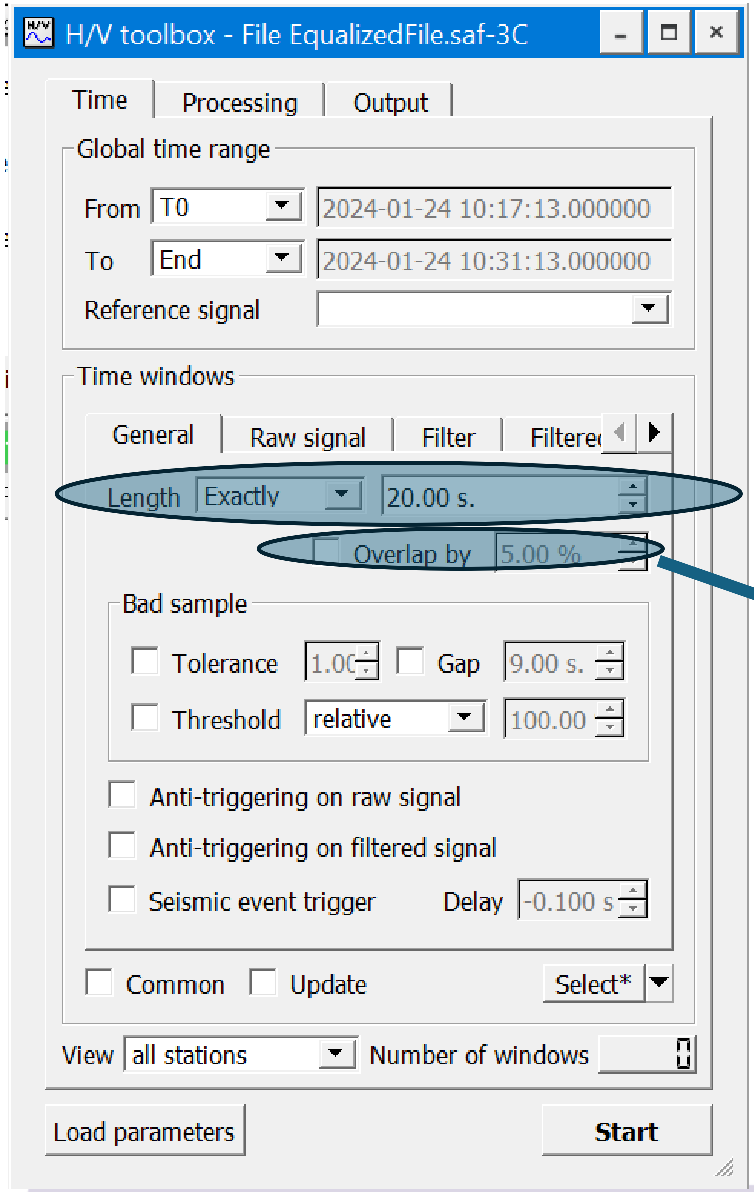


H/V peak frequency:
Grayed area: f_0 and σ
Light gray: -stand. dev. (from windows)
Dark gray: +stand. dev. (from windows)

Red dashed area: unreliable results from 10/window_length criteria (called T10)



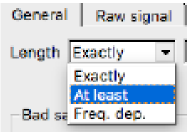
Time window length



Time window length

EXACTLY: you give the time window length

AT LEAST: you give a minimum and a maximum time window length. So a window has the minimum fixed length and increases its length until the maximum fixed length or a sample rejected by the anti-trigger (if applied)



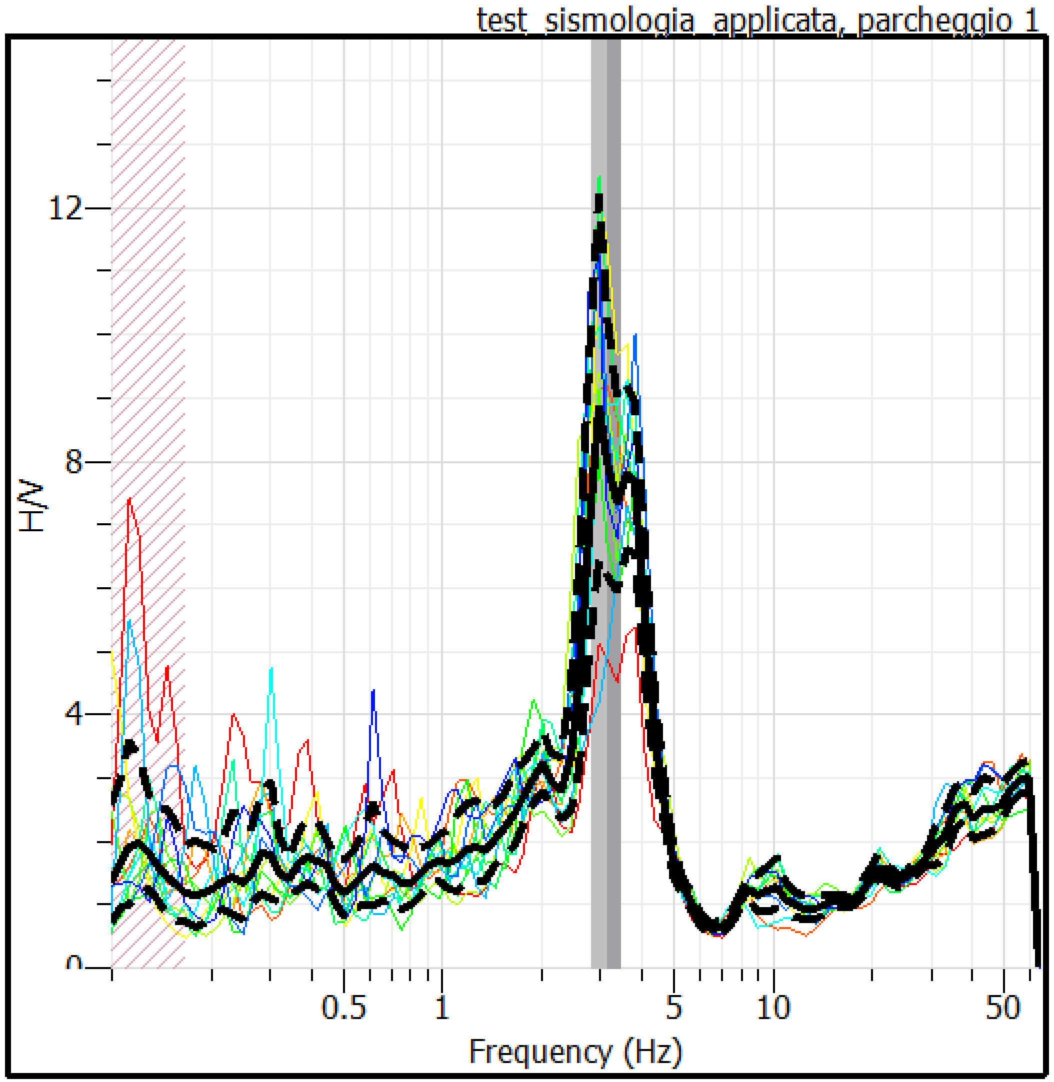
This option forces the program to define the windows with an overlap (useful if you are short in time recording)

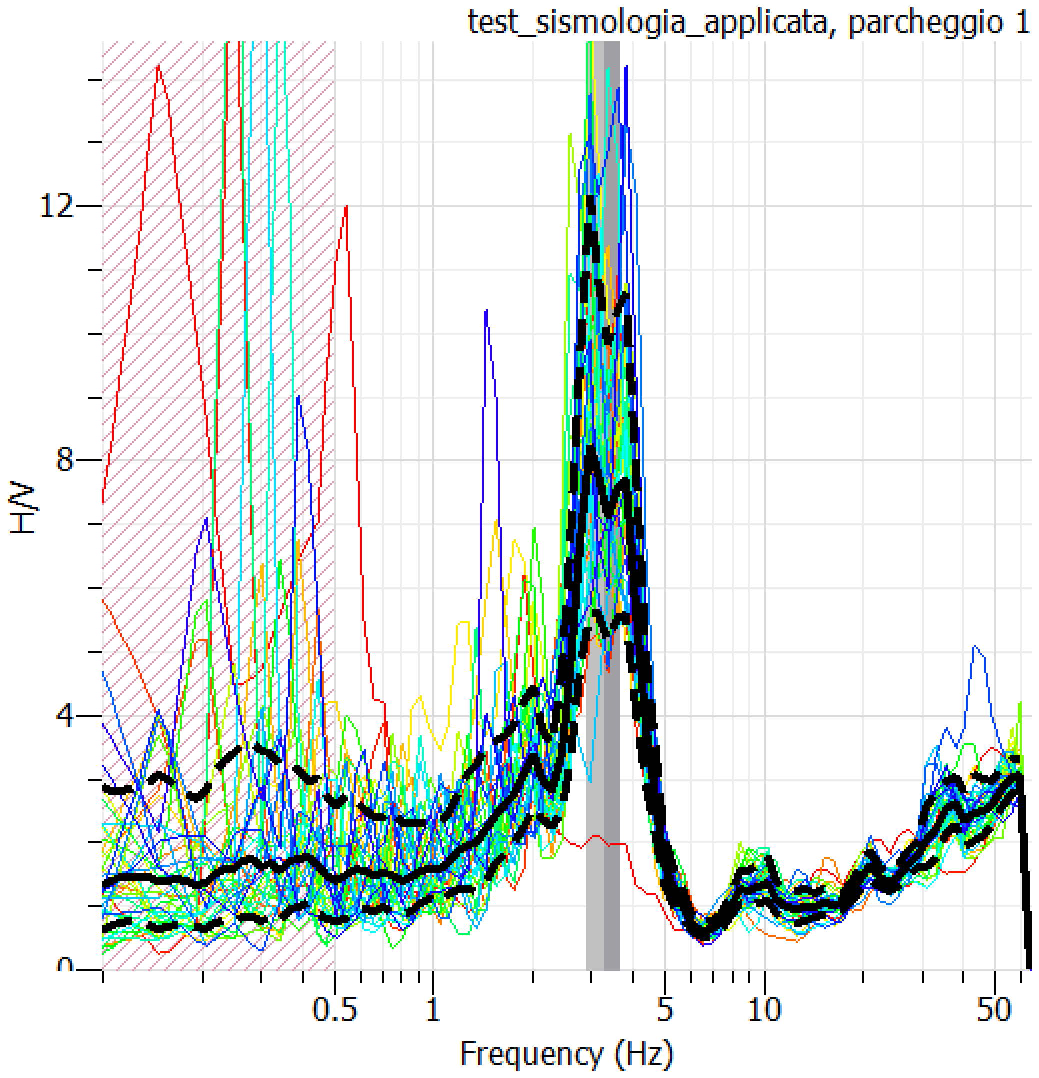
But (10/window length) could not be lower than the natural frequency of the seismometer

→ i.e. 25 s. windowing allows you to down until 0.4 Hz

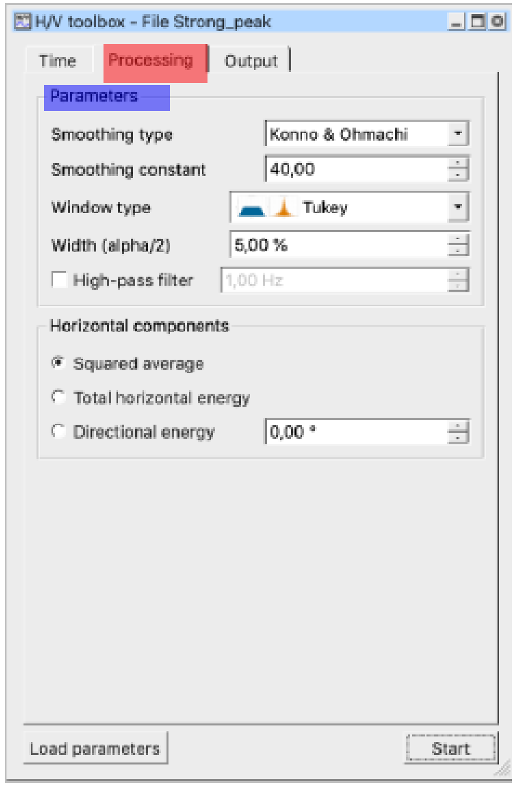
→ i.e. 5 s. seismometer allows you maximum windows length of 50 s. so to down until 0.2 Hz

$$10/w_l > f_{seismometer}$$

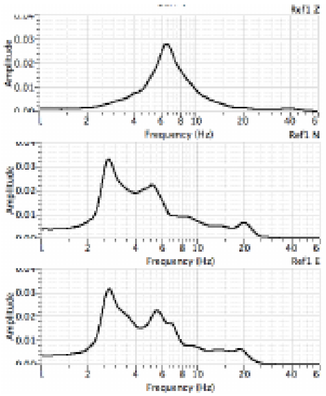

test_sismologia_applicata, parcheggio 1
H/V
12
8
4
0
0.5
1
5
10
50
Frequency (Hz)


test_sismologia_applicata, parcheggio 1
H/V
12
8
4
0
0.5
1
5
10
50
Frequency (Hz)

Processing parameters



Computation of Fourier amplitude spectra + smoothing



For each window of each component

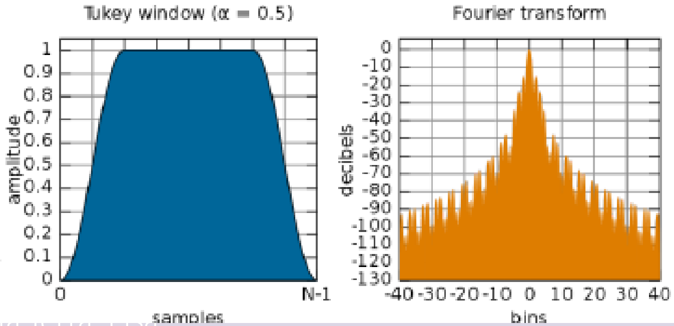
For a each window in time (for each component)

Time windows are tapered before computing Fourier transform.

By default in geopsy, we apply a Tukey window (before it was a cosine window) generally with 5% bandwidth on both ends of the signal

$[T_{\text{init+5\% length of the window}} - T_{\text{end-5\% length of the window}}]$

Tukey taper with 25% bandwidth on both ends of the signal

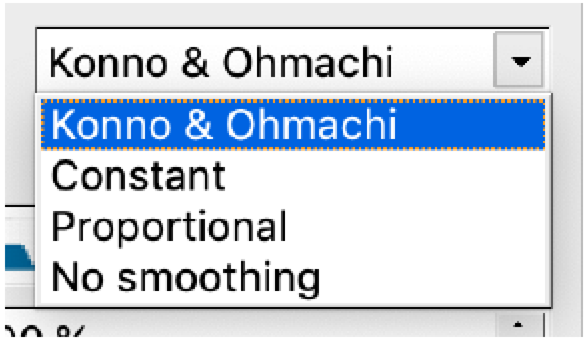


Processing parameters

Smoothing with the "Konno-Ohmachi" function

$$\frac{\sin\left(\left(\log_{10}\left(\frac{f}{fc}\right)\right)^{b}\right)}{\left(\left(\log_{10}\left(\frac{f}{fc}\right)\right)^{b}\right)^{4}}$$

f is the frequency,
fc is the central frequency,
b is the bandwidth coefficient.



Constant

The smoothing function has a triangular shape centered on the current frequency and its width is equal to "Band width"

Proportional

The smoothing function has a triangular shape and its width depends upon the current frequency. The half width is defined by percentage*frequency. The value of "percentage" cannot be greater or equal to 100%.

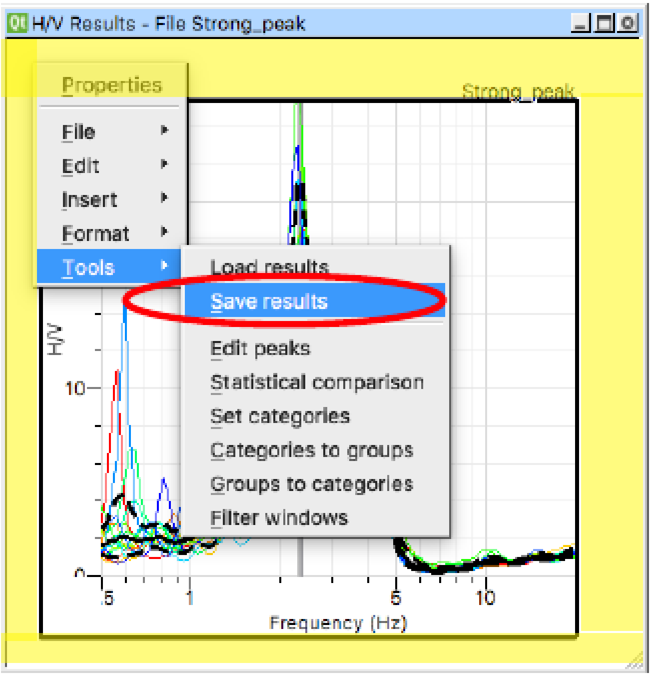
No smoothing

No smoothing is applied.

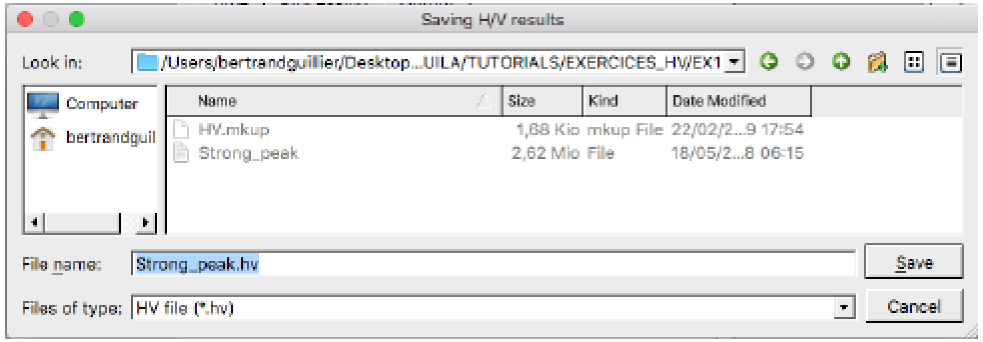
Export HV results

Until now, we have checked the graphic part, but the processing and the results can be saved in files

- H/V results → «station_name».hv
- the H/V processing parameters → «station_name».log



From outside the graphic (in yellow).



Export HV results

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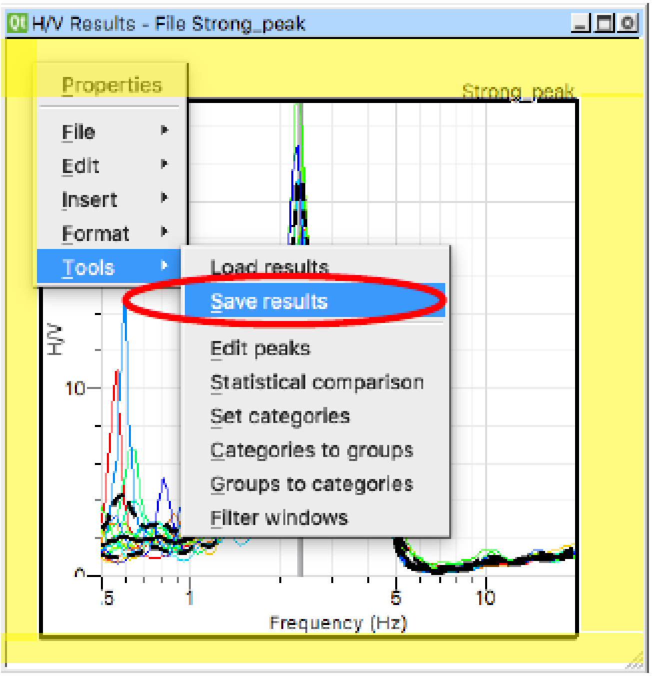
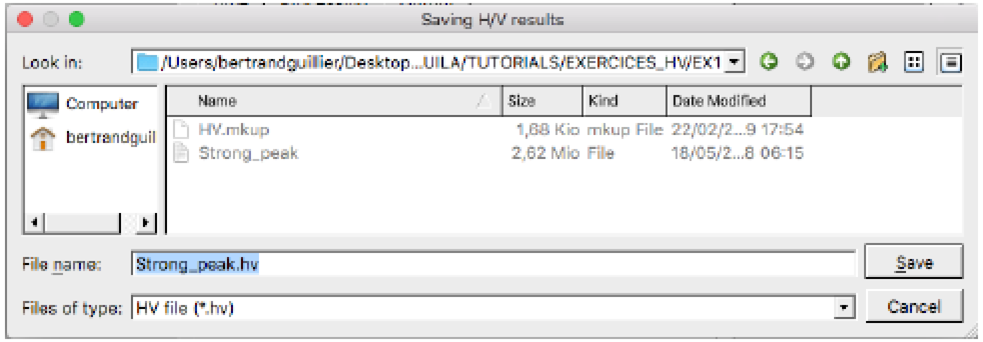


From outside the graphic (in yellow).



HVSR – time window selection

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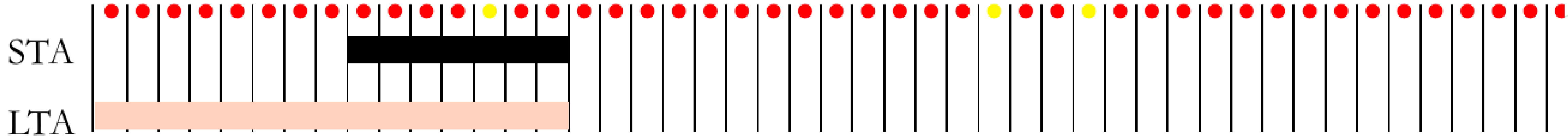
STA/LTA algorithm

● =1 ● =11

STA average on 2 samples
LTA average on 10 samples

Sample space



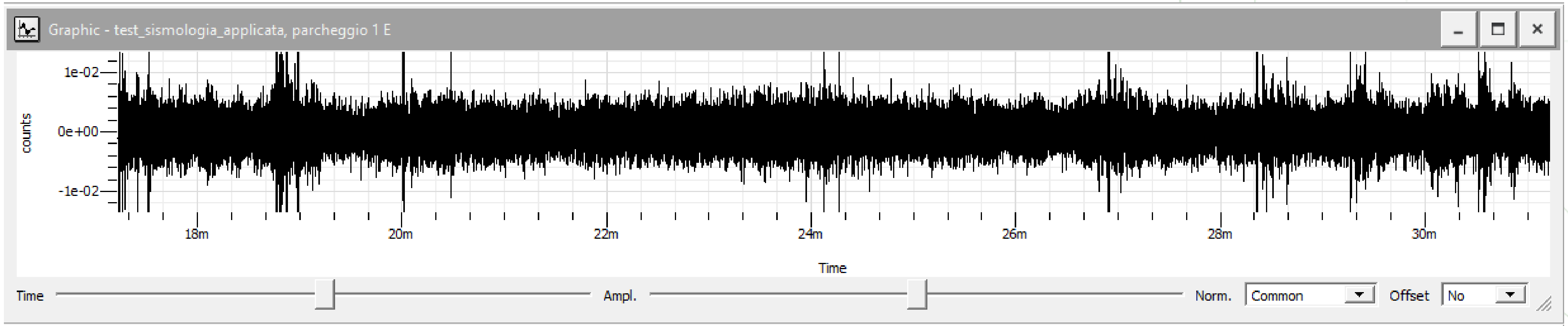
Value space

$$V_{10(STA)} = \left(\sum_{i=9}^{10} abs(value(i)) \right) / 2 \qquad V_{n(STA)} = \left(\sum_{i=n-1}^{n} abs(value(i)) \right) / 2$$

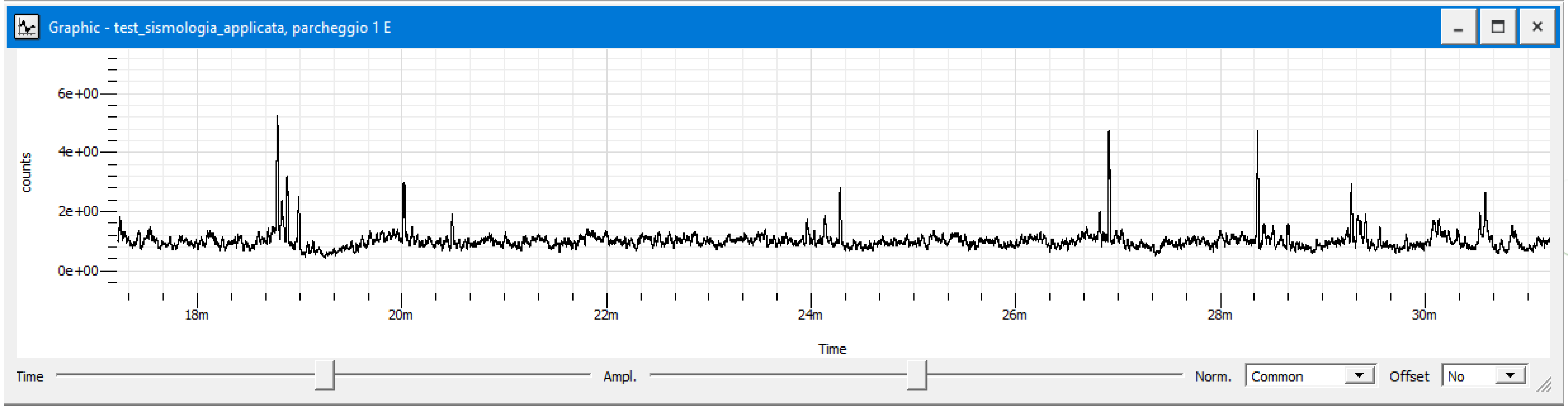
STA	1	1	1	6	6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	6	6	1	6	6	1	1	1	1	1	1	1	1	1	1	1	1	1	1
LTA	1	1	1	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1	2	2	2	3	3	3	3	3	3	3	2	2	2	1	1	1	1	1	1

$$V_{10(LTA)} = \left(\sum_{i=1}^{10} abs(value(i)) \right) / 10 \qquad V_{n(LTA)} = \left(\sum_{i=n-9}^{n} abs(value(i)) \right) / 10$$

STA/LTA

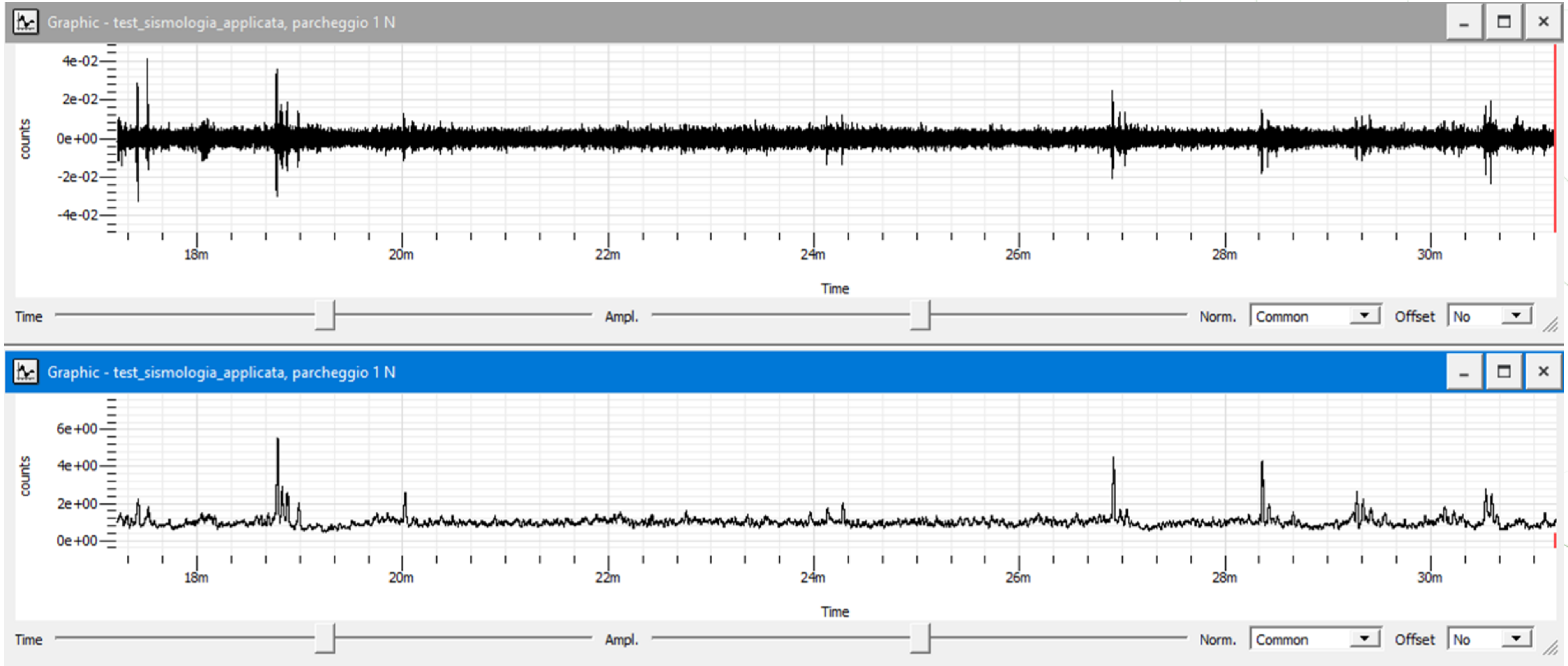


Original SIGNAL
East



STA/LTA

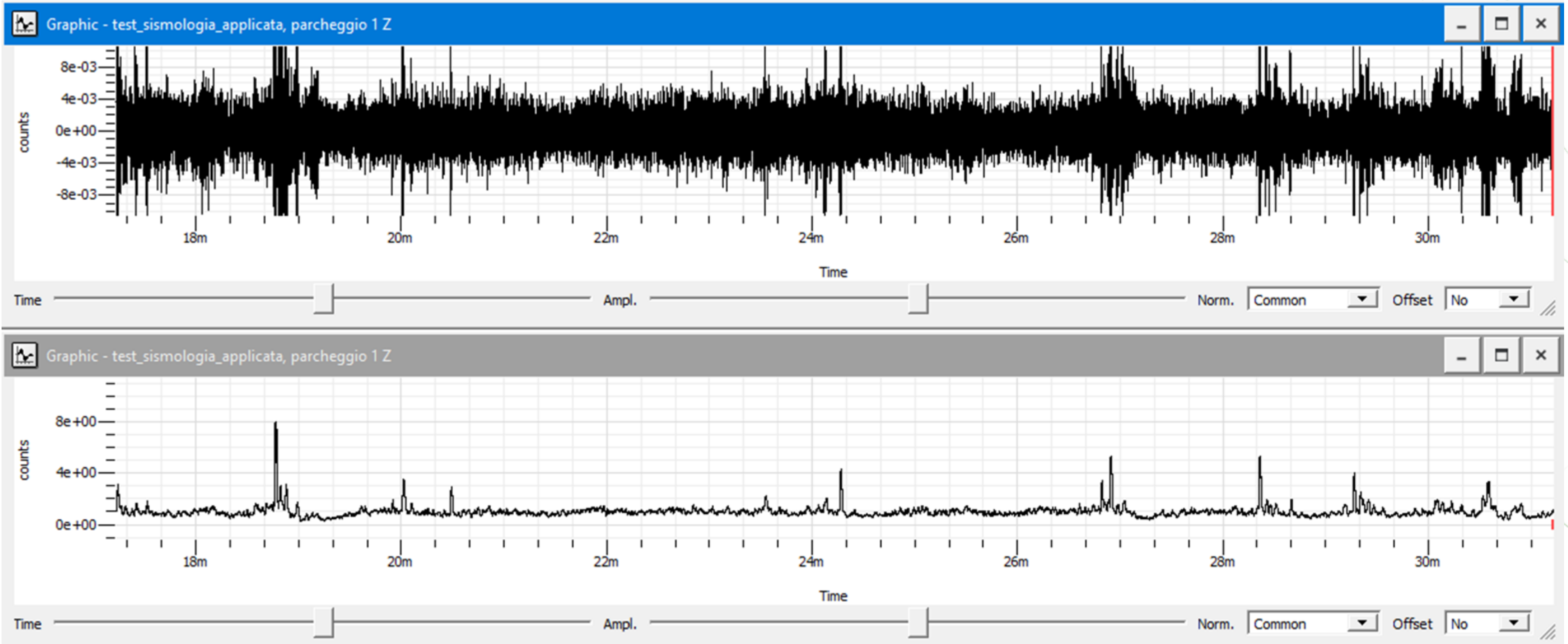
STA window = 1s
LTA window = 30 s



Original SIGNAL North

STA/LTA

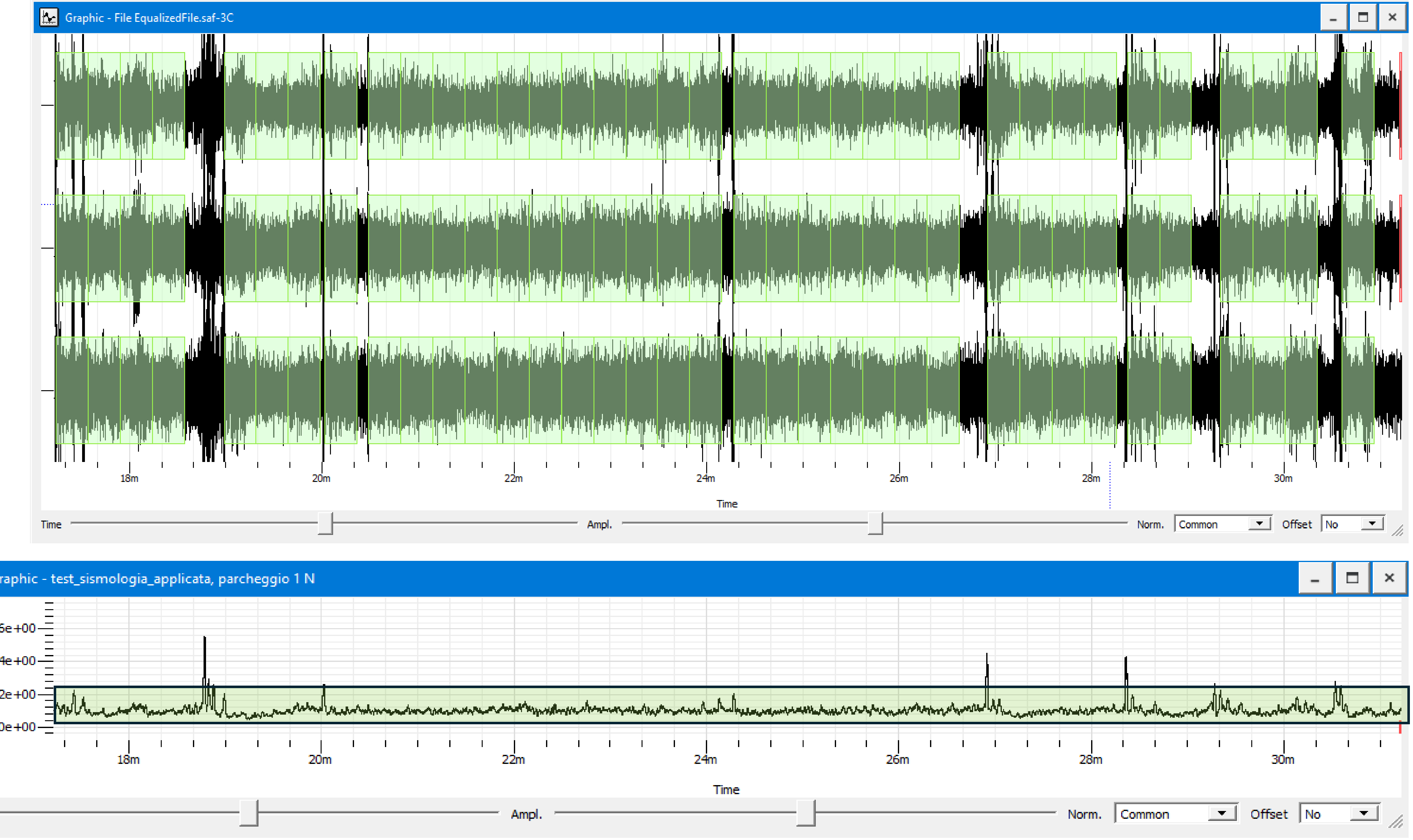
STA window = 1s
LTA window = 30 s



Original SIGNAL vertical

STA/LTA

STA window = 1s
LTA window = 30 s



Graphic - File EqualizedFile.saf-3C
18m
20m
22m
24m
26m
28m
30m
Time
Time
Ampl.
Norm.
Common
Offset
No
raphic - test_sismologia_applicata, parcheggio 1 N
6e+00
4e+00
2e+00
0e+00
18m
20m
22m
24m
26m
28m
30m
Time
Ampl.
Norm.
Common
Offset
No

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THANKS!

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