Passive seismic methods: ambient noise

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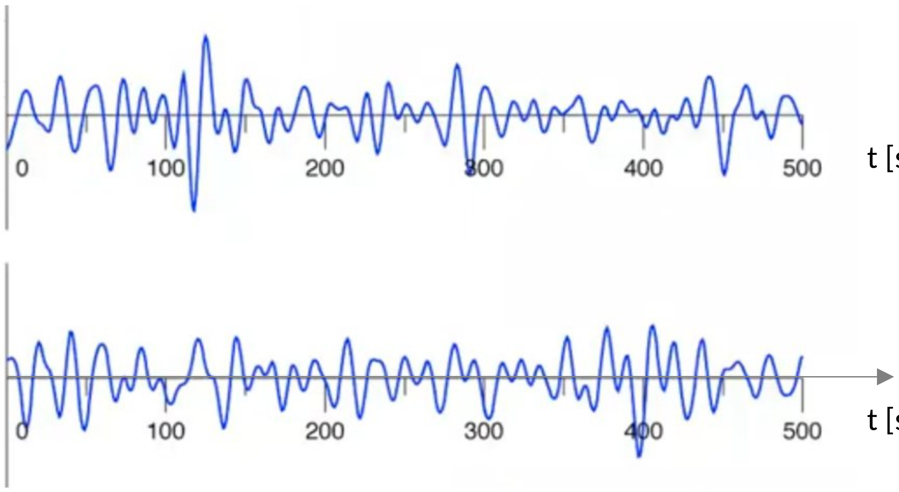
USES2 – Workshop #2

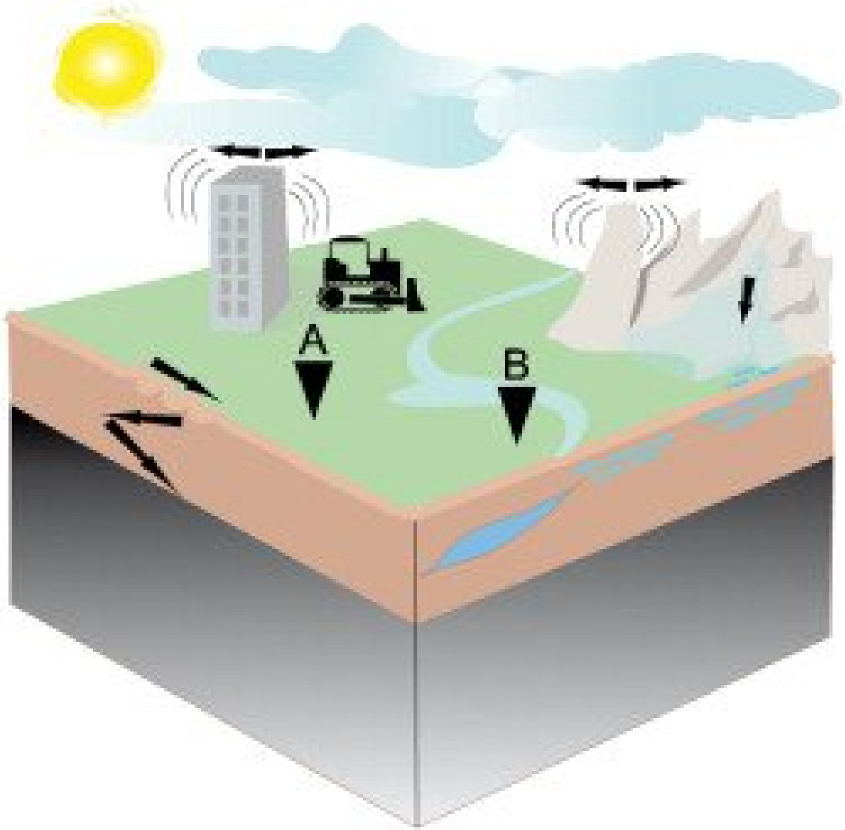
Ambient seismic noise

- Ambient seismic noise includes all vibrations produced by natural and anthropic sources:
  - ✓ **Natural sources**: earthquakes, microseisms (ocean waves, wind, tidal movements, etc.) ☾ f < 1 Hz
  - ✓ **Anthropic sources**: train, road traffic, factories, etc. ☾ f > 1Hz

STATION A

STATION B



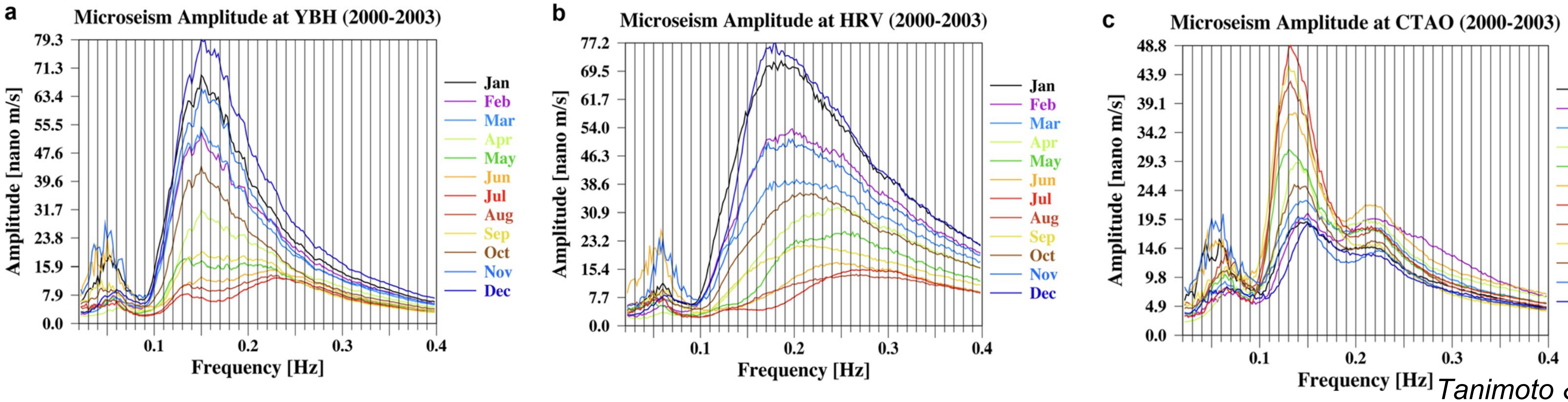


Larose et al., 2015

Ambient seismic noise

- Natural seismic sources span between 0.003 Hz and 1.0 Hz, and can be classified as (Tanimoto & Anderson, 2023):
  - ✓ **The hum**: background oscillations of the Earth, excited by ocean waves ☾ 0.003 Hz – 0.015 Hz
  - ✓ **Primary microseisms**: from distant ocean waves interacting with the seafloor ☾ 0.05–0.07 Hz
  - ✓ **Secondary microseisms**: from the wave-wave interactions in the nearby oceans ☾ 0.1 – 0.4 Hz
  - ✓ **Transient phenomena**: cyclones, wind-generated ocean waves, tornadoes, etc. ☾ 0.3 – 2 Hz

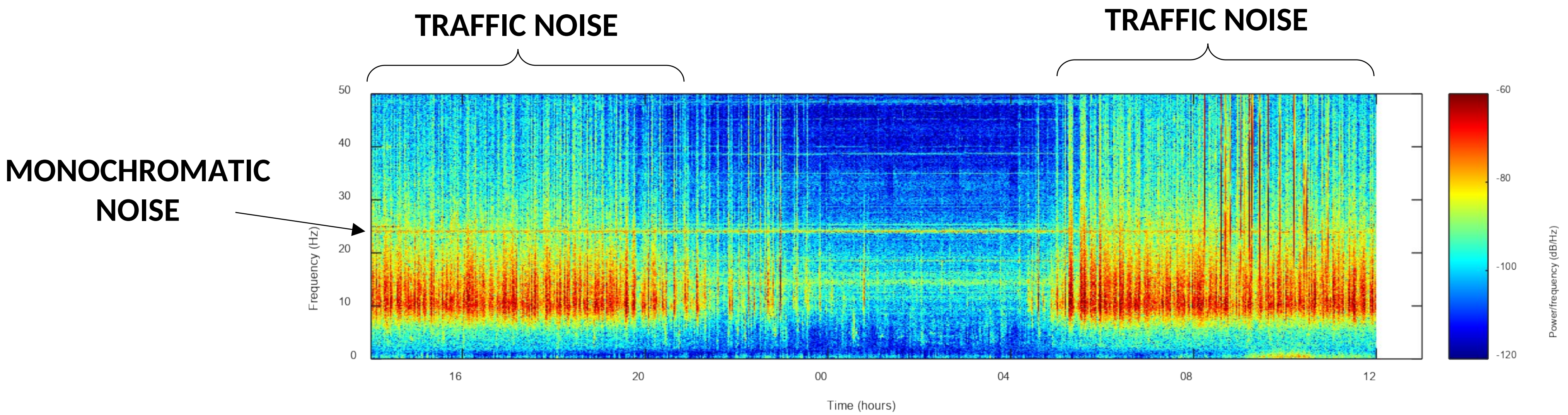
SEASONAL VARIATIONS



Tanimoto & Anderson, 2023

Ambient seismic noise

- Anthropic sources generally show a **daily/weekly periodicity**.
- **Traffic** is one of the main source of anthropic noise (vehicles, trains, planes, etc.).
- **Strong monochromatic noises** can be produced by industrial machinery, compressors, pumps, etc.
- **Spectrograms** (frequency – time diagrams) can help recognizing these noises and their spectral distribution.



Barone et al., 2023

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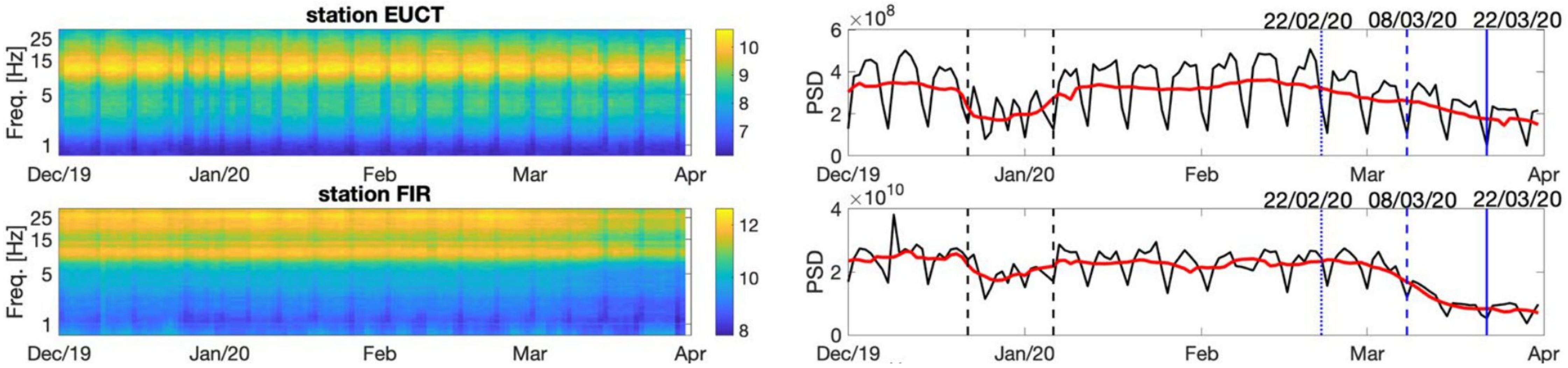
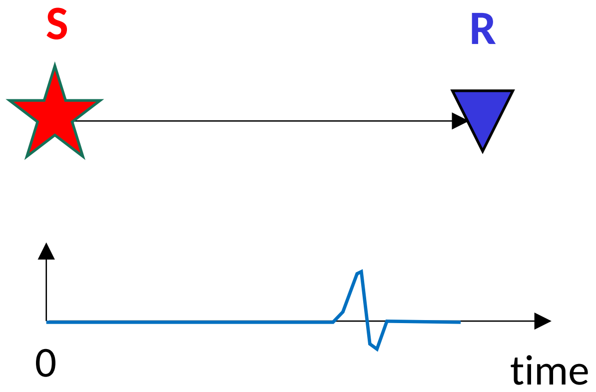


Poli et al., 2020

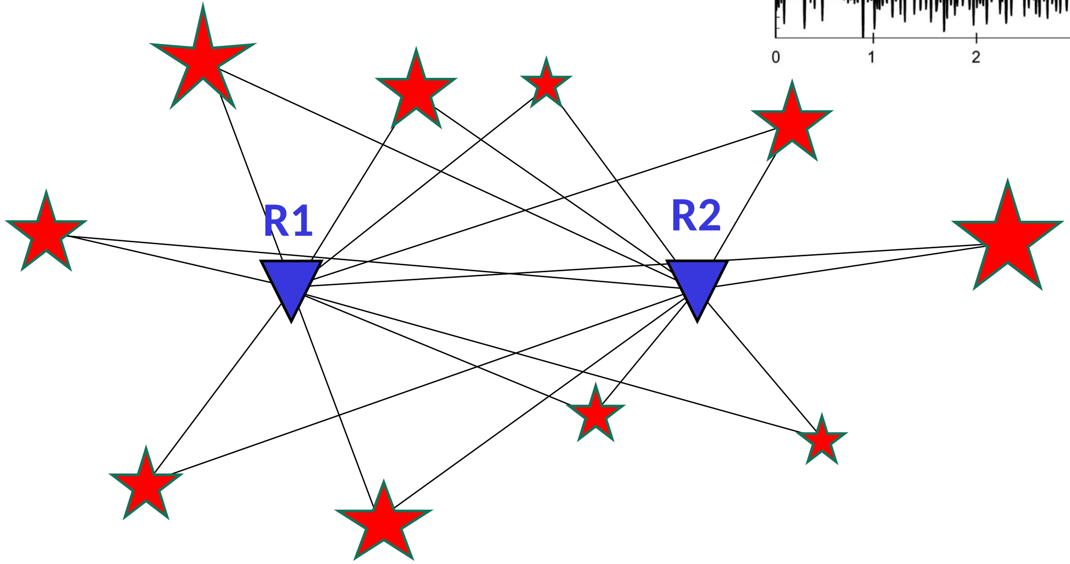
Active versus passive seismic methods

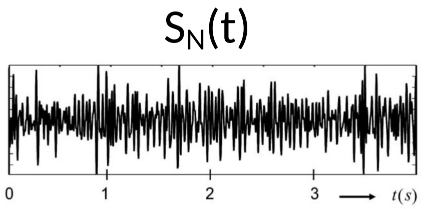
- **Seismic methods** analyse the seismic wavefield to infer the characteristics of the propagation medium.
- **Active methods** make use of seismic sources such as sledgehammers, weight drops, vibroseis, dynamite, etc. to generate a seismic wavefield at known locations.
- **Passive methods** analyse the (random) ambient noise wavefield recorded by two stations and reconstruct the Green's function (impulsive response) between them.

ACTIVE



PASSIVE





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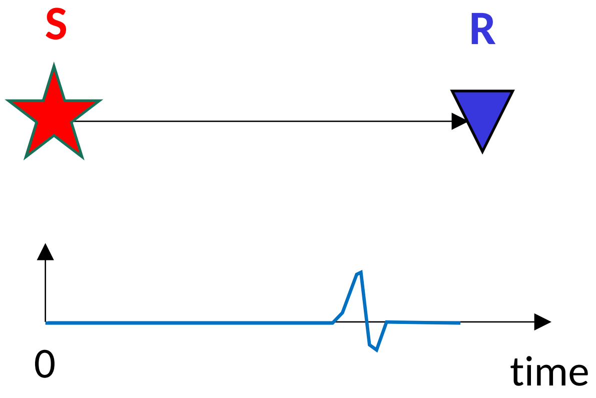
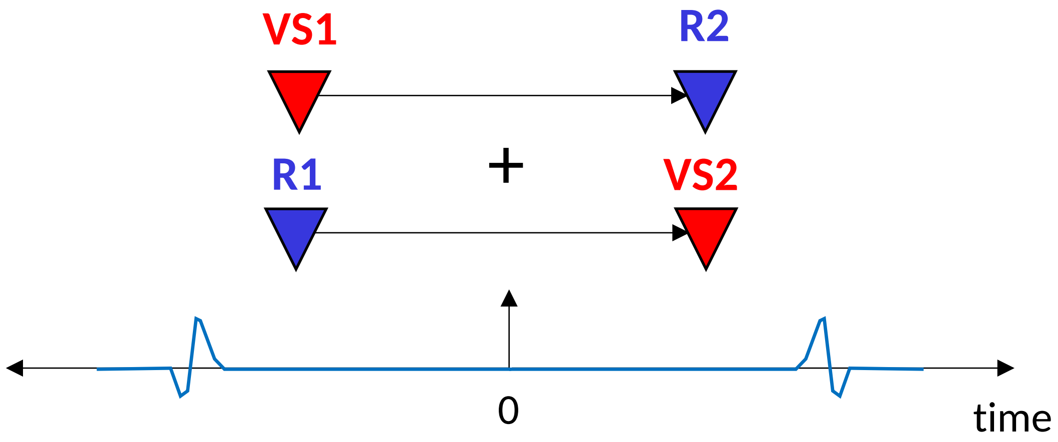


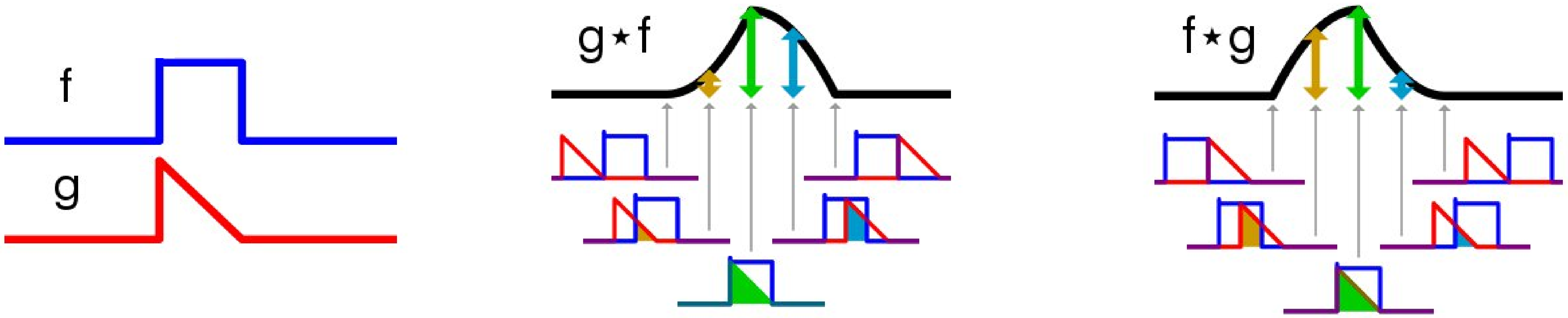
PASSIVE



Passive seismic interferometry

- **Crosscorrelation** is the mathematical operation at the base of passive seismic interferometry.
- The cross-correlation measures the **similarity between signals**, and can be seen as the integral of the product of the two functions, where one function is shifted:

$$z(t) = x(t) \otimes y(t) = \int_{-\infty}^{+\infty} \overline{x(\tau)}\, y(t+\tau)\, d\tau$$



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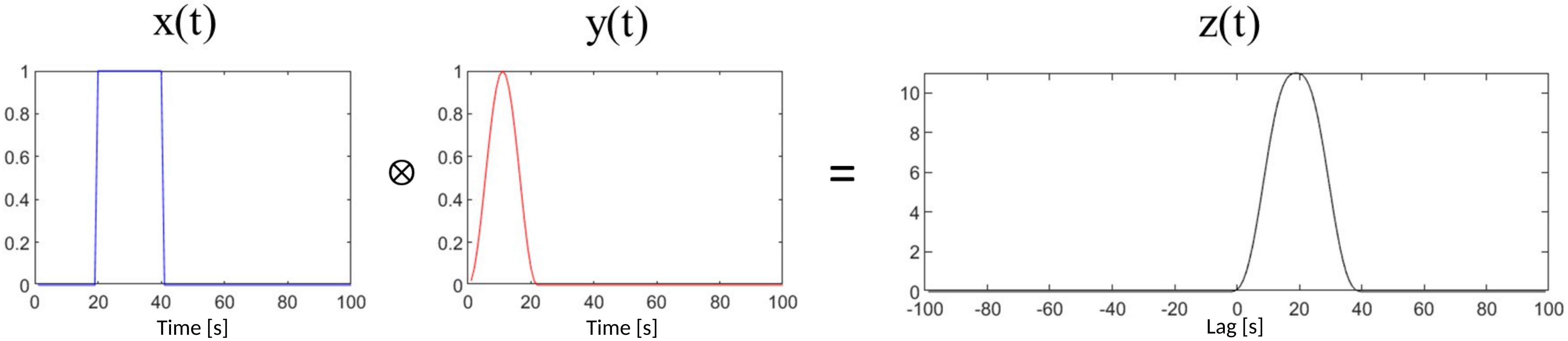
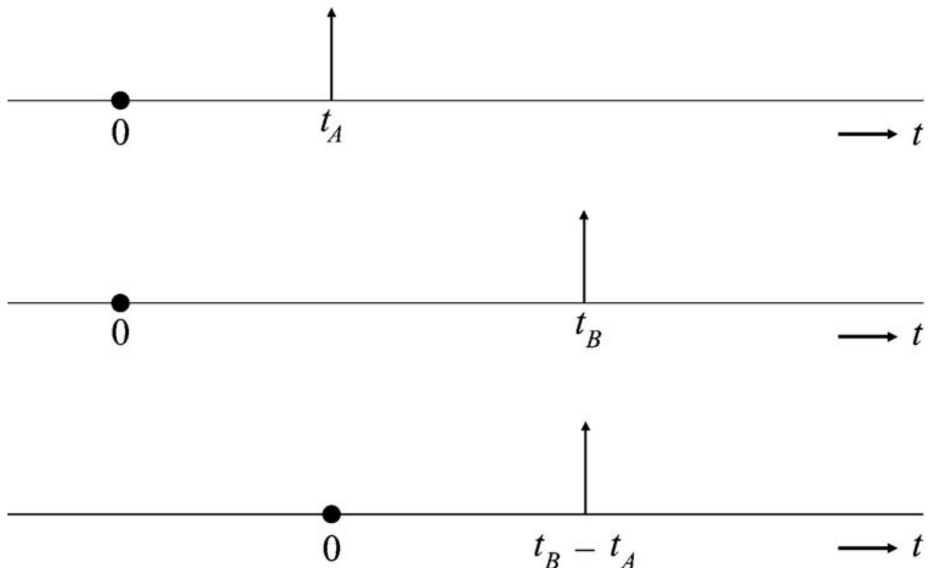


Passive seismic interferometry

- Seismic interferometry involves the **crosscorrelation** of responses at different receivers to obtain the **Green's function** between these receivers (Wapenaar et al., 2010).

Wapenaar et al., 2010

$s = \delta(t)$



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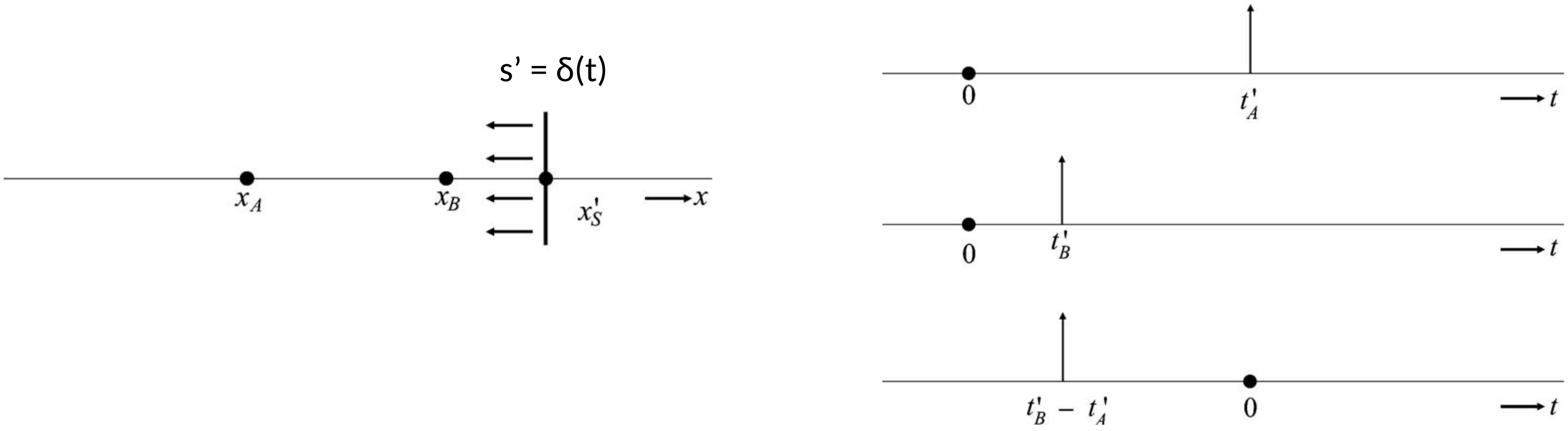

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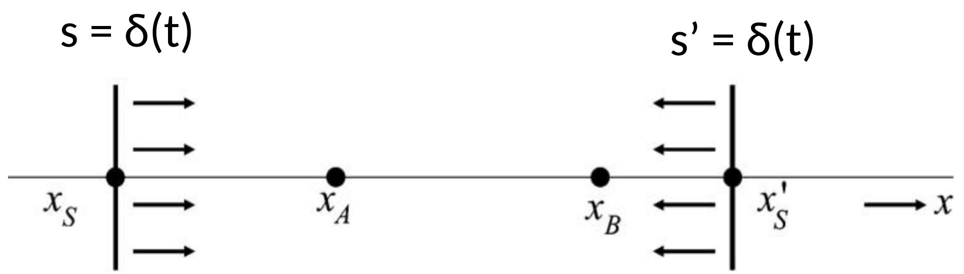

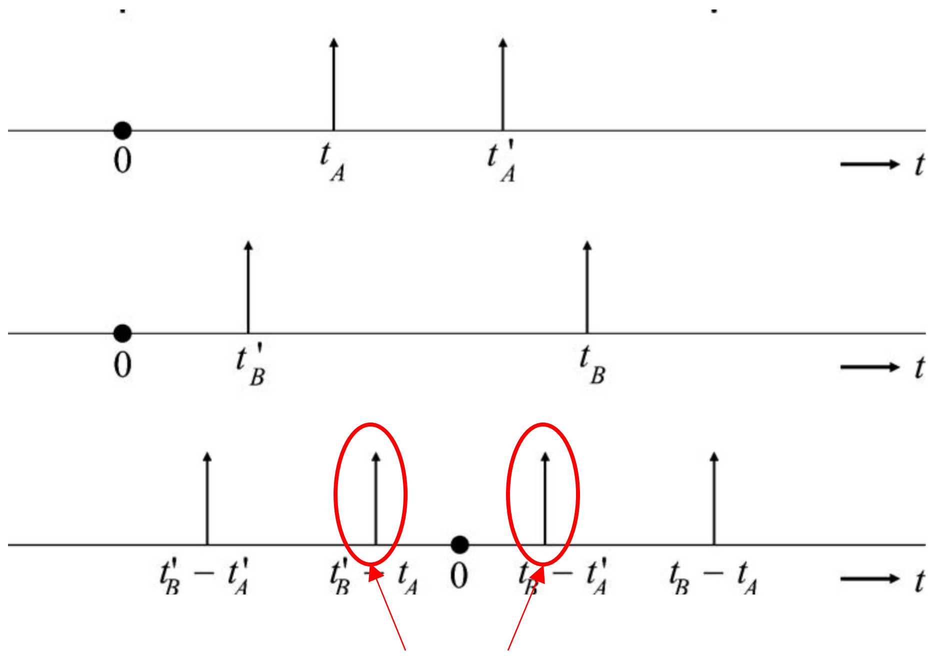

Noise sources are correlated, I have cross-terms (no physical meaning)

Passive seismic interferometry

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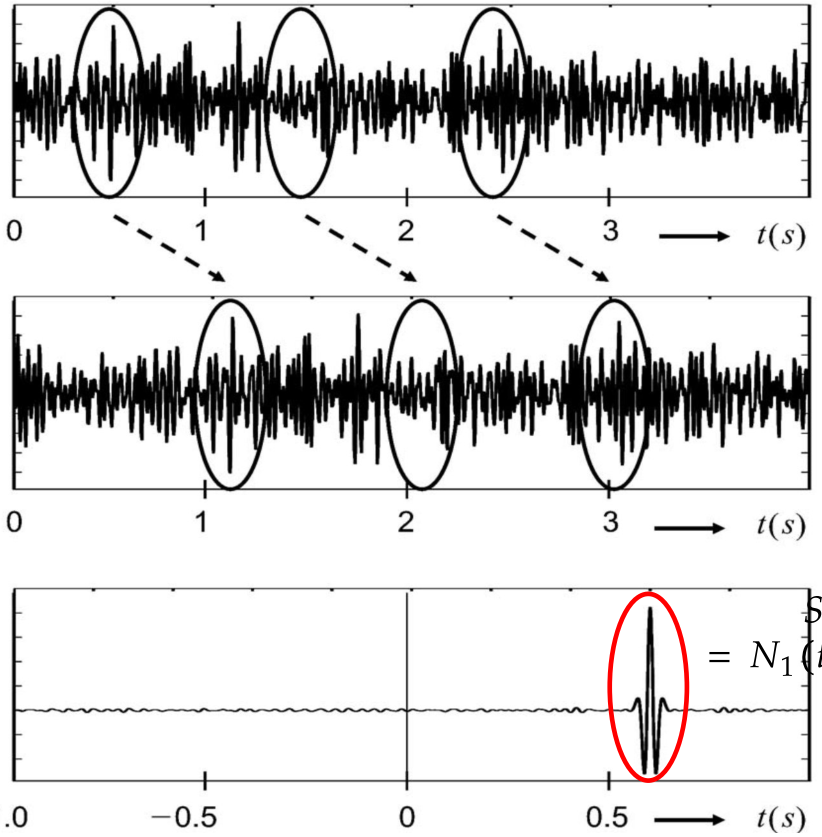
Wapenaar et al., 2010

s = $N_1(t)$



$S_N(t) = N_1(t) \otimes N_1(t)$

Passive seismic interferometry

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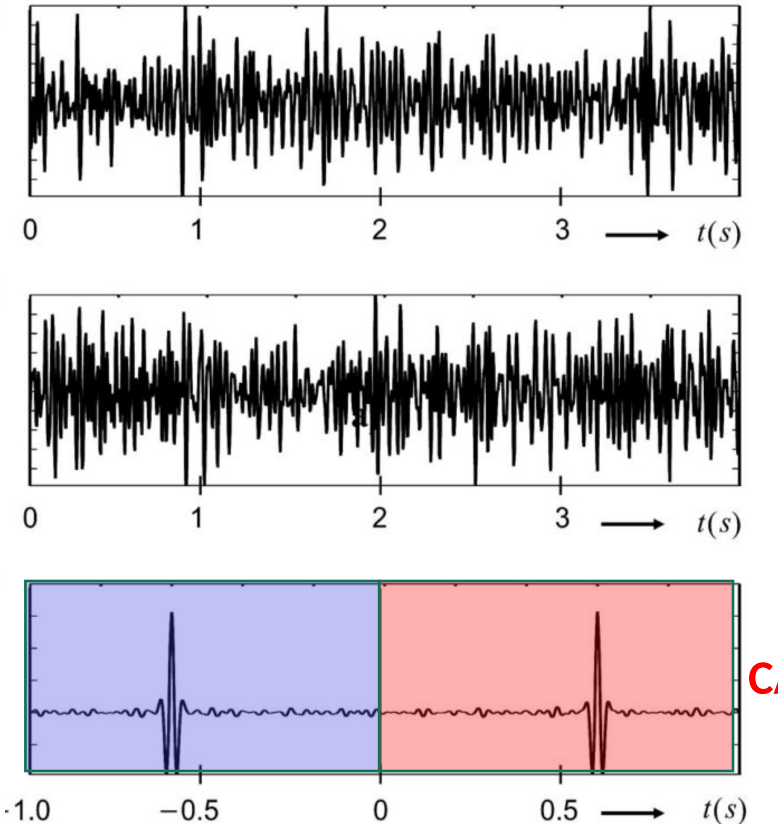
Wapenaar et al., 2010

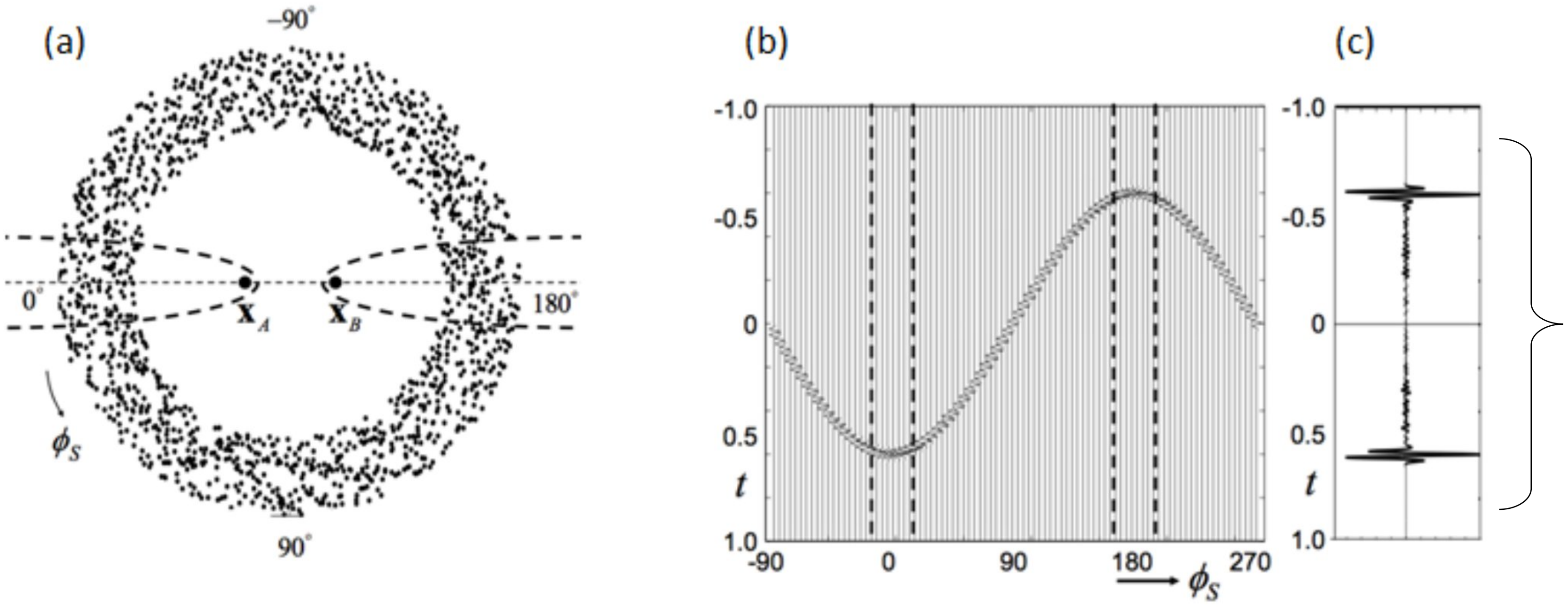
s = $N_1(t)$ s' = $N_2(t)$

Noise sources are uncorrelated
($N_1(t)*N_2(t) = 0$), no cross-terms!



Passive seismic interferometry

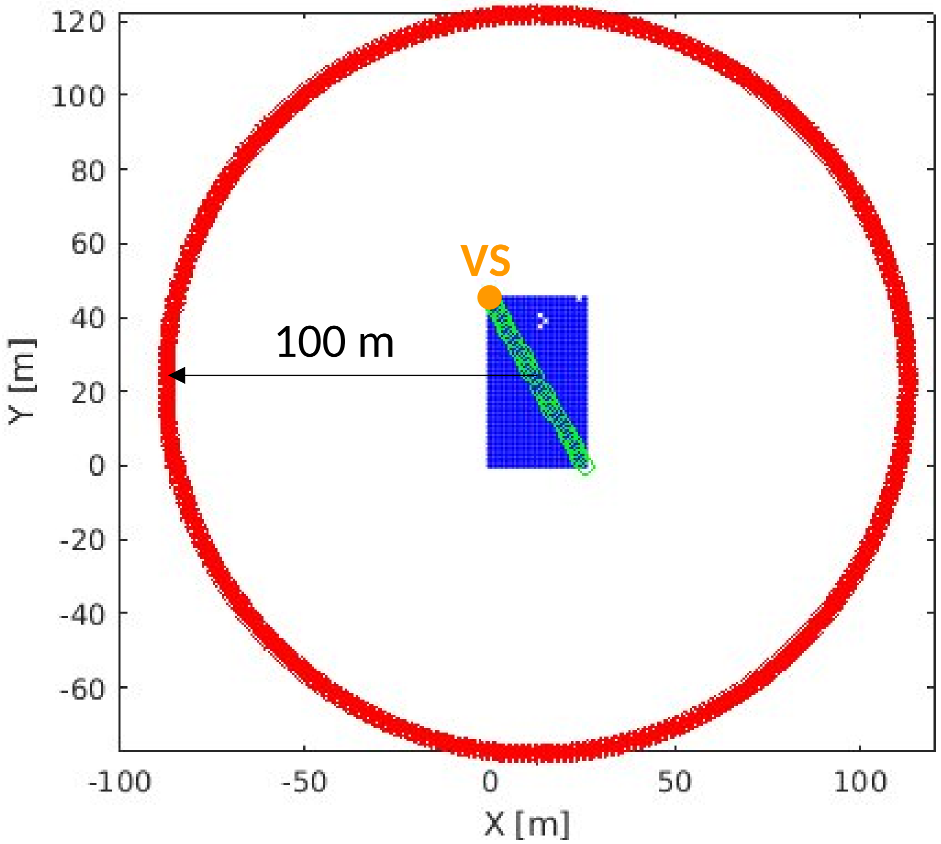
- If the **noise sources are distant, uncorrelated and isotropically distributed in azimuth**, only sources in the Fresnel zones contribute constructively ☾ I can reconstruct the Green's function!



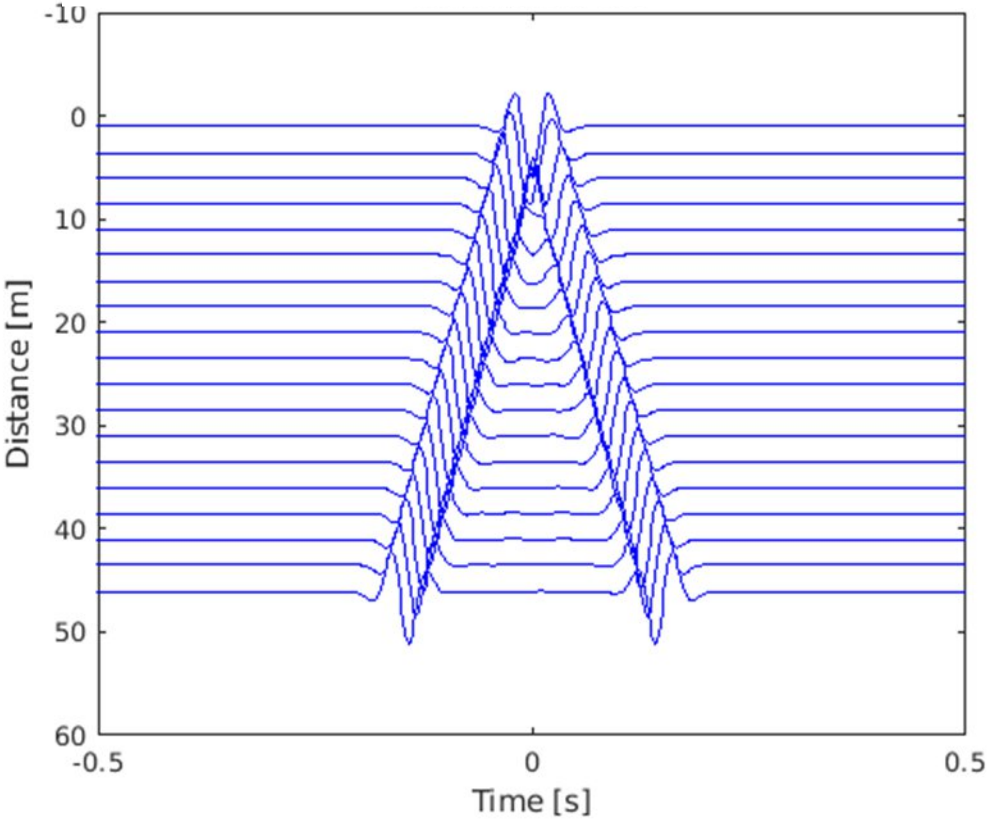
WHEN THE NOISE SOURCE ILLUMINATION IS HOMOGENEOUS IN AZIMUTH…
THE GREEN'S FUNCTION IS SYMMETRIC!

Wapenaar et al., 2010

Passive seismic interferometry – noise source distribution



Cross-correlation function along the diagonal



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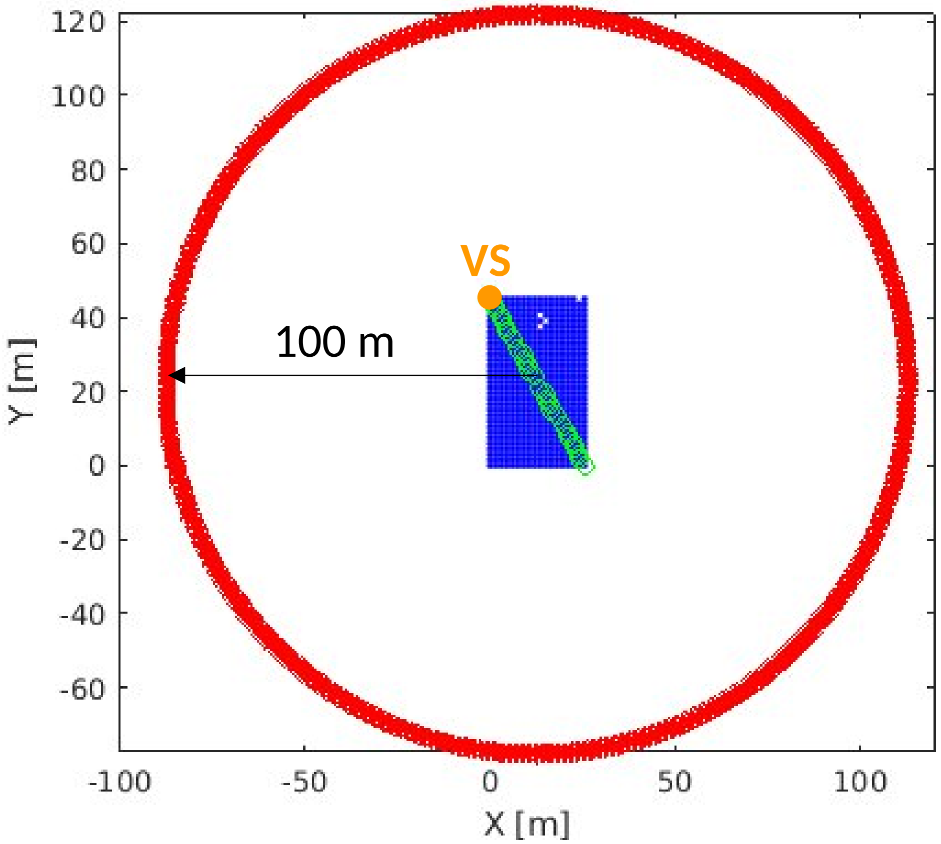

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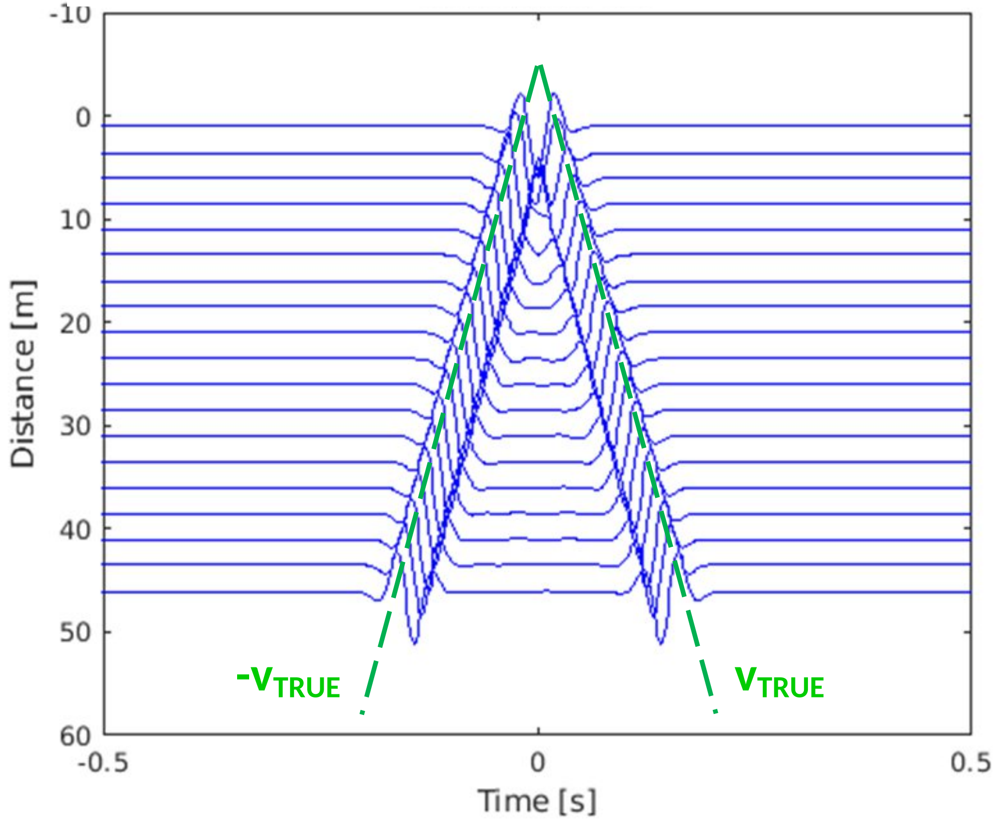

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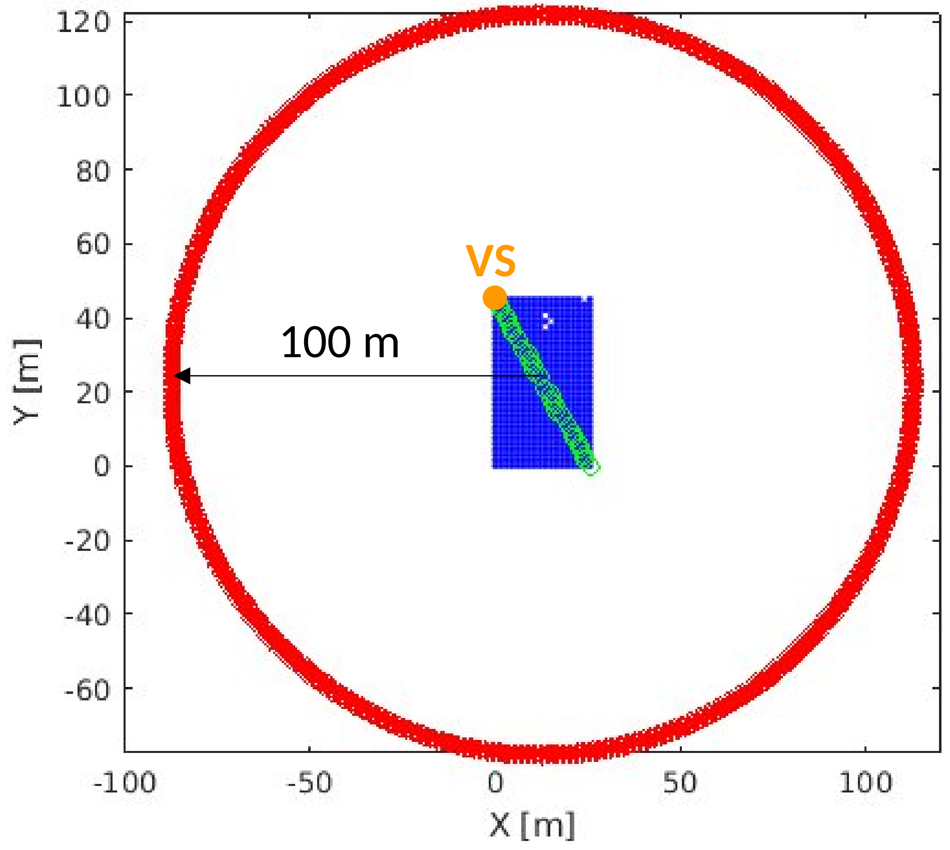
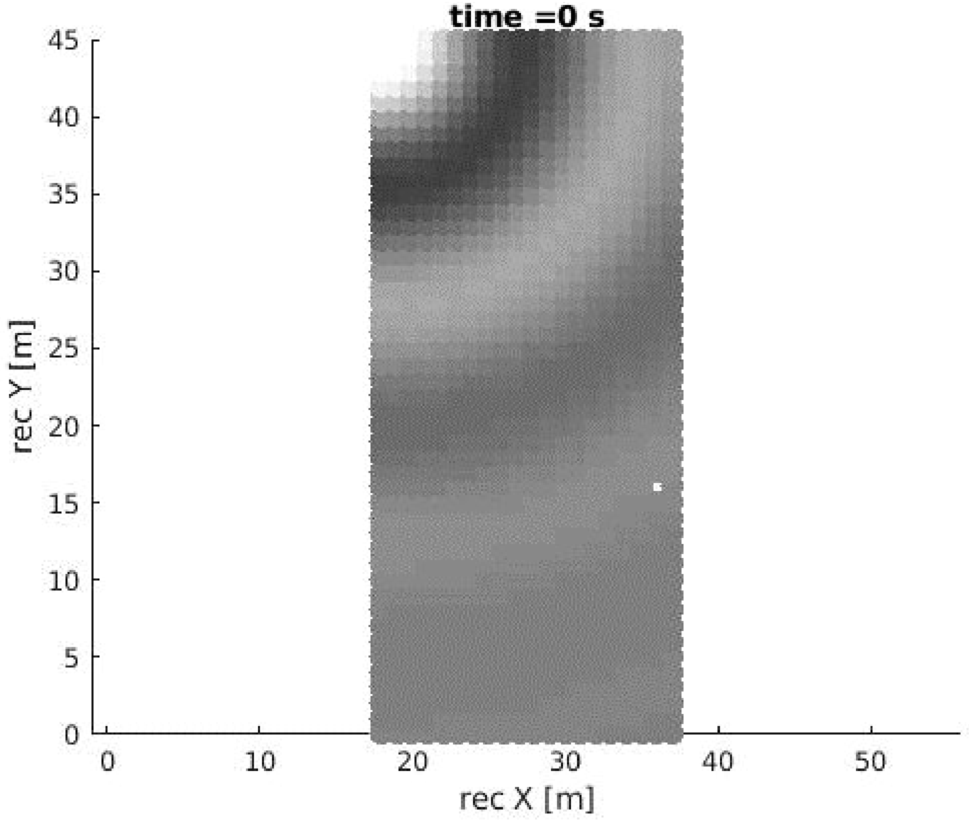


Cross-correlation function filtered at 20 Hz



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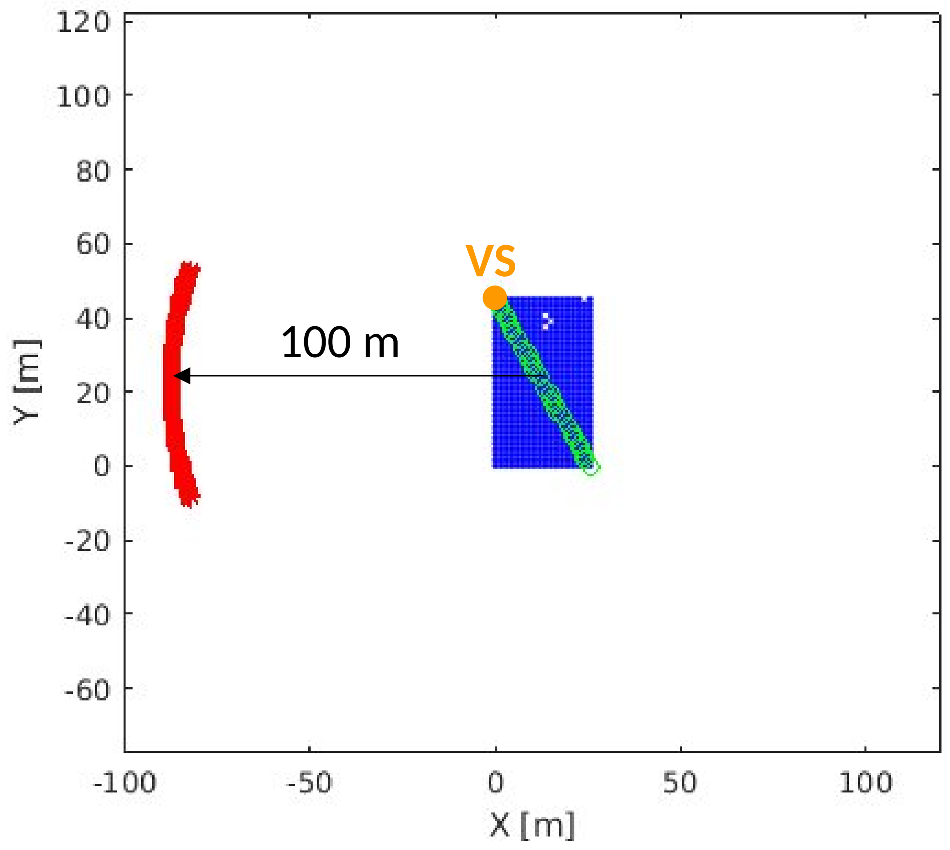
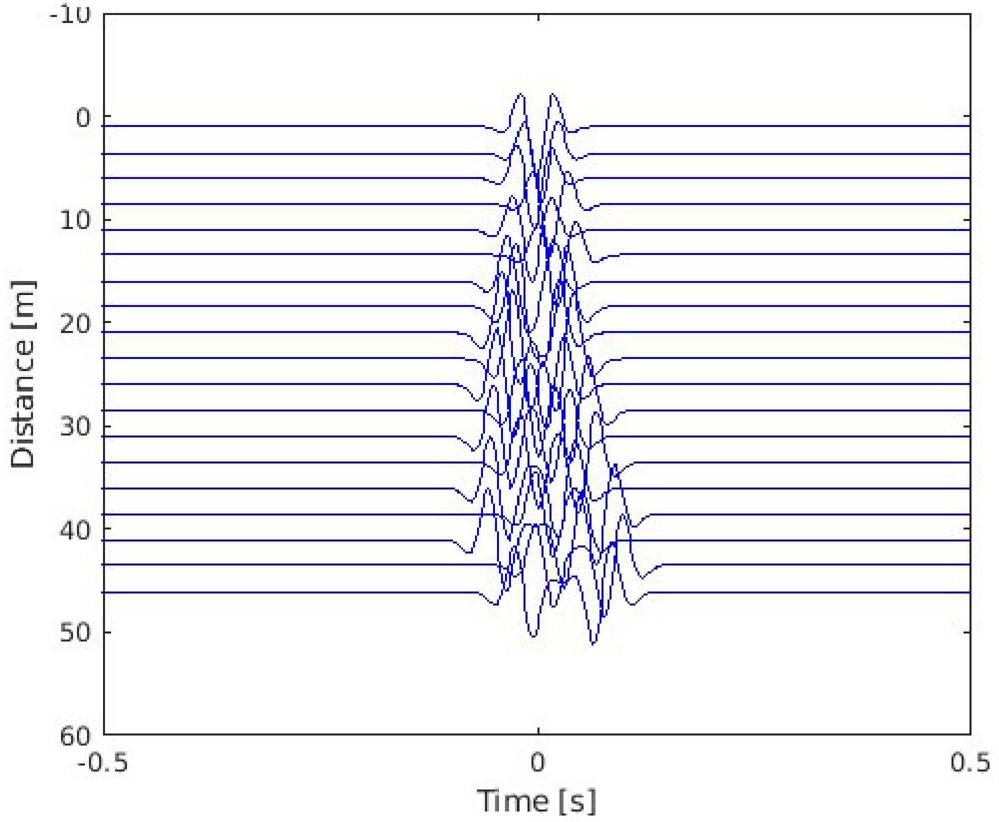


Cross-correlation function along the diagonal



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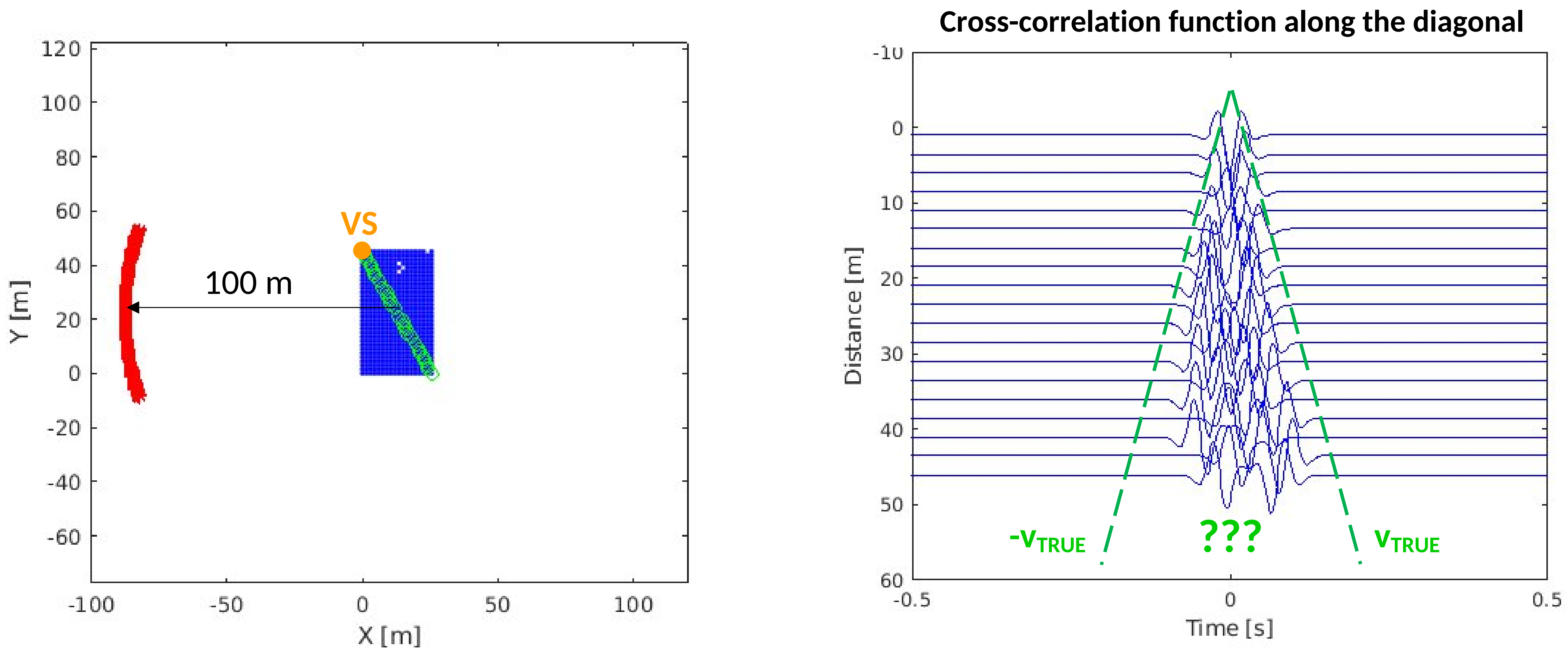

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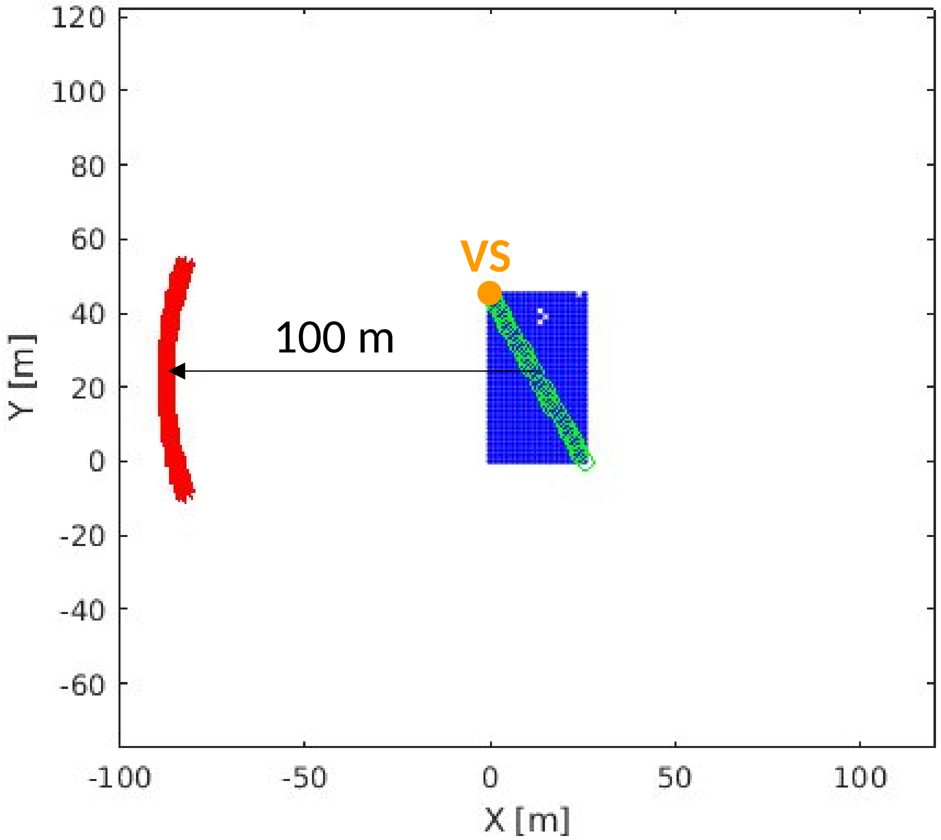
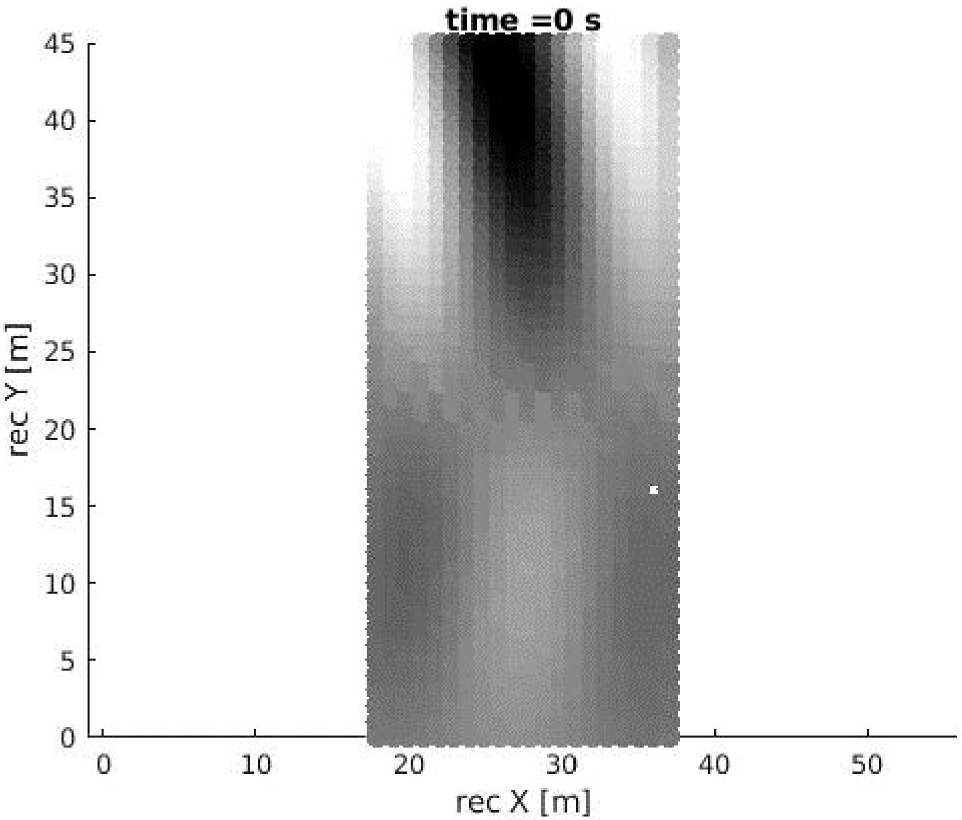
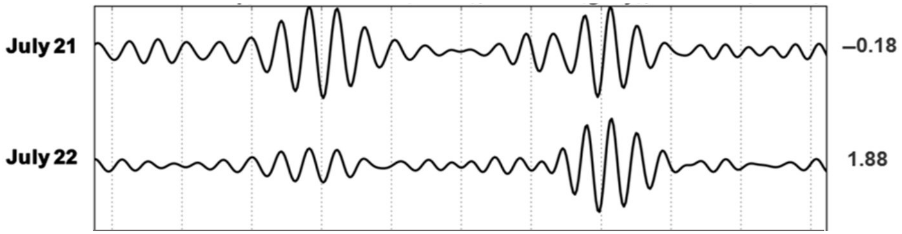


Cross-correlation function filtered at 20 Hz



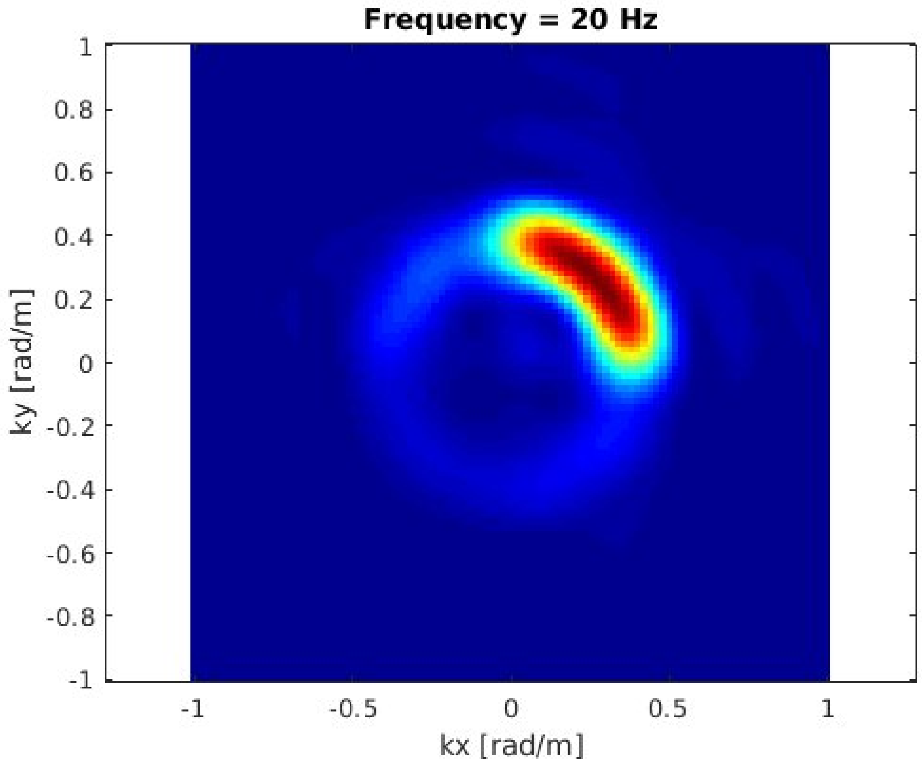
Passive seismic interferometry – noise source distribution

- The isotropic distribution of noise sources is hardly met in nature.
- Directional noise sources cause the **asymmetry of Green's function**, that could **bias a later velocity analysis**.
- Some authors have attempted to quantify and correct for traveltime biases due to uneven source distribution (Delaney et al., 2017).
- Noise source distribution can be measured through **correlation asymmetry** (Ermert et al., 2016) or **beamforming** (Lacoss et al., 1969).



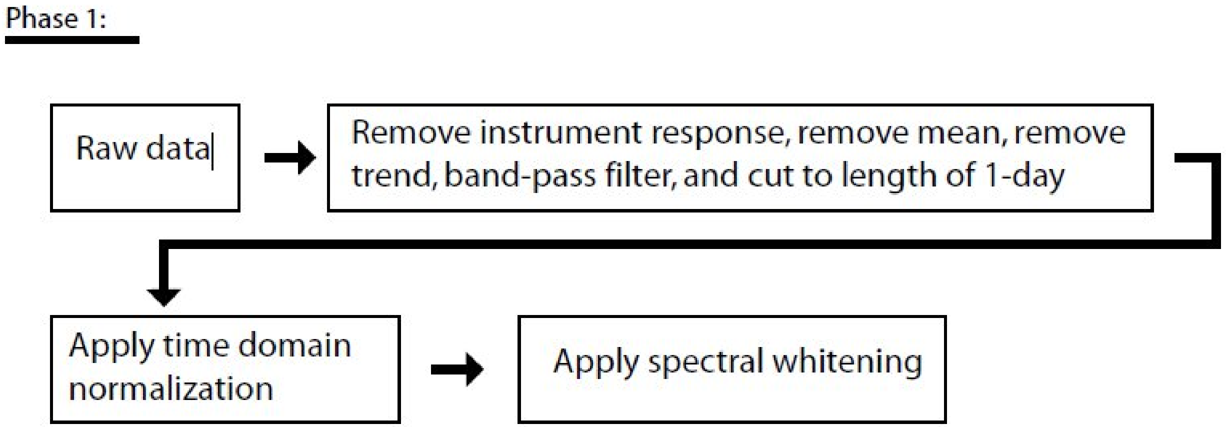
Delaney et al., 2017

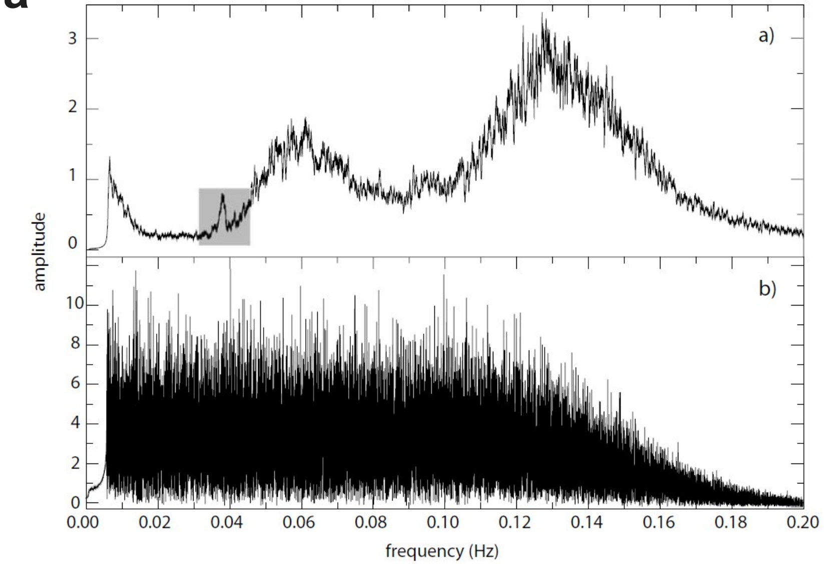
BEAMSPECTRUM



Passive seismic interferometry – noise source distribution

- **Wave scattering** caused by subsurface heterogeneities naturally redirect the seismic energy in different directions and partly compensates for this problem (Pedersen and Kruger, 2007; Froment et al., 2010).
- During processing, several **normalizations** are applied to each time window (**spectral whitening, one-bit**, etc.) before crosscorrelation, in order to remove strong transient signals (Bensen et al., 2007).
- **Positive-lags and negative-lag correlations** are also generally **averaged**.

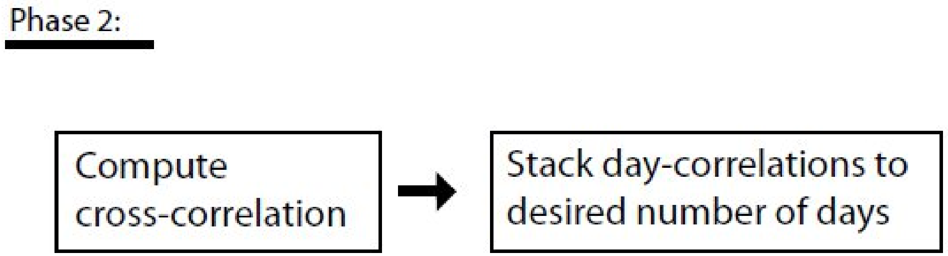


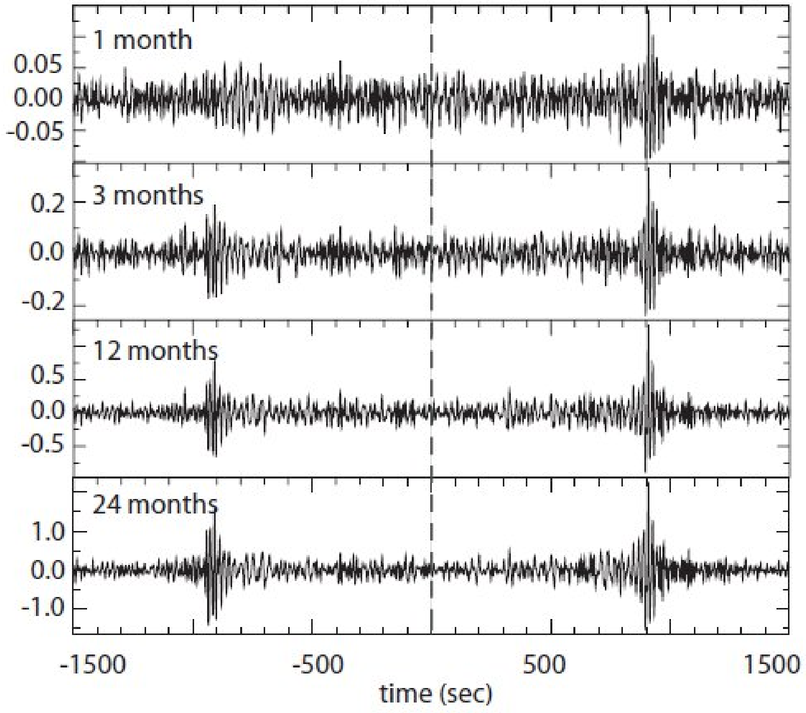


Bensen et al., 2007

Passive seismic interferometry – temporal window

- The choice of the **duration of the noise record** is critical.
- Using longer noise series should increase the S/N ratio and compensate for the natural seasonal fluctuations (Yang and Ritzwoller, 2008; Barone et al., 2024).





Bensen et al., 2007

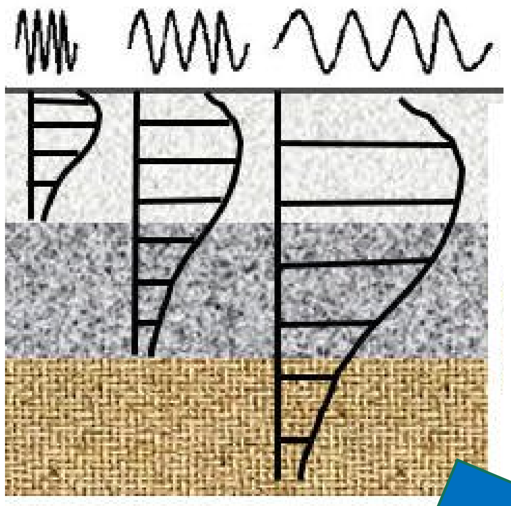
Passive seismic interferometry – surface wave velocities

- In principle, it is possible to reconstruct both body waves and surface waves. However, since the **surface wave wavefield is predominant**, seismic interferometry is mostly used to derive surface wave velocities.
- **Surface waves are dispersive**: different frequencies sample different portions of the subsoil, thus they travel with different velocities.

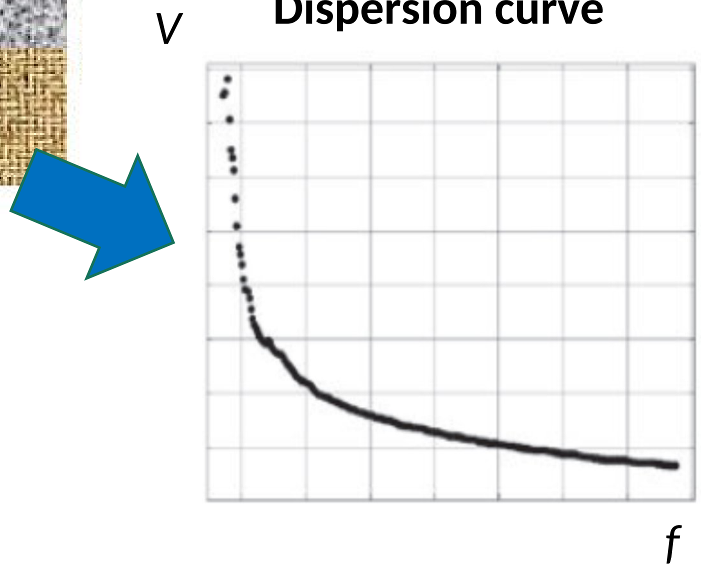
Phase 3:

Measure group and/or phase velocity

Dispersive propagation



Dispersion curve



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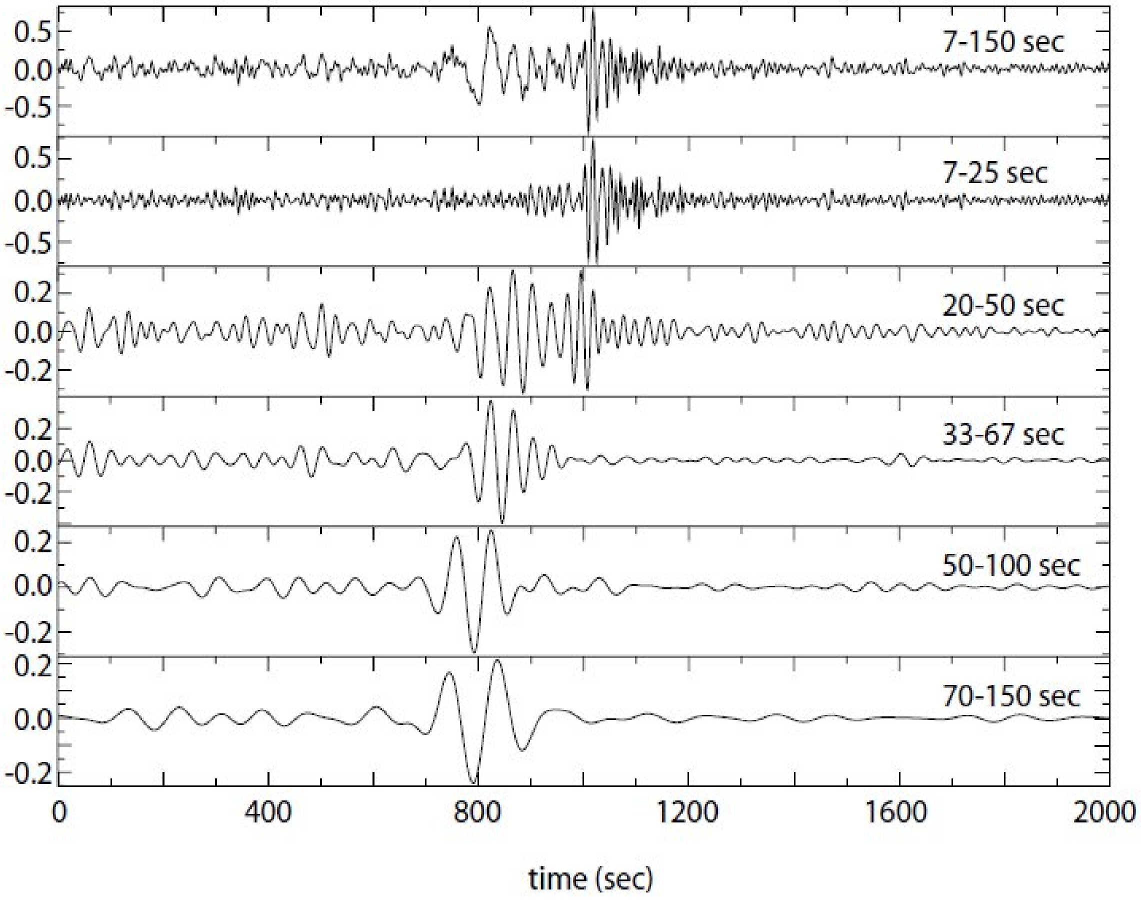
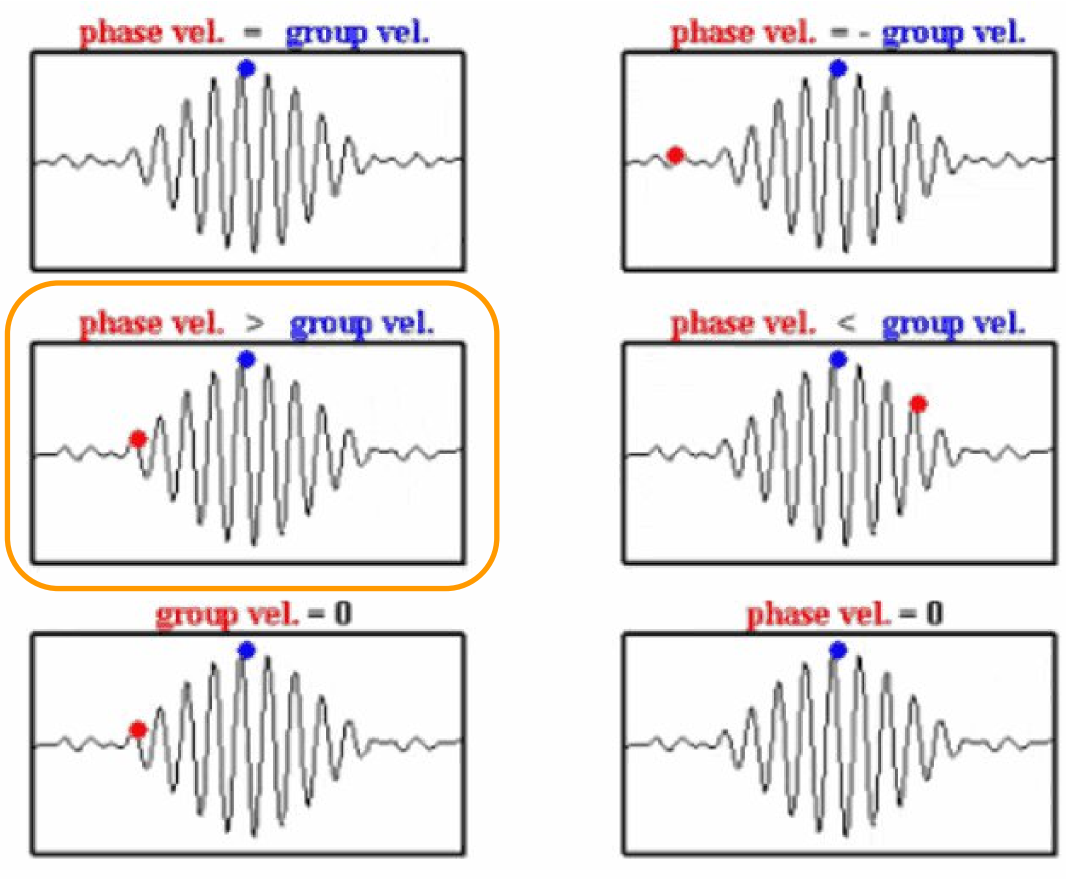


Bensen et al., 2007

Passive seismic interferometry – surface wave velocities

- Two types of surface waves velocities can be measured:
  - The **phase velocity** is the velocity of propagation of individual phases
  - The **group velocity** is the velocity of propagation of the envelope of the wave.
- For surface waves, phase velocities are generally higher than group velocities.
- Both phase and group surface wave velocities strongly depend on the distribution of **shear-wave velocity (Vs)** with depth.

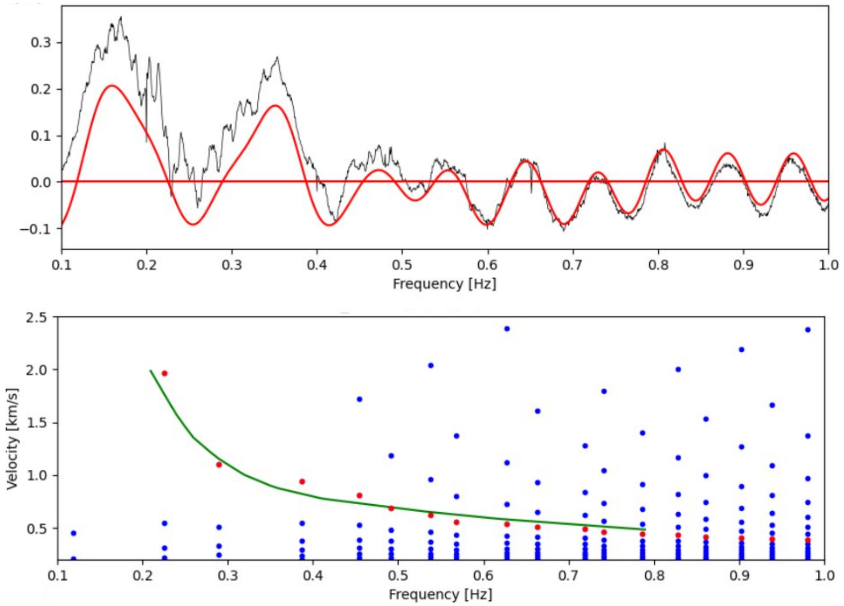


https://www.reddit.com/

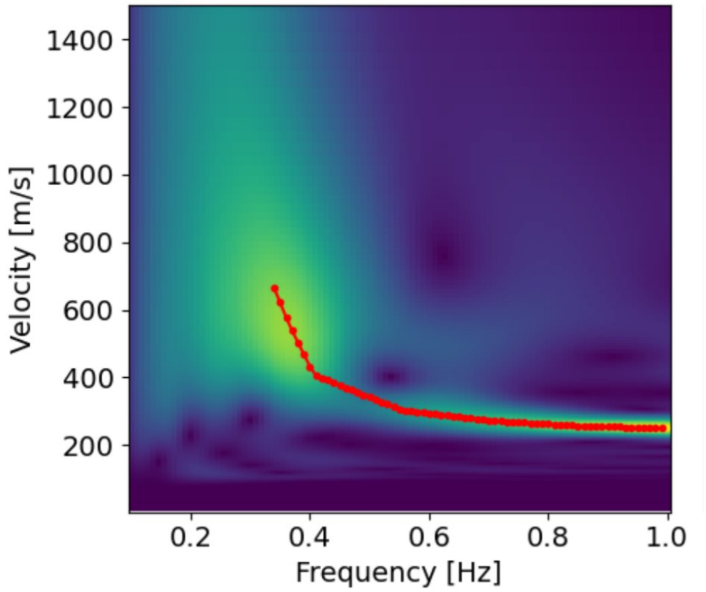
Passive seismic interferometry – surface wave velocities

- Several methods are available to derive surface wave velocities:
  - The **cross-spectra analysis** analyses the real part of the cross-spectrum and derives **phase velocities**
  - The **Frequency-Time Analysis** - **FTAN** (Dziewonski et al., 1969) allows the computation of **group velocities**

CROSS SPECTRUM



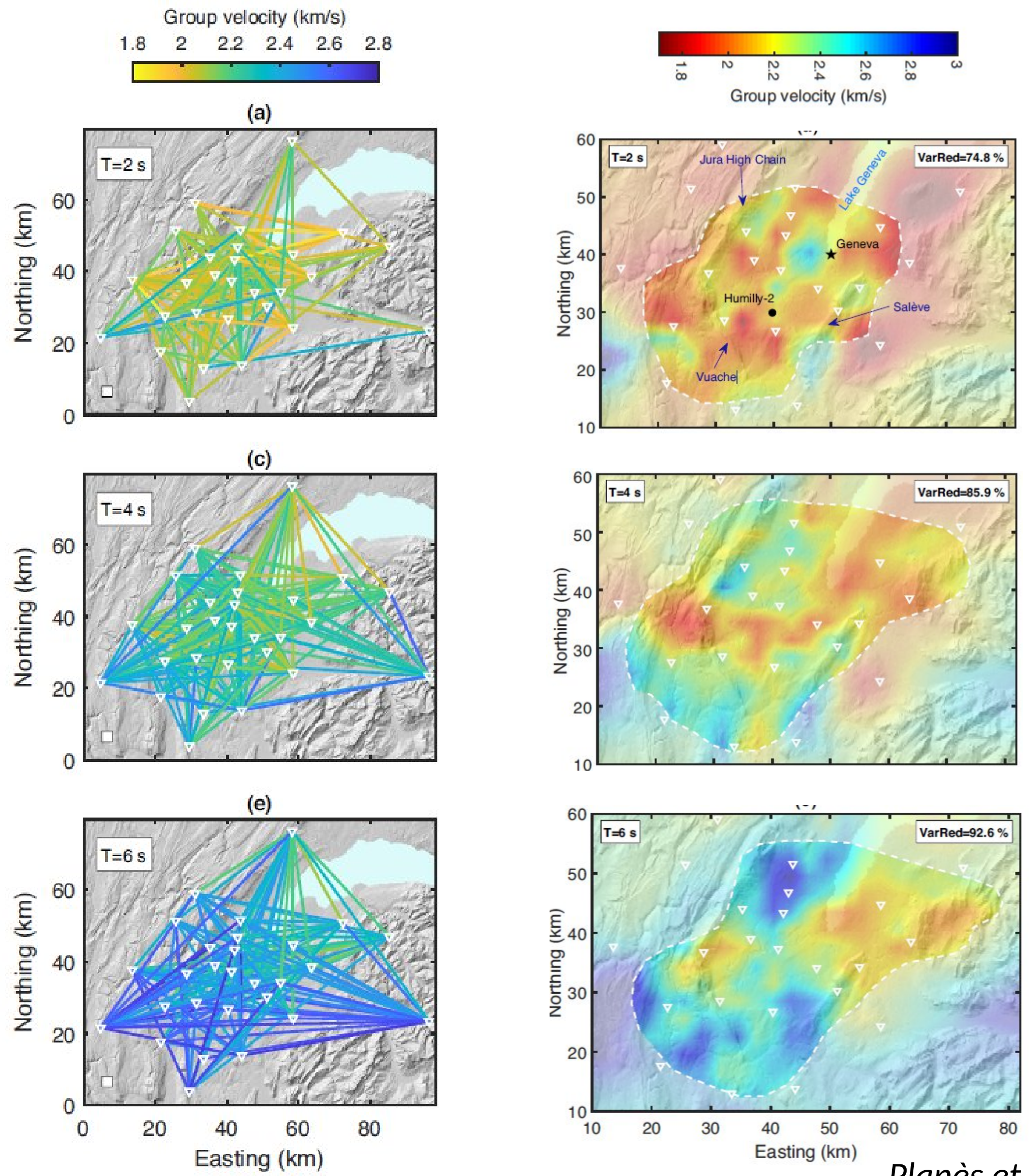
FTAN



Barone et al., 2024

Ambient noise tomography

- Combination of passive seismic interferometry and **surface wave tomography** allows the retrieval of the spatial distribution of seismic velocities for different frequencies.
- **Depth inversion** is then needed to infer shear-wave velocities (Vs) as a function of depth.
- The final **3D Vs model** can be used for:
  - ➢ Earthquake localization
  - ➢ Structural interpretation
  - ➢ Identification of buried manufactures
  - ➢ Etc.



Planès et al., 2020

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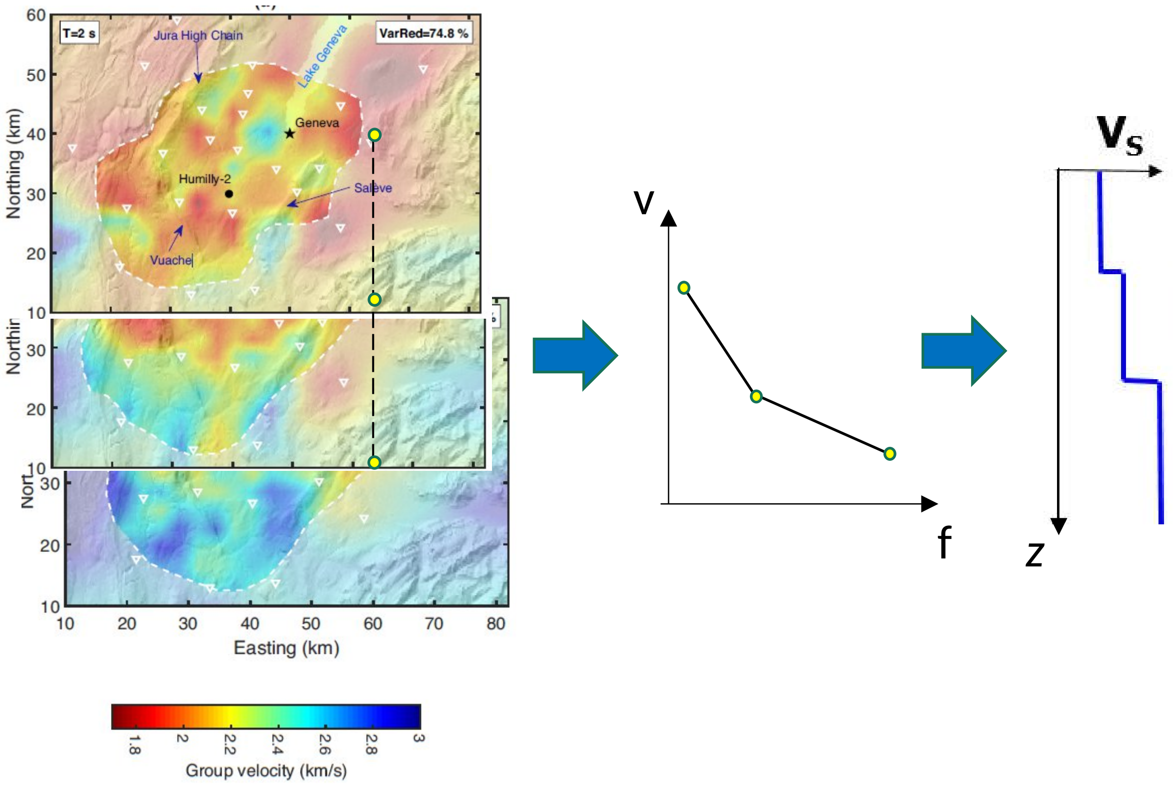

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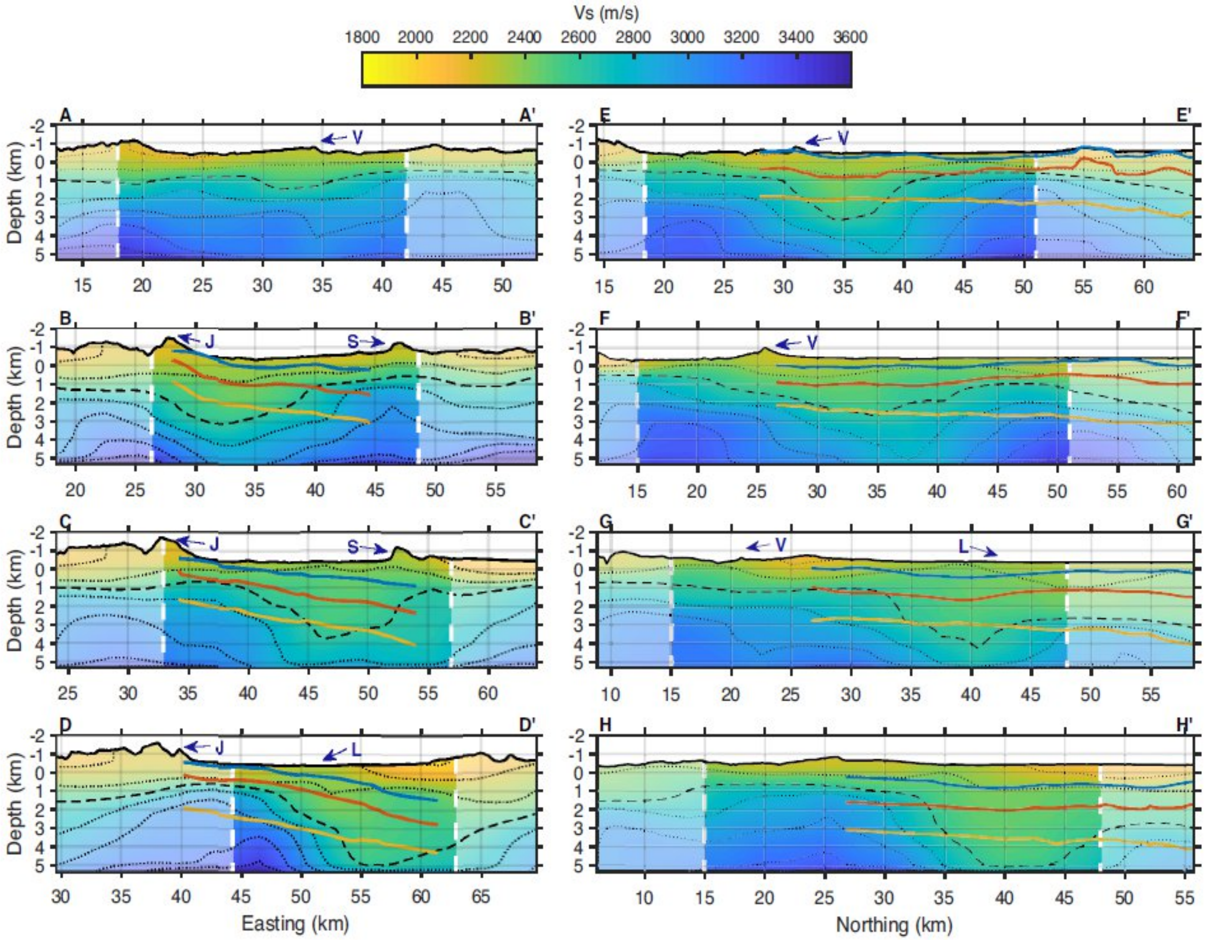
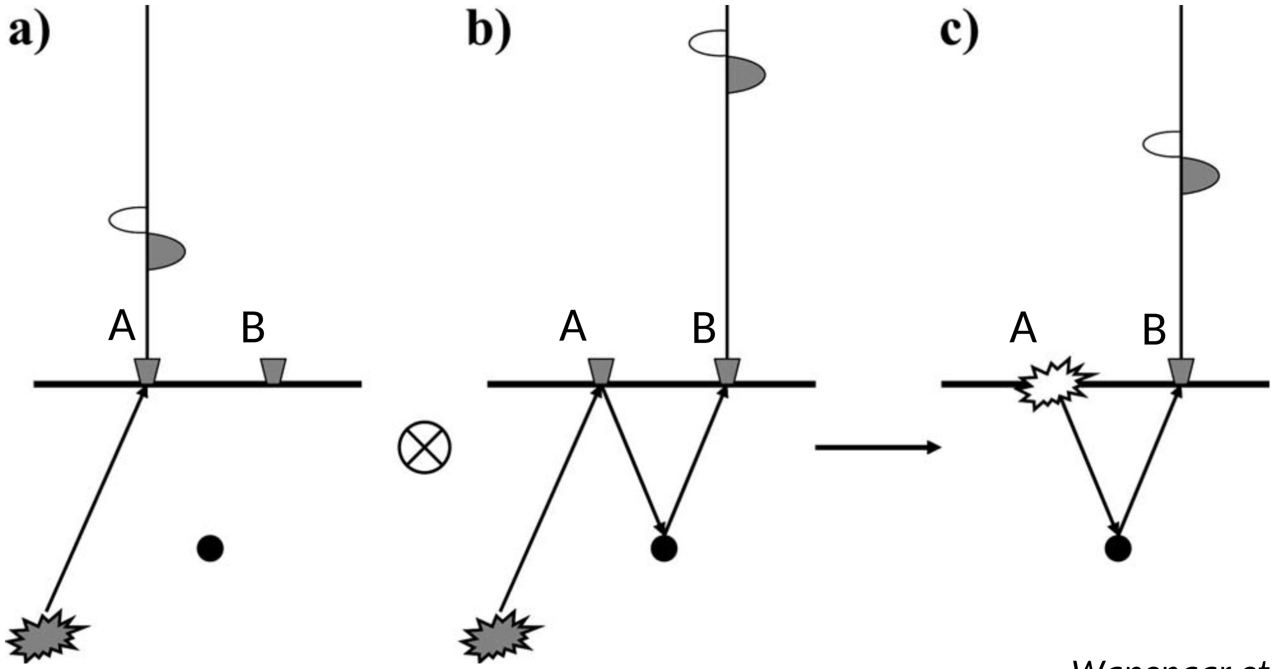


Planès et al., 2020

Reflected-wave interferometry

- **Reflections** can also be reconstructed through **passive seismic interferometry**, provided that we have **deep noise sources**.
- Crosscorrelation of noise data virtually eliminates the path from the source to the first receiver.



Wapenaar et al., 2010

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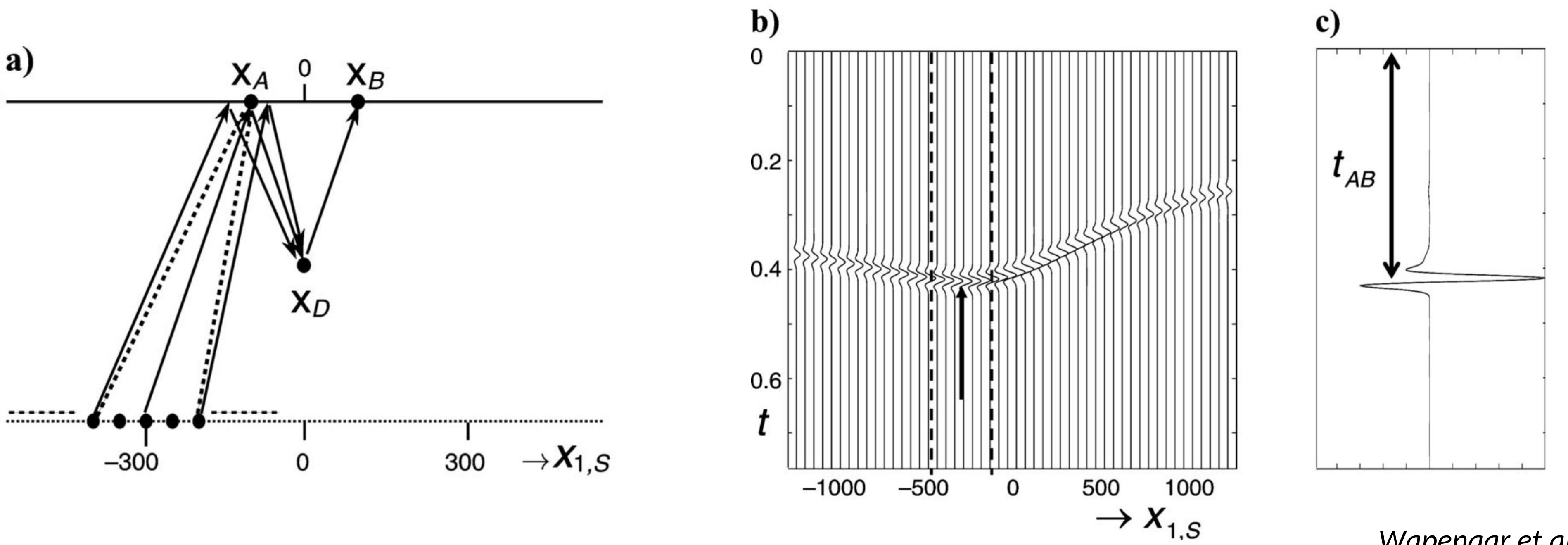
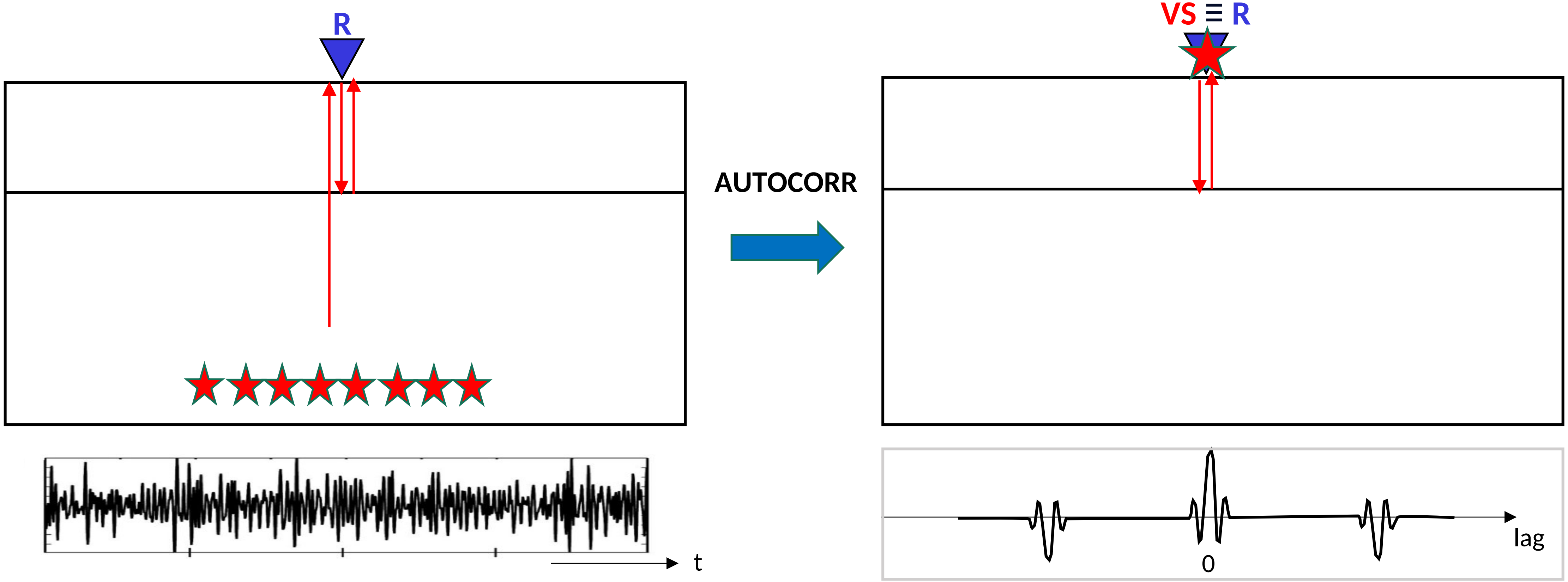


Wapenaar et al., 2010

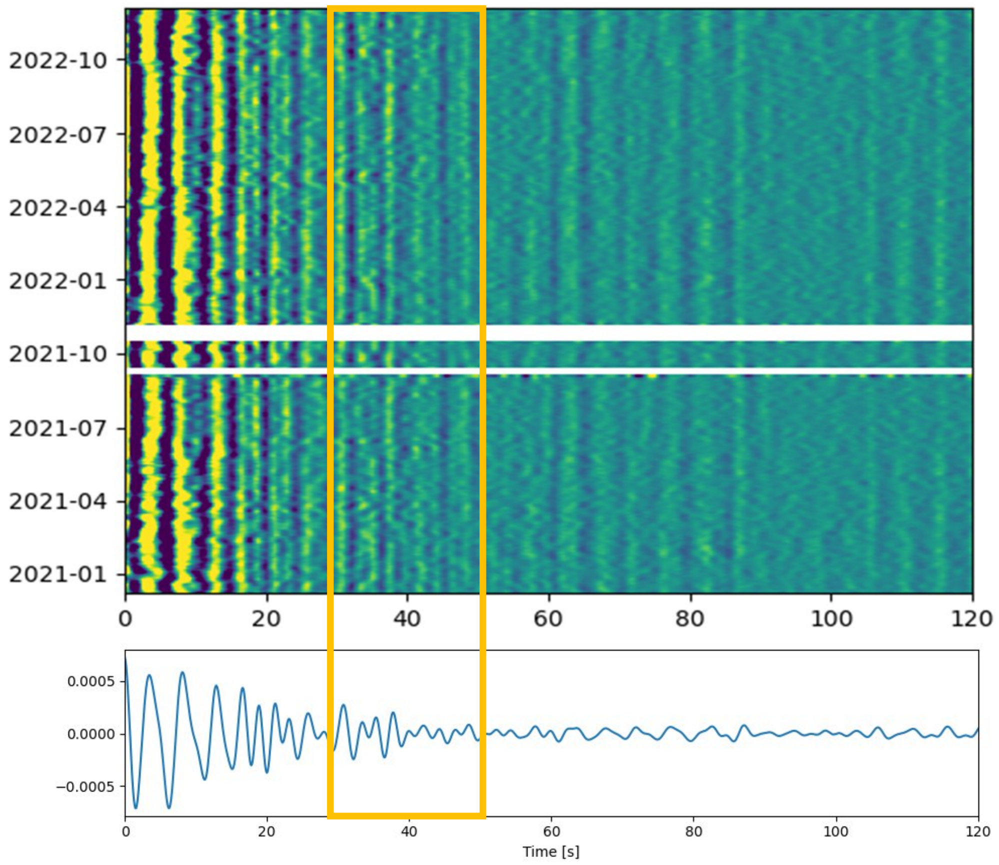
Reflected-wave interferometry

- This method is particularly interesting in the case of **single stations**: the noise record can be **autocorrelated** to get the Green's function at the station location, multiplied by -1.



Coda-wave interferometry

- **Dynamic analysis** can also be performed, in order to monitor possible changes in the seismic velocities (**coda wave interferometry**).
- Cross-correlations are computed for different time intervals (e.g., on a daily base).
- Possible **velocity variations** (stretching/compression) are detected in the coda of the cross-correlation.
- NB: The choice for the coda is to get rid of possible **effects due to the variation of the noise source directionality**!



WAVEFORM COHERENCE:

$$CC(\varepsilon) = \frac{\int_{t_1}^{t_2} \varphi^{\mathrm{curr}}[t(1-\varepsilon)]\,\varphi^{\mathrm{ref}}[t]\mathrm{d}t}{\sqrt{\int_{t_1}^{t_2} (\varphi^{\mathrm{curr}})^2[t(1-\varepsilon)]\,\mathrm{d}t \int_{t_1}^{t_2} (\varphi^{\mathrm{ref}})^2[t]\mathrm{d}t}}$$

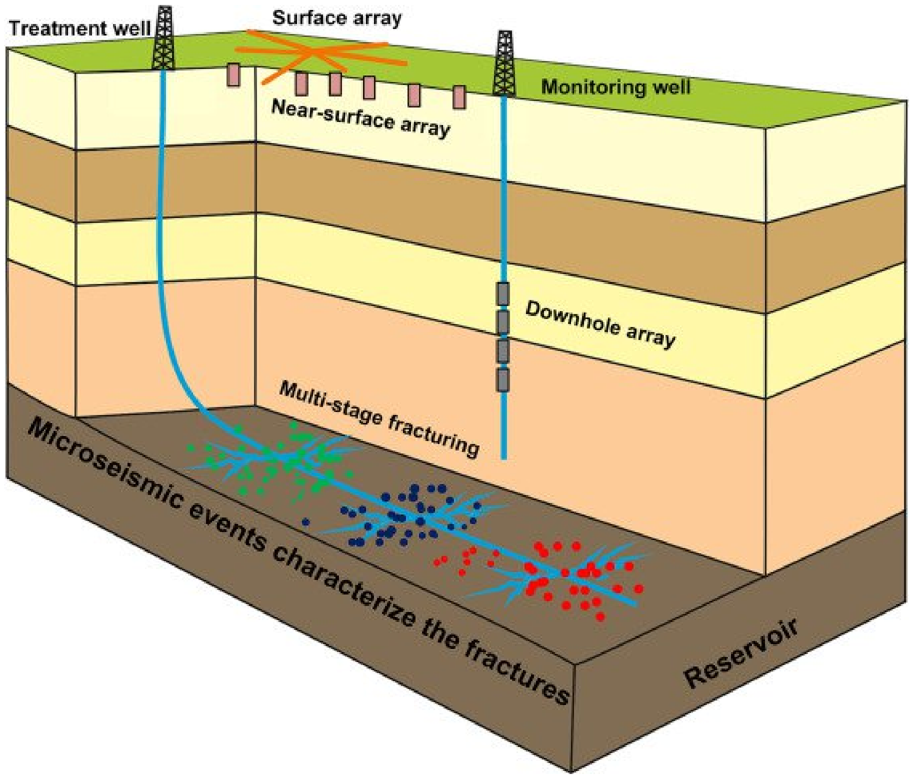
VELOCITY VARIATION:

$\varepsilon = -dt/t = dv/v$

REAL-CASE STUDIES

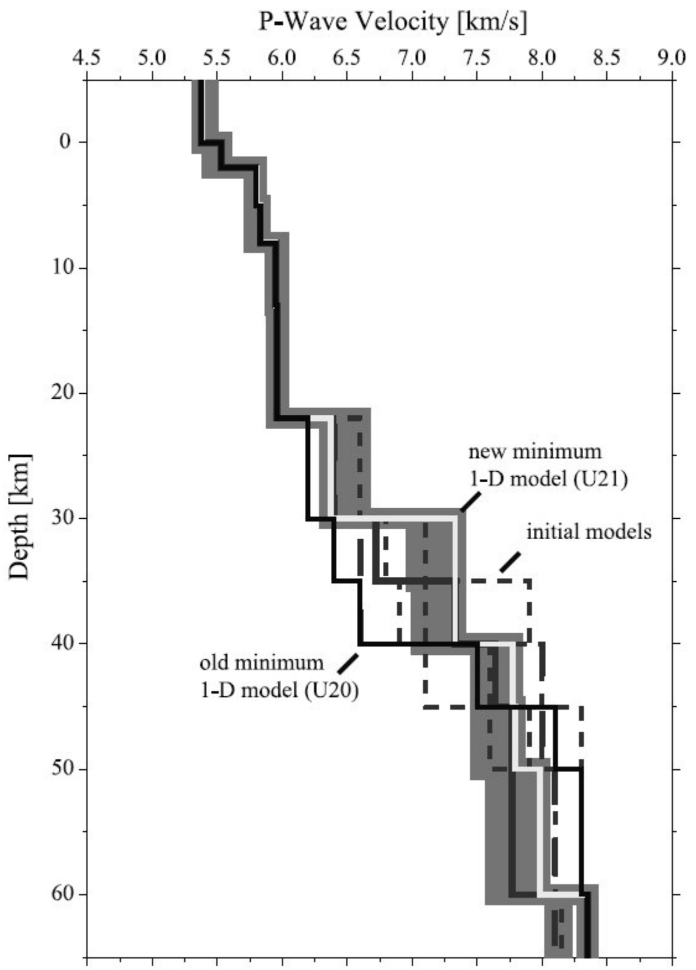
Reservoir scale study – Microseismic monitoring network

- Micro-seismicity monitoring is key to ensure safe operations when **injecting/producing fluids** in the subsurface.
- It is used to locate seismic/microseismic events in the vicinity of the reservoirs.
- Common networks include surface, near-surface and downhole stations, with inter-station distances of a few to several kilometers.
- A correct location of microseismic events depends on:
  - ✓ The number of stations recording the event
  - ✓ A correct picking of P- and S- phases
  - ✓ **An accurate P- and S-wave velocity model**
  - ✓ The location algorithm used



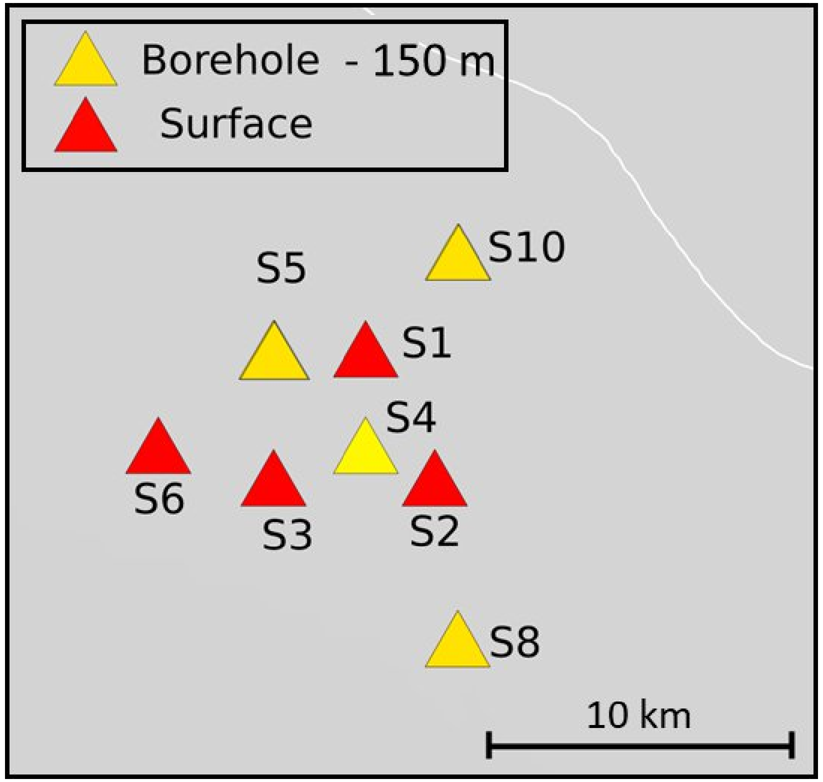
Reservoir scale study – Microseismic monitoring network

- While P-wave velocities can be constrained through reflection seismic, S-wave velocities are difficult to measure, especially in an intermediate depth range:
  - ✓ **Regional models** are generally available from literature, which are not representative of the local conditions.
  - ✓ **Well-log data** could also be available, but it refers to single locations and to a limited depth range.
  - ✓ In absence of any Vs measure, **empirical Vp/Vs relations** are used.
- We use the continuous ambient noise data recorded by micro-seismicity monitoring networks to derive a S-wave velocity model of the subsurface.



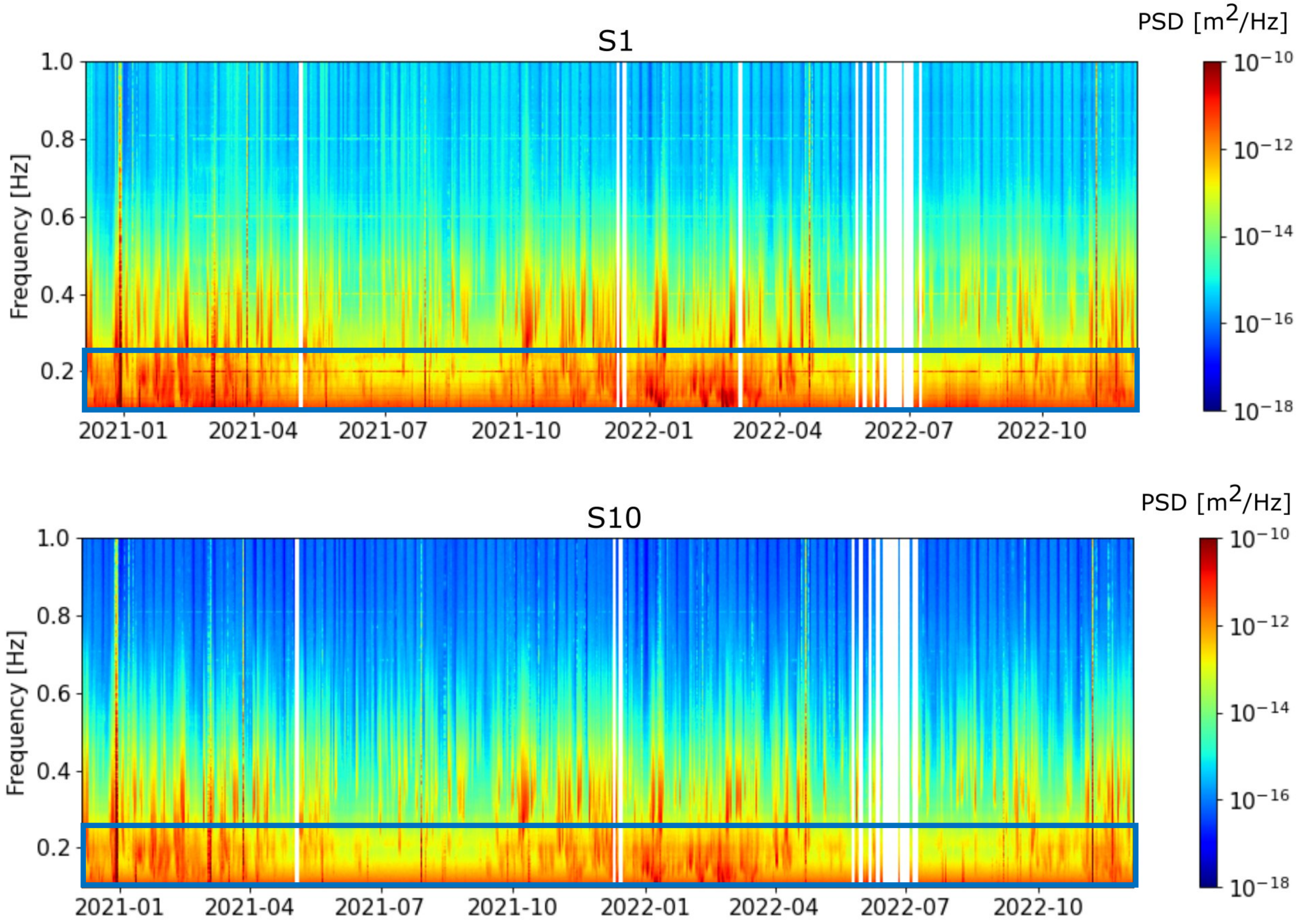
Reservoir scale study – Microseismic monitoring network

- Permanent local seismic network deployed around a **gas storage site**.
- The network is located in an alluvial plane (flat topography).
- The distribution of anthropic noise sources is rather homogeneous.
- Data from **8 seismic stations**: 4 at the surface, 4 in a shallow borehole (150 m).
- 3-component short period seismometers (1 s).
- Inter-station distances between 2.2 km and 13.5 km.
- Analysis of 2 **years of continuous data**, only **Z component**.



Reservoir scale study – Microseismic monitoring network

- The noise distribution in time shows different behaviours for different frequency bands:
  - **Microseismic range (0.1 - 0.25 Hz)** ☾ seasonality (1 year period)
  - **Intermediate range (0.25 – 0.5 Hz)** ☾ sparse amplitude peaks, with 2-3 days duration, associated to local wind-generated sea waves
  - **Anthropic range (> 0.5 Hz)** ☾ weekly pattern



Reservoir scale study – Microseismic monitoring network

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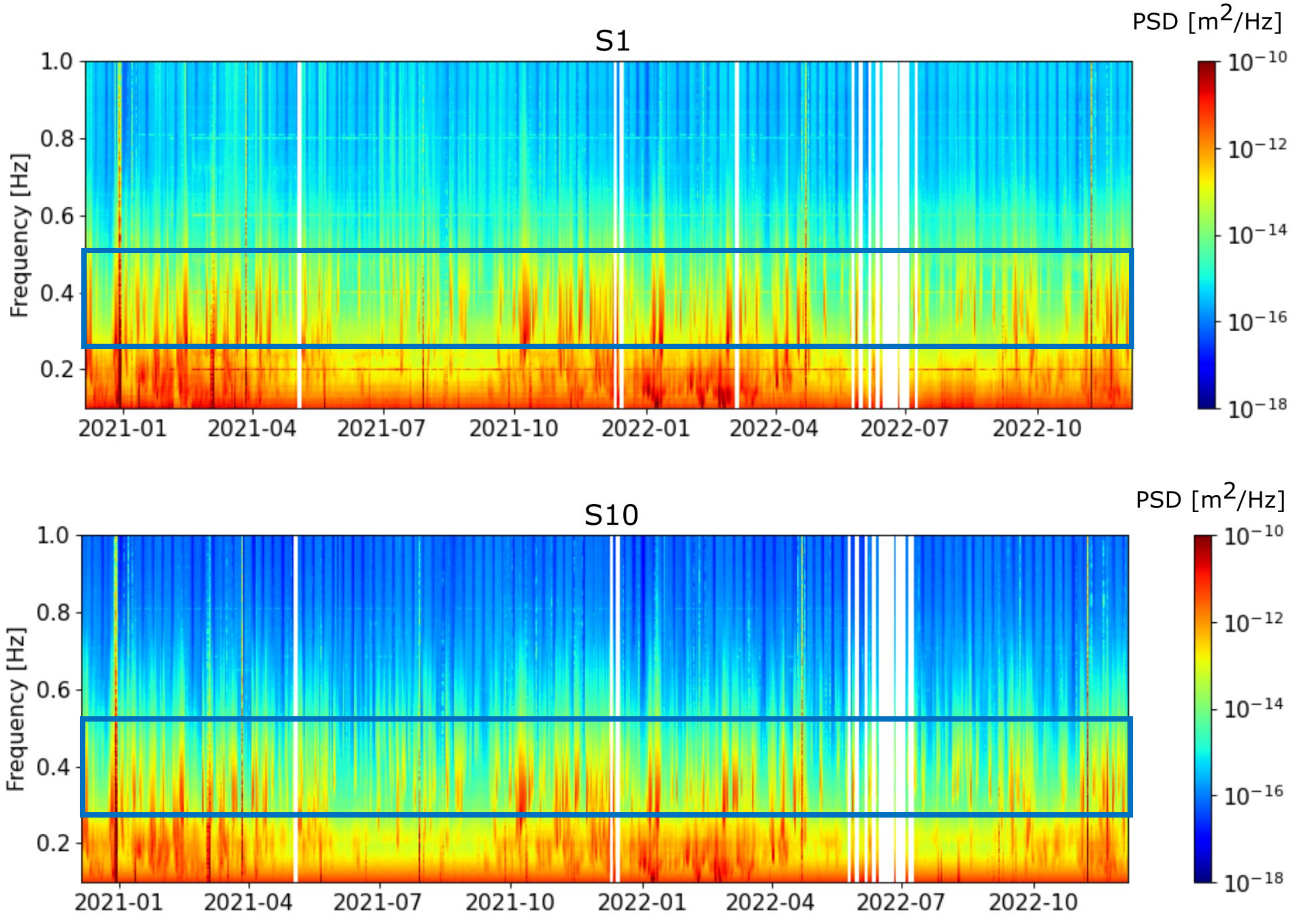

Reservoir scale study – Microseismic monitoring network

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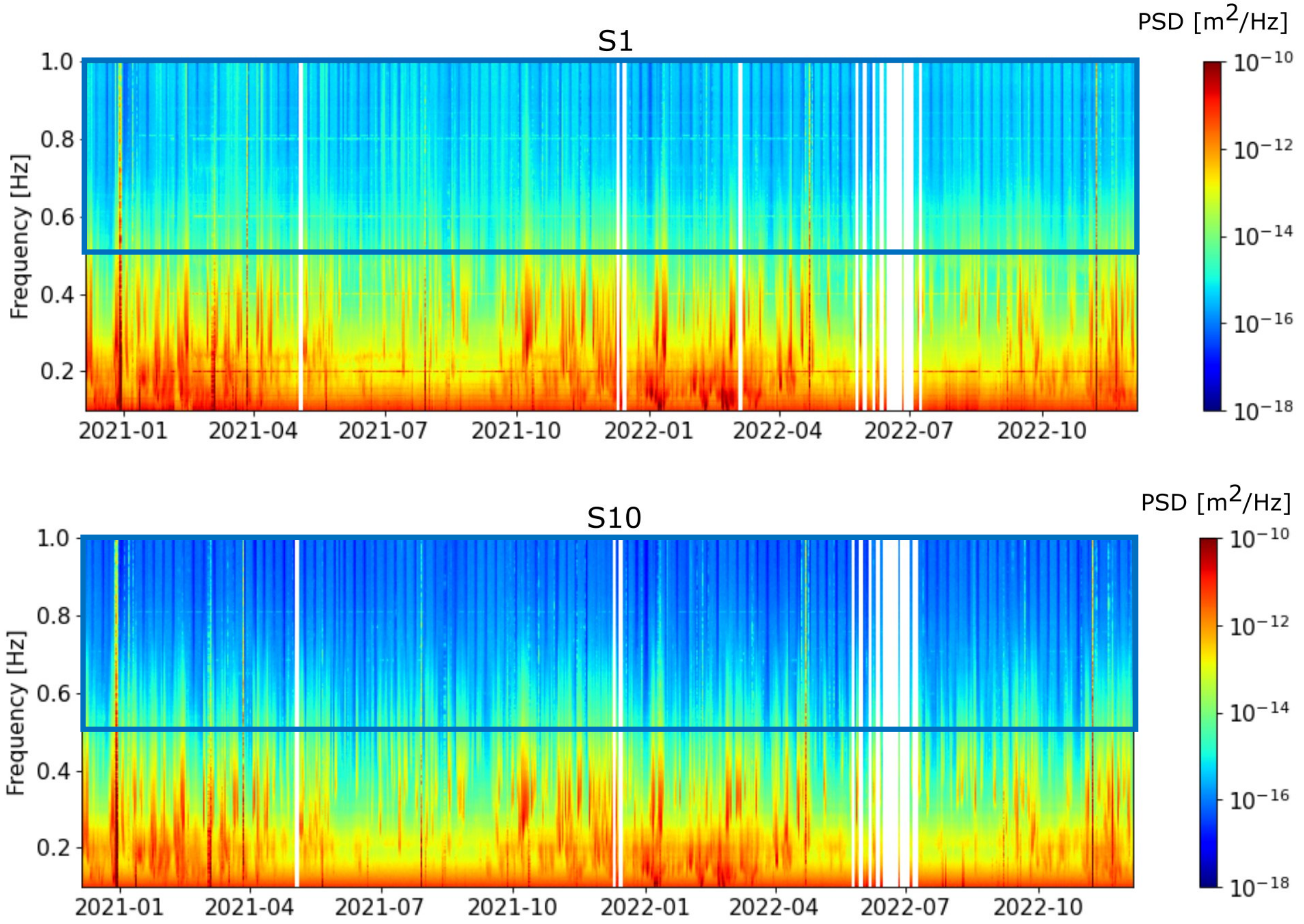
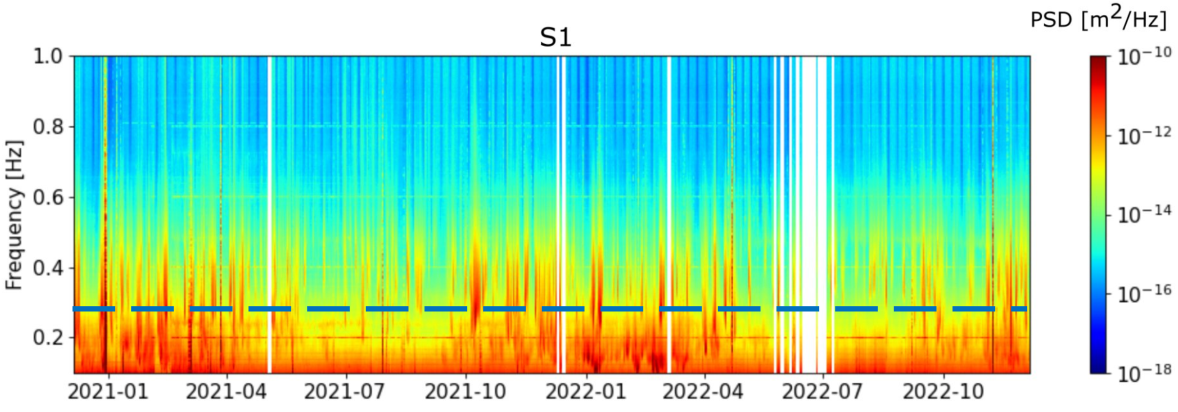
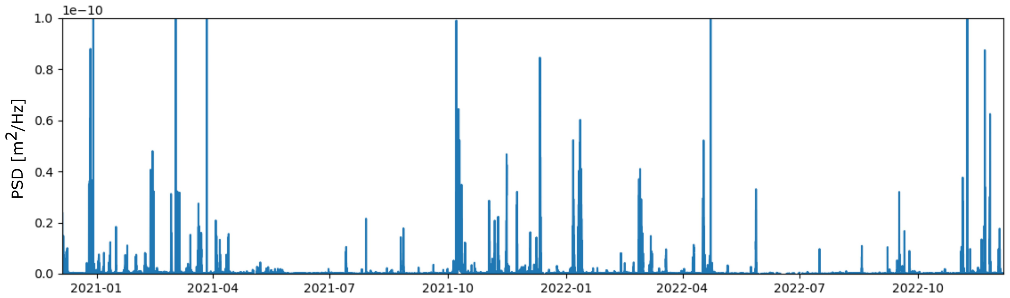
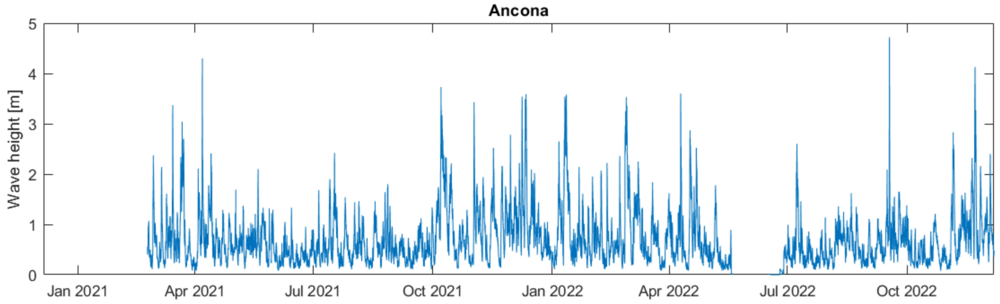
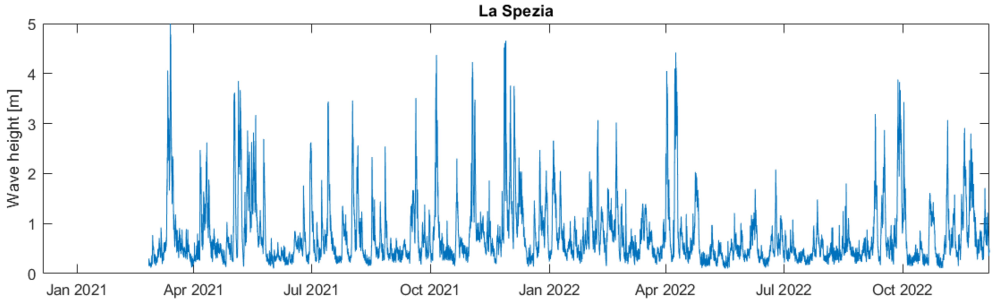


Reservoir scale study – Microseismic monitoring network



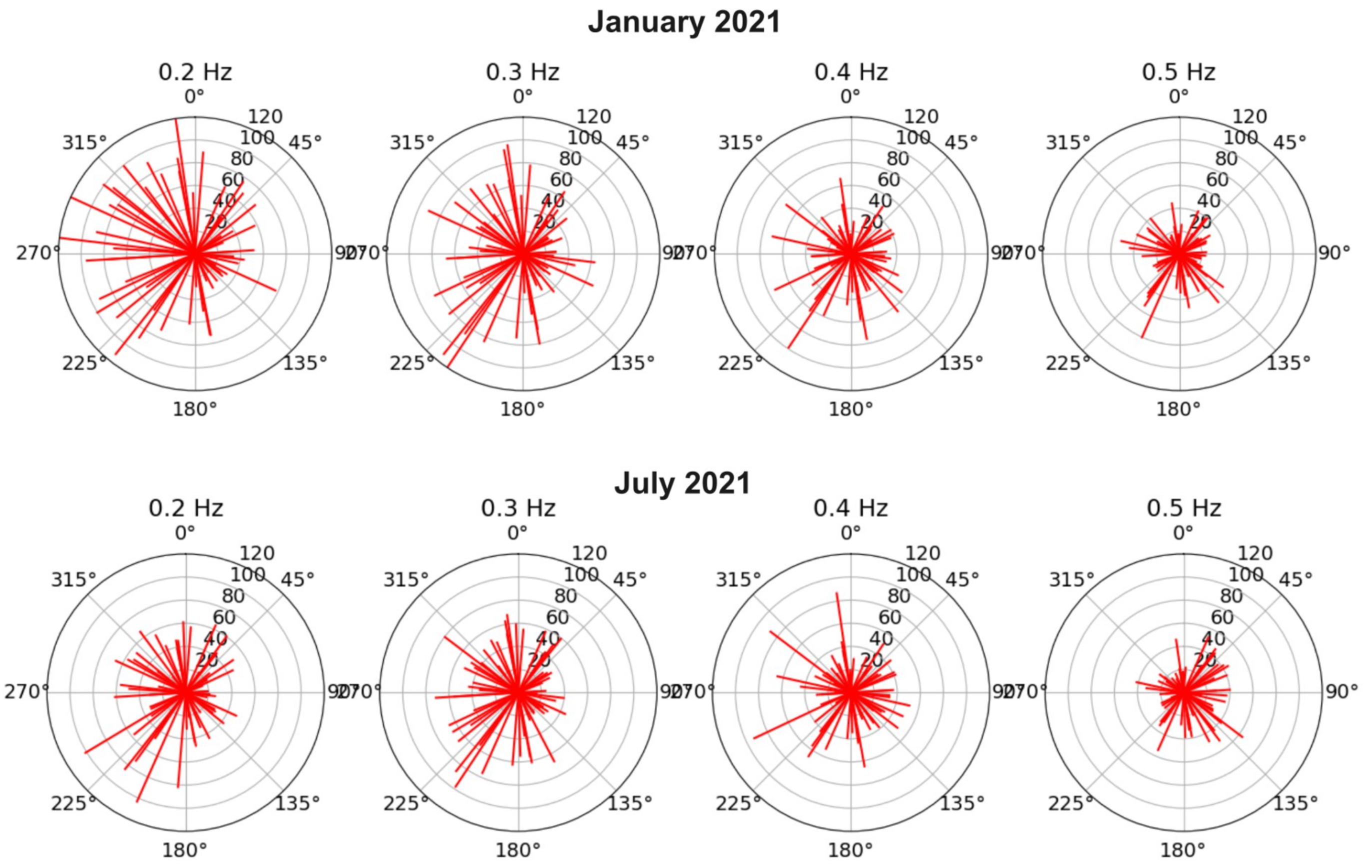




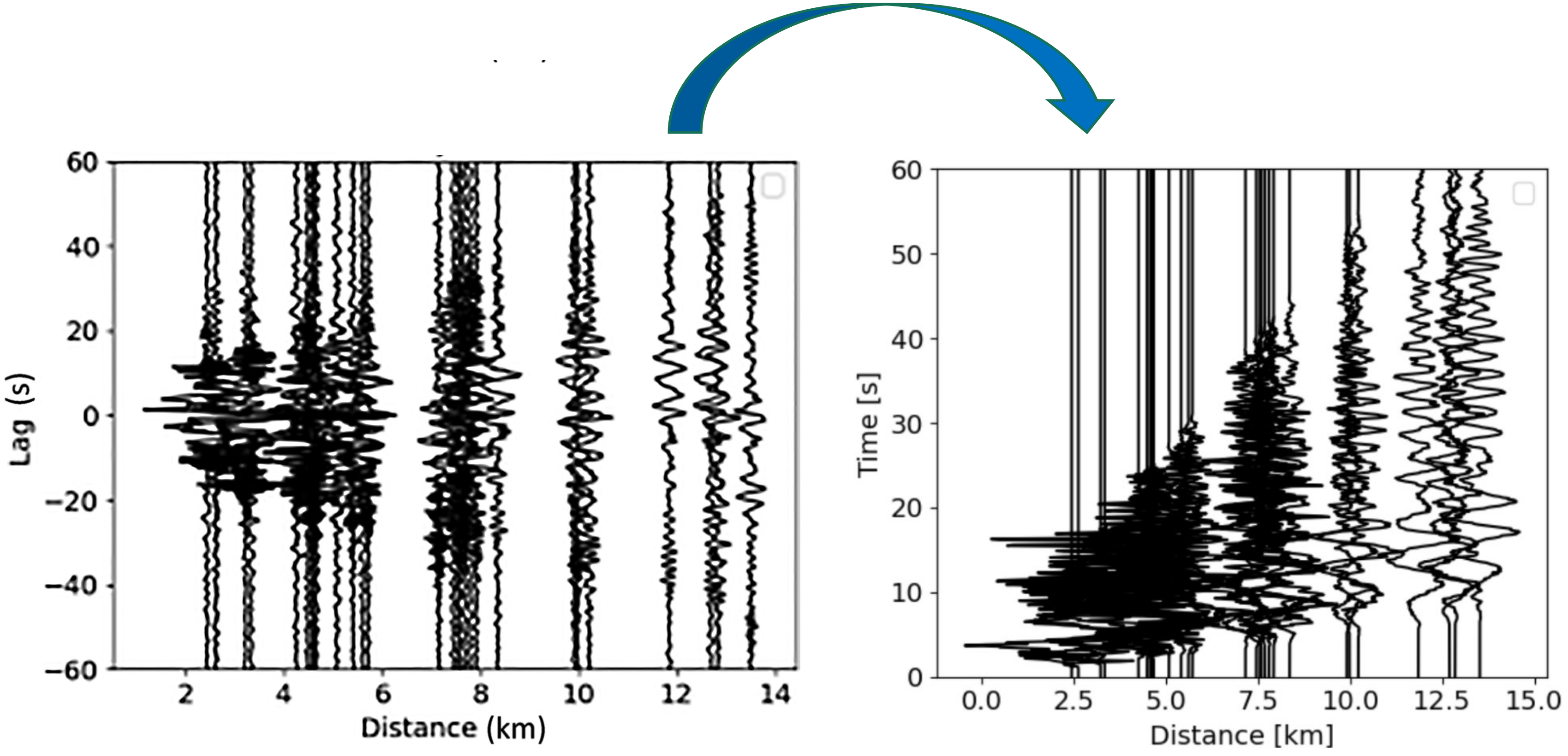


Reservoir scale study – Microseismic monitoring network

- Strong **seasonal effects** are evident in the **secondary microseisms range**, where stronger noise is propagating from North-West (Atlantic Ocean) during winter.
- Slight differences are also observable in the intermediate frequency range, although the general pattern is unchanged.



Reservoir scale study – Microseismic monitoring network



SELECTION OF 30 m WINDOWS

↓

PRE-PROCESSING (de-spiking, de-mean,

↓

SPECTRAL WHITENING

↓

CROSS-CORRELATION

↓

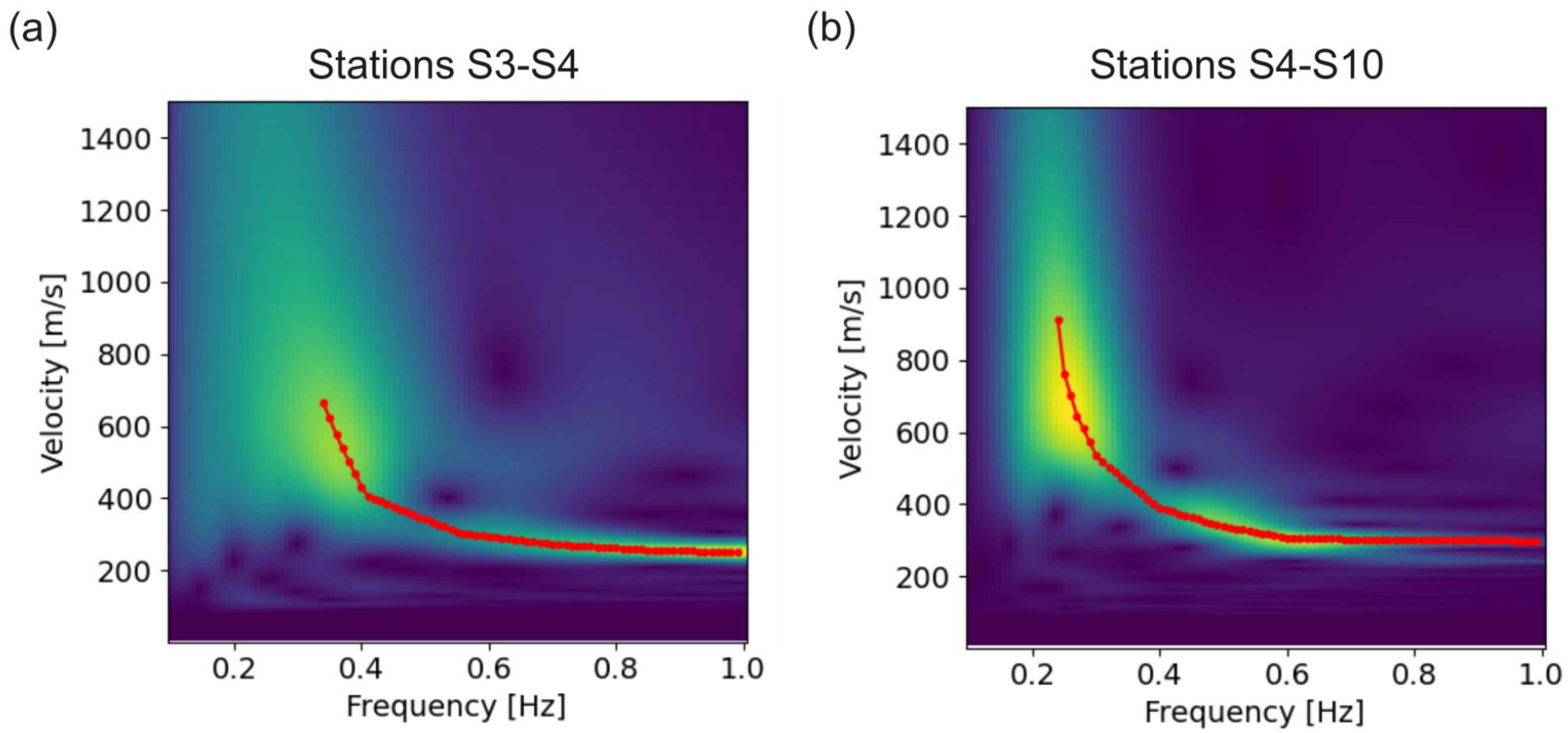
STACK OVER DIFFERENT WINDOWS

↓

POSITIVE-LAG AND NEGATIVE-LAG AVERAGE

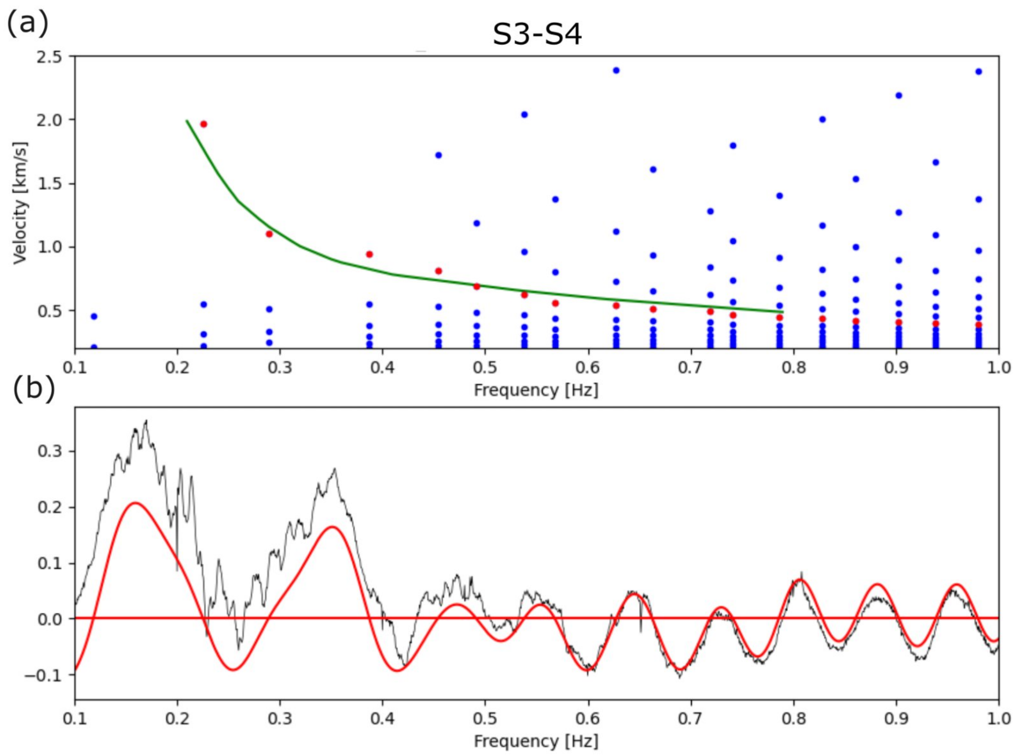
Reservoir scale study – Microseismic monitoring network

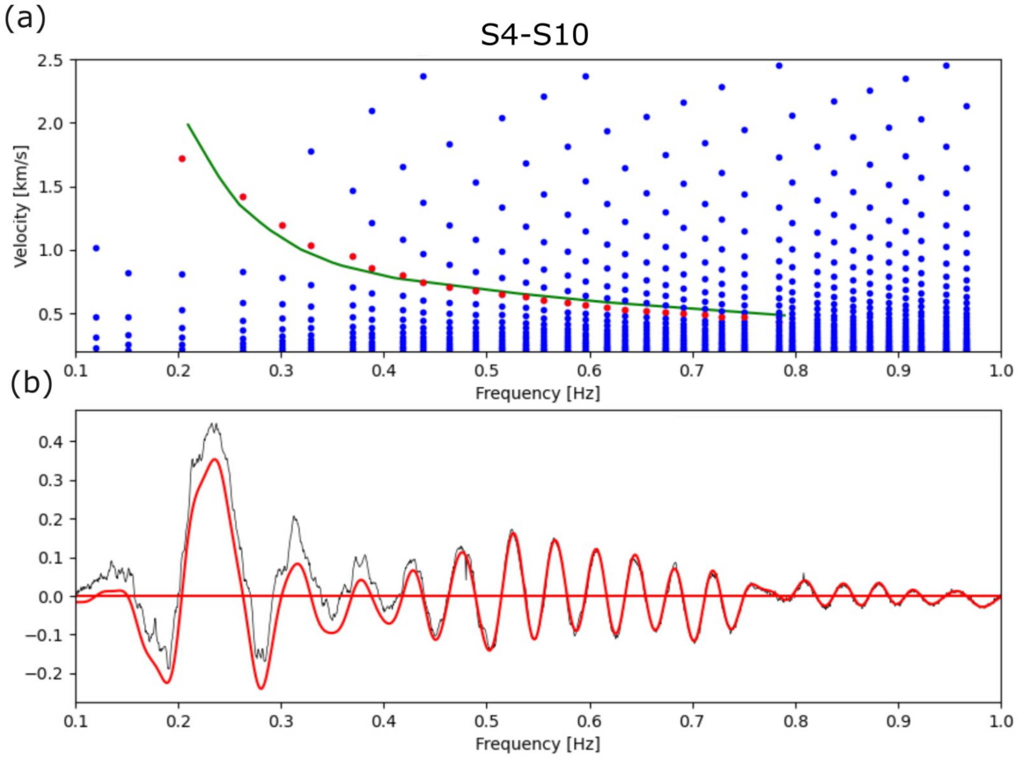
- The **FTAN method** has been applied to infer **group velocity dispersion curves** for all receiver pairs.



Reservoir scale study – Microseismic monitoring network

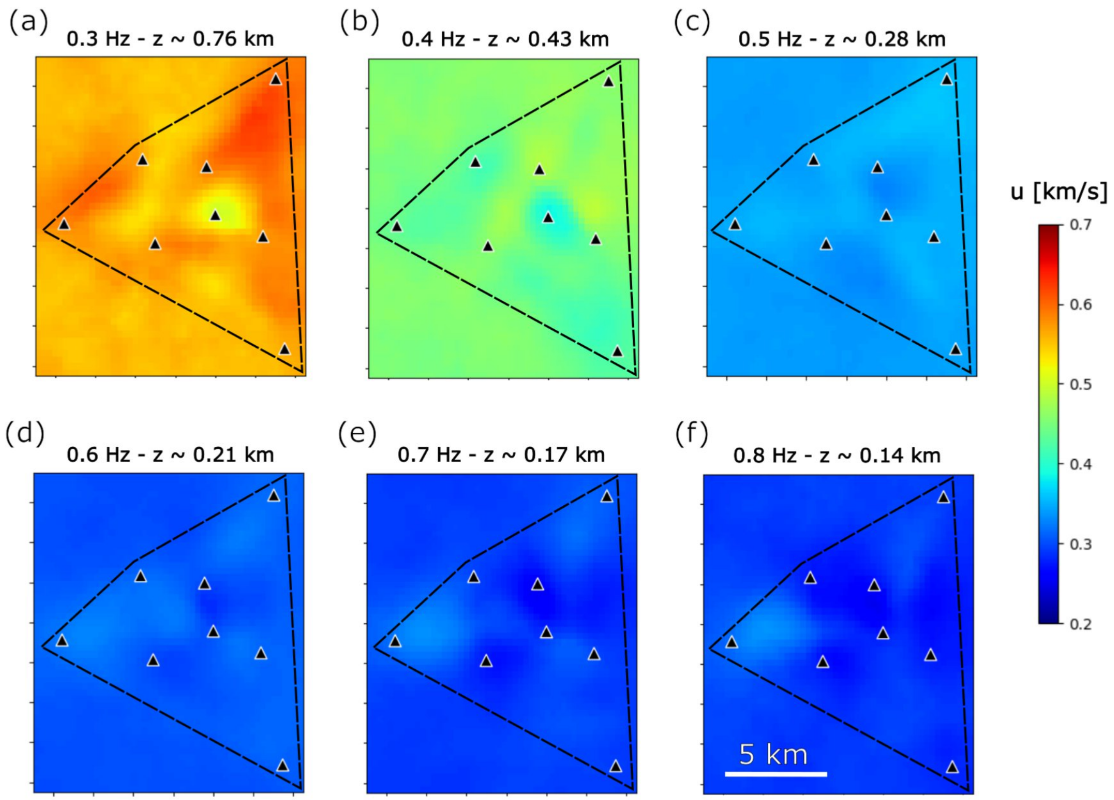
- The **analysis of cross-spectra** has been applied to infer **phase velocity dispersion curves** for all receiver pairs.

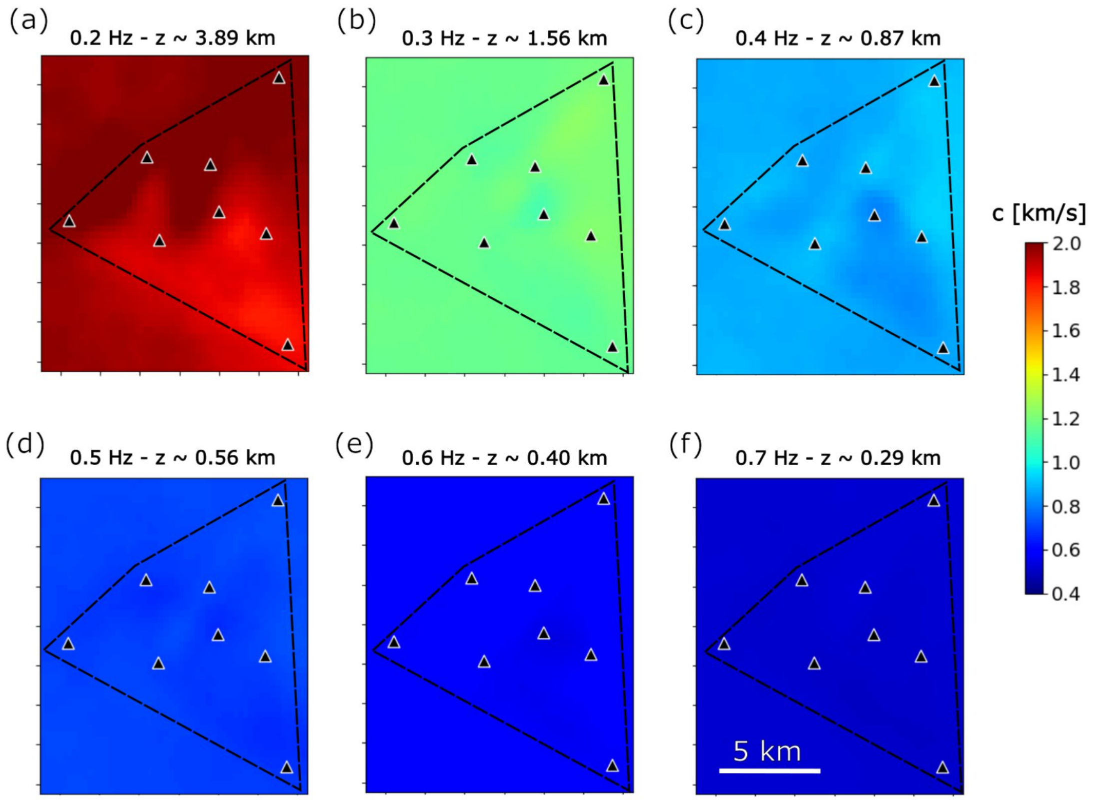




Reservoir scale study – Microseismic monitoring network

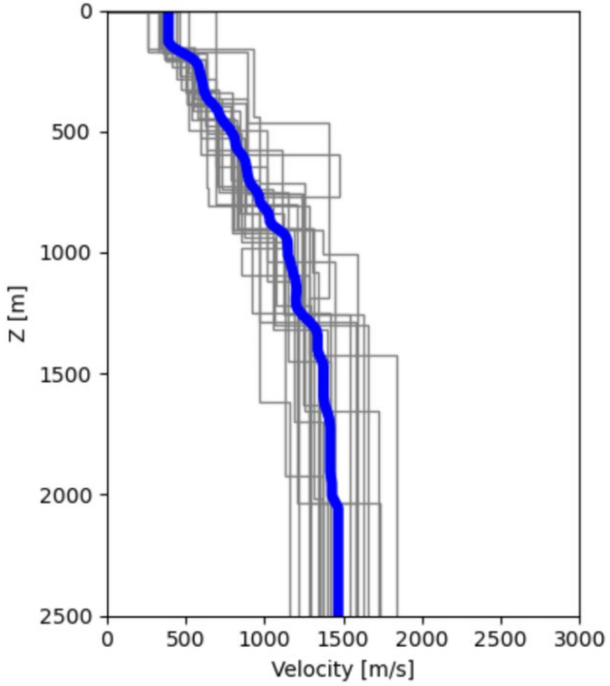
- **Surface wave tomography** has been applied to both group and pahse velocity measures to derive group and phase velocity maps.

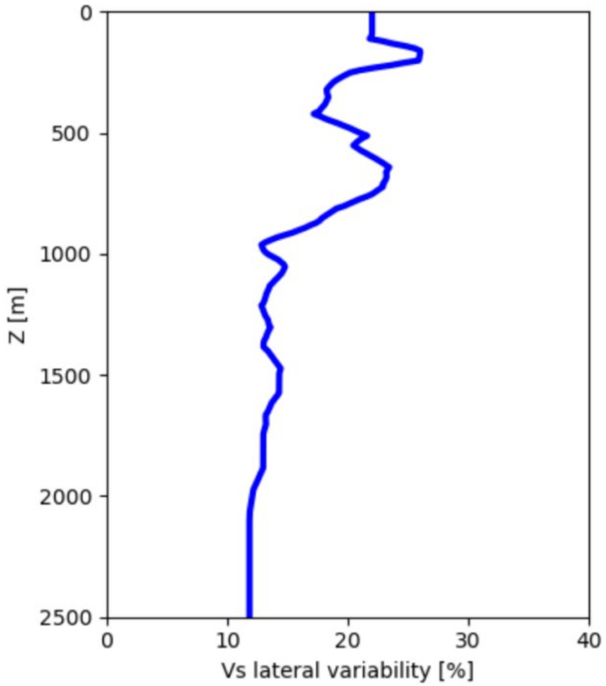




Reservoir scale study – Microseismic monitoring network

- Due to the **small lateral variability** observed, a **1D Vs velocity profile** was derived by jointly inverting all local group and phase dispersion curves and averaging them.
- This Vs profile can be used to precisely locate seismic events around the reservoir.

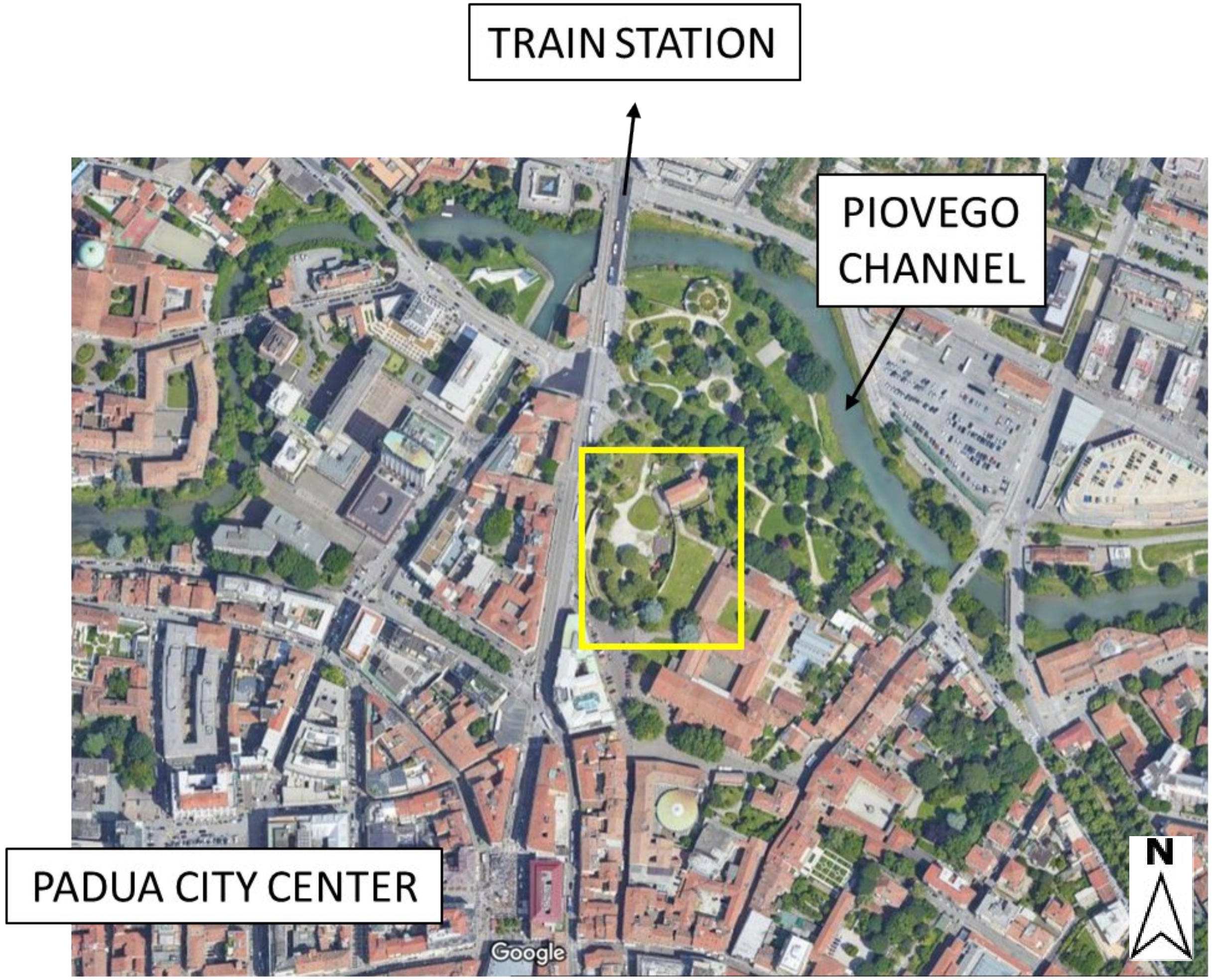


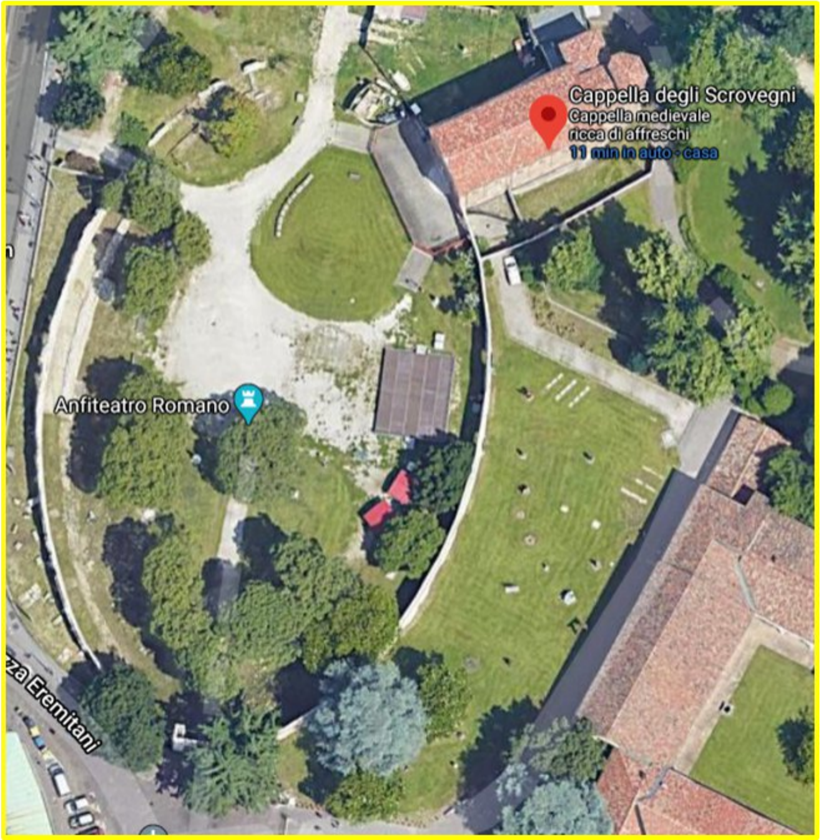


Engineering scale study – the Scrovegni Chapel

- The **Scrovegni Chapel in Padua**, with its famous **Giotto's fresco cycle,** as been recenty included in the **UNESCO world heritage list**.
- The chapel is located in a **very complex area**: remains of different historical buildings coexist, including a **Roman amphitheatre**, generating extremely heterogeneous subsoil conditions.
- Many open questions: the **role of the crypt** of the chapel, the **position of the radials** of the amphitheatre, the possible **presence of a gallery** along the major axis of the amphitheatre, etc.
- Both **active and passive surface wave analysis** has been applied, using a dense 3D acquisition scheme (almost **1500 seismic nodes**!).

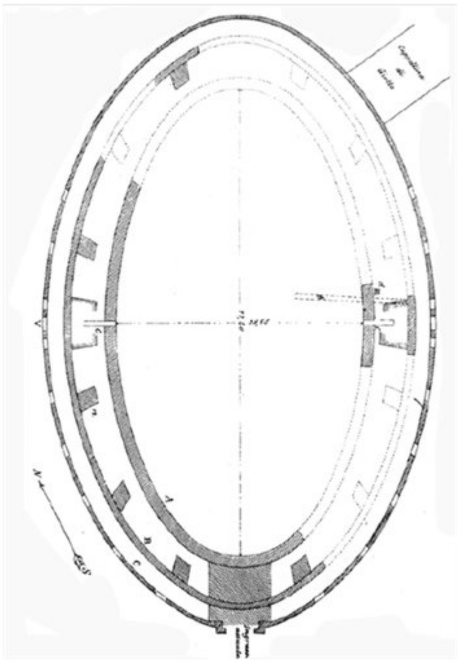
Engineering scale study – the Scrovegni Chapel



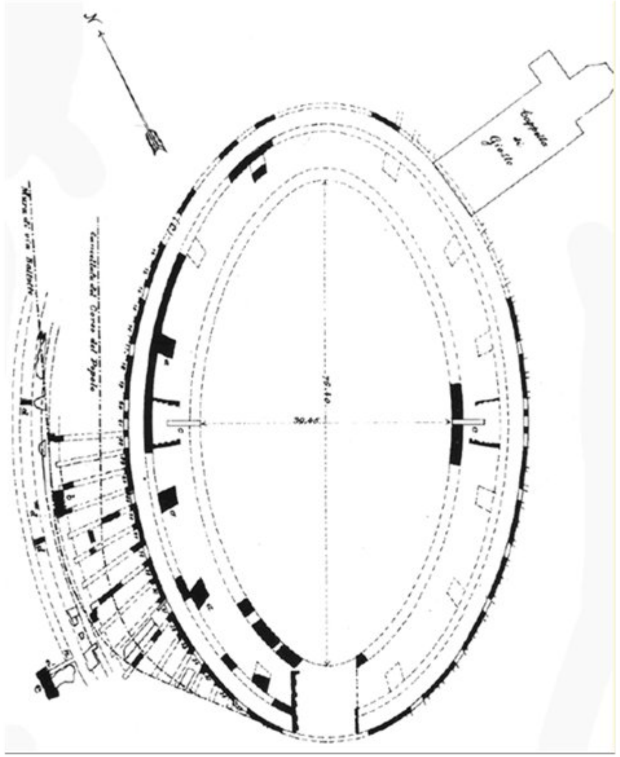


Engineering scale study – the Scrovegni Chapel

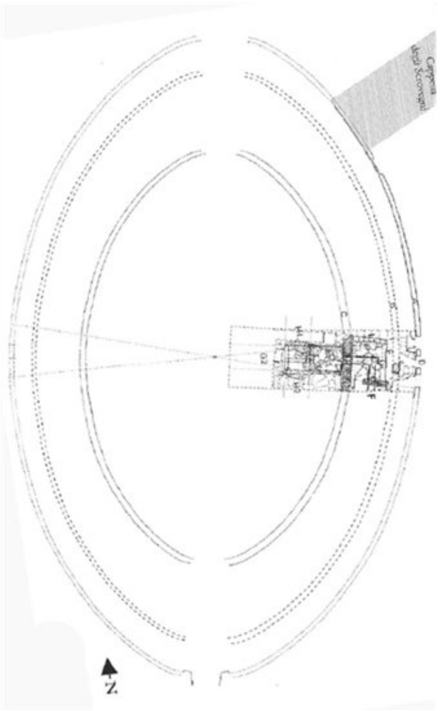
Excavations 1880-1881



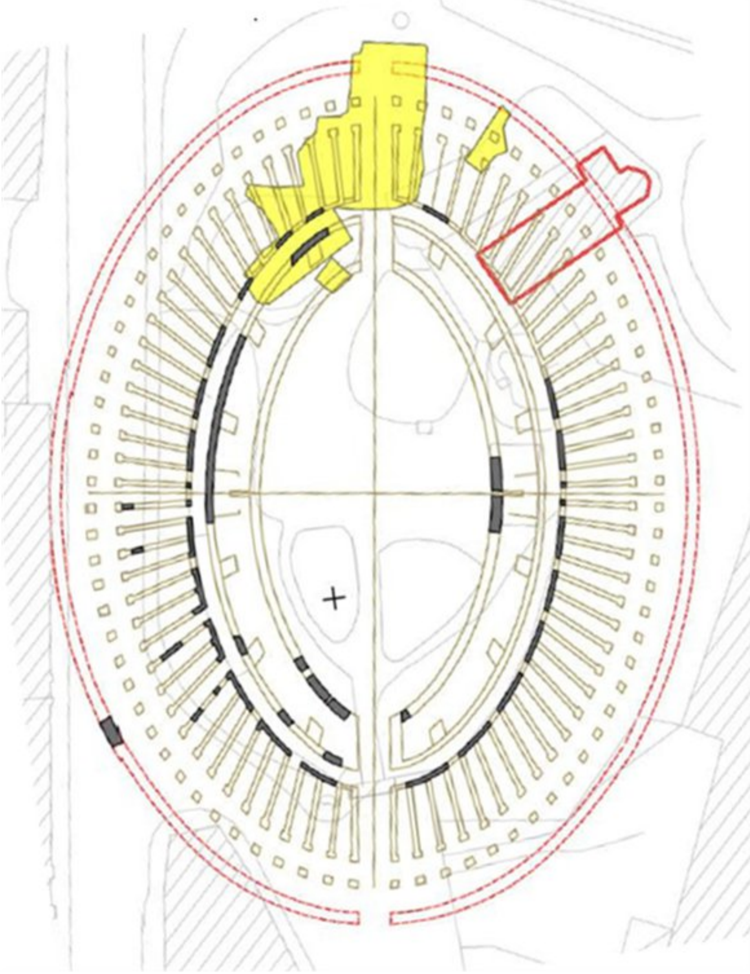
Excavations 1906-1907



Excavations 2006

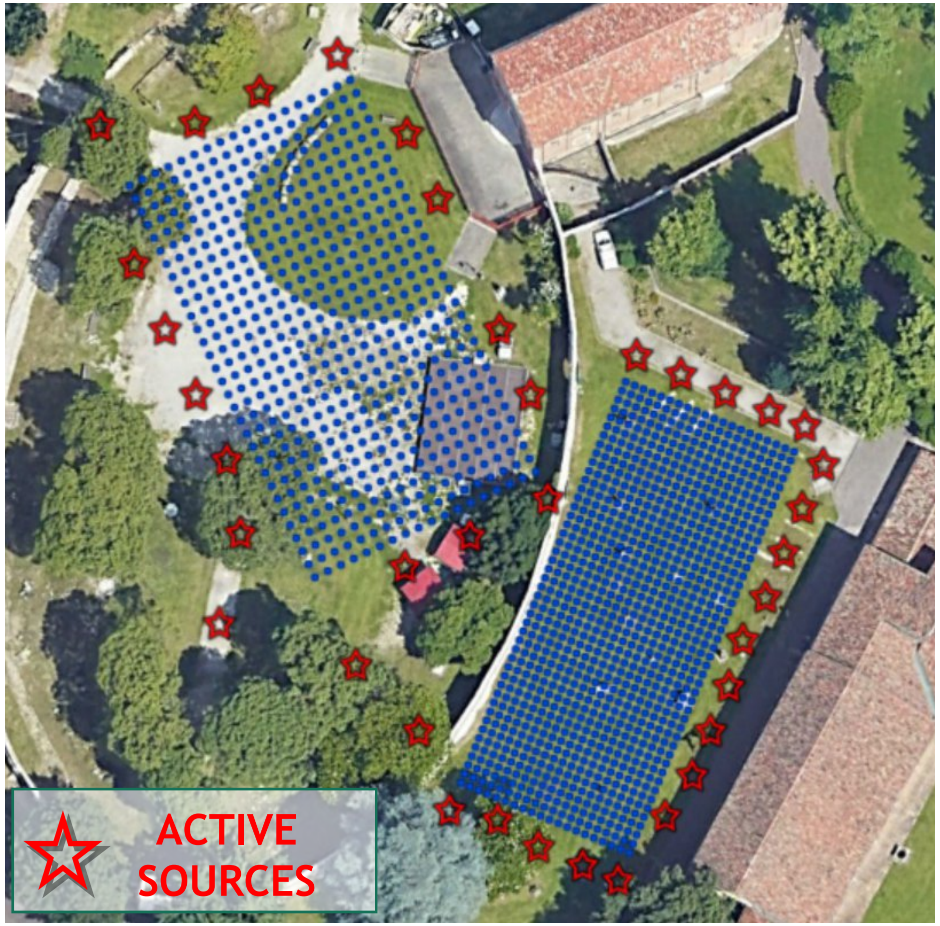


Excavations 2013



Engineering scale study – the Scrovegni Chapel

- **1478 single node vertical sensors** (Stryde nodes) covering two rectangular areas.
- X and Y spacing inside the amphitheatre: **1.5 m**.
- X and Y spacing outside the amphitheatre: **1 m**.
- About **22 hours passive+active** continuous recording.
- Active source: **weight drop** (70 kg from 1.5 m), **38 shot positions** all around the receivers, covering all azimuths.
- **Virtual sources**: all receivers at the sides of the two rectangles (94 + 128)



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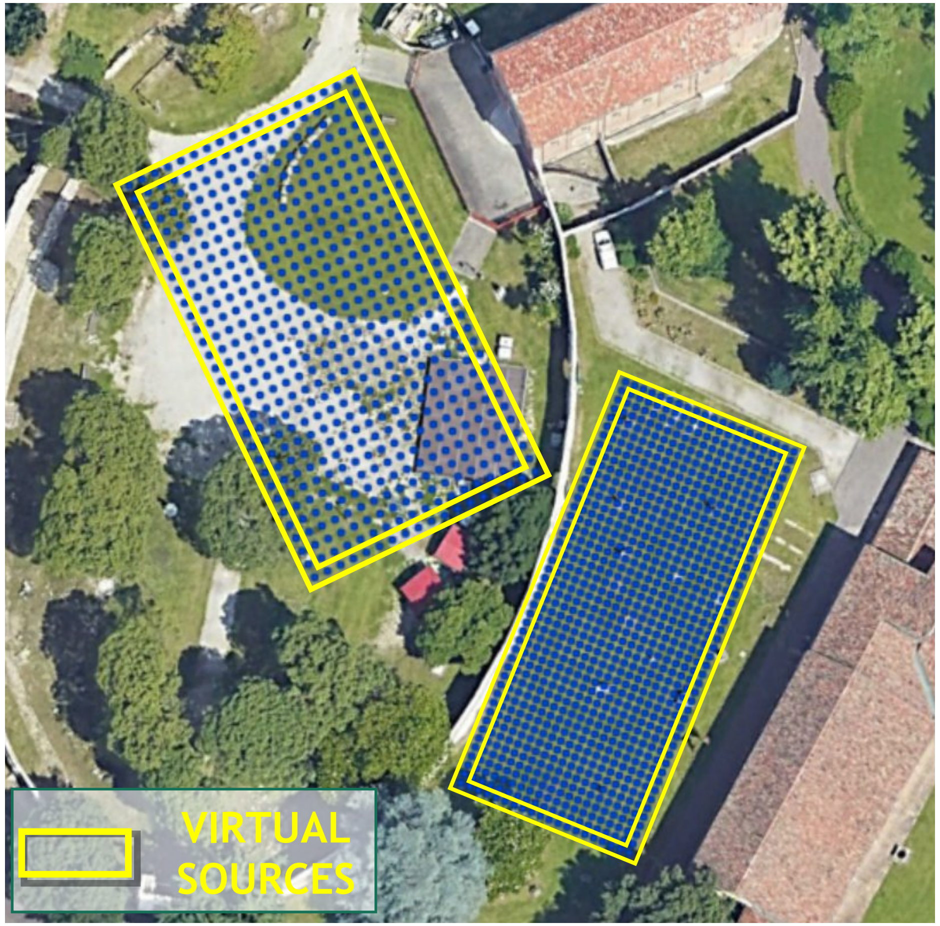

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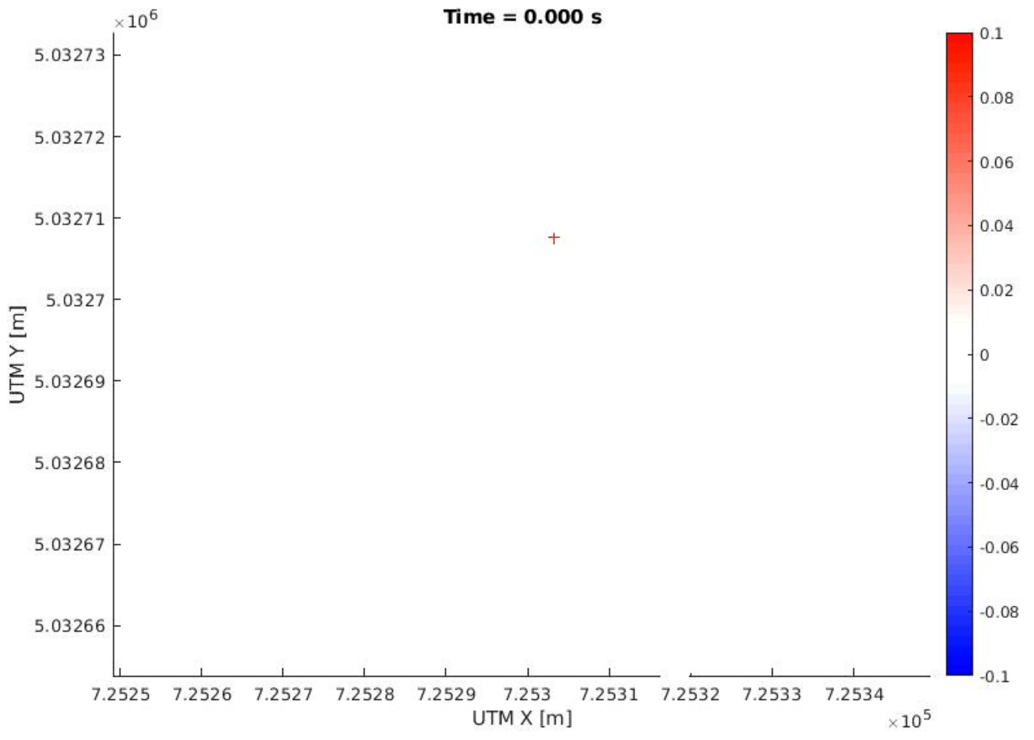
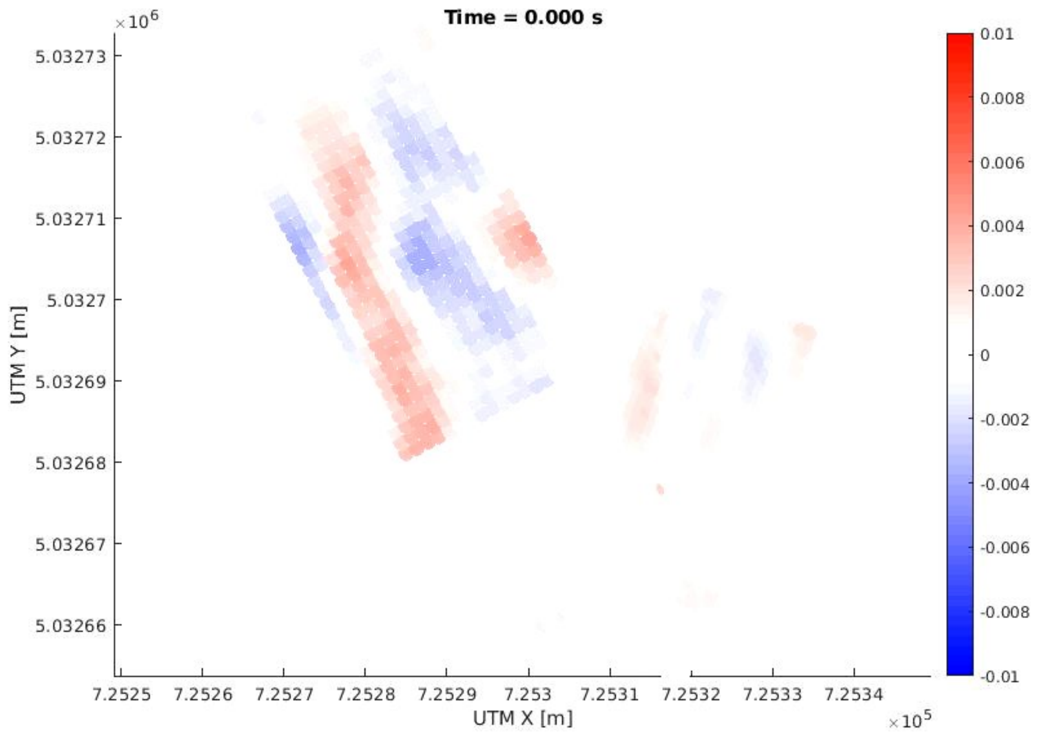
Engineering scale study – the Scrovegni Chapel

ACTIVE SHOT RECORD

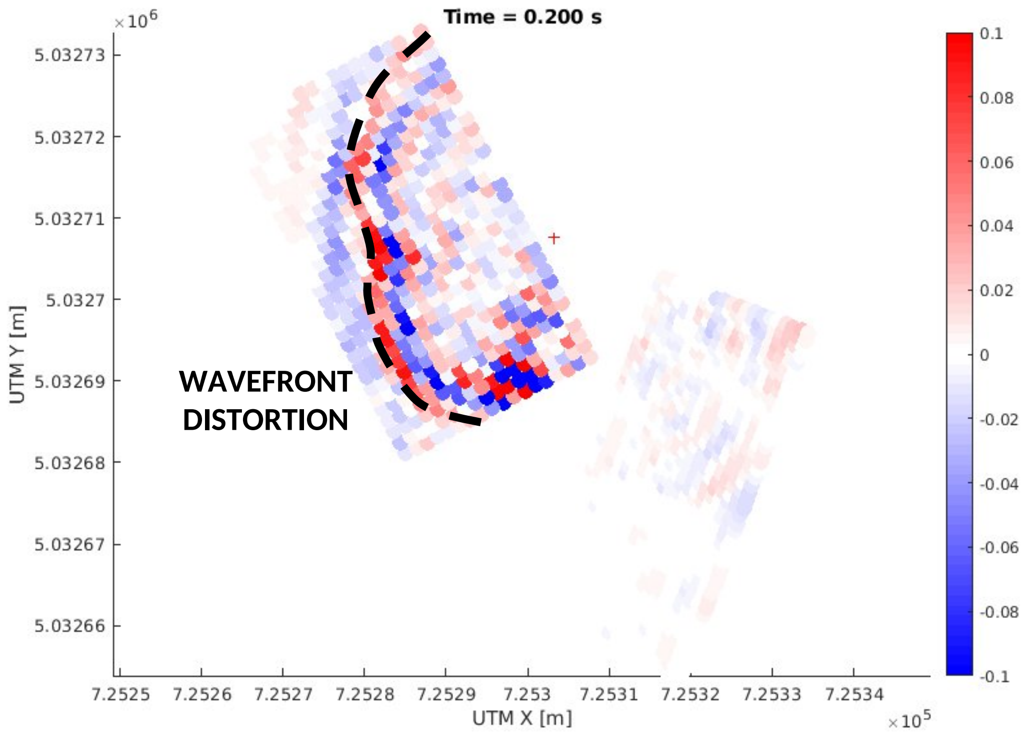


AMBIENT NOISE RECORD



Engineering scale study – the Scrovegni Chapel

ACTIVE SHOT RECORD



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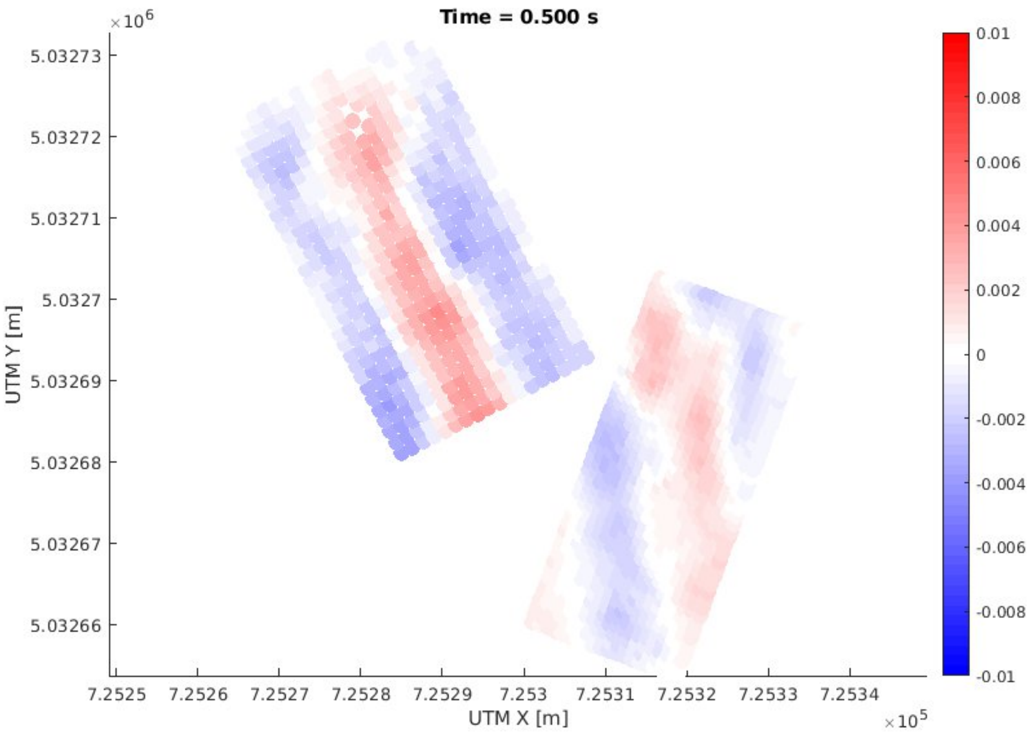
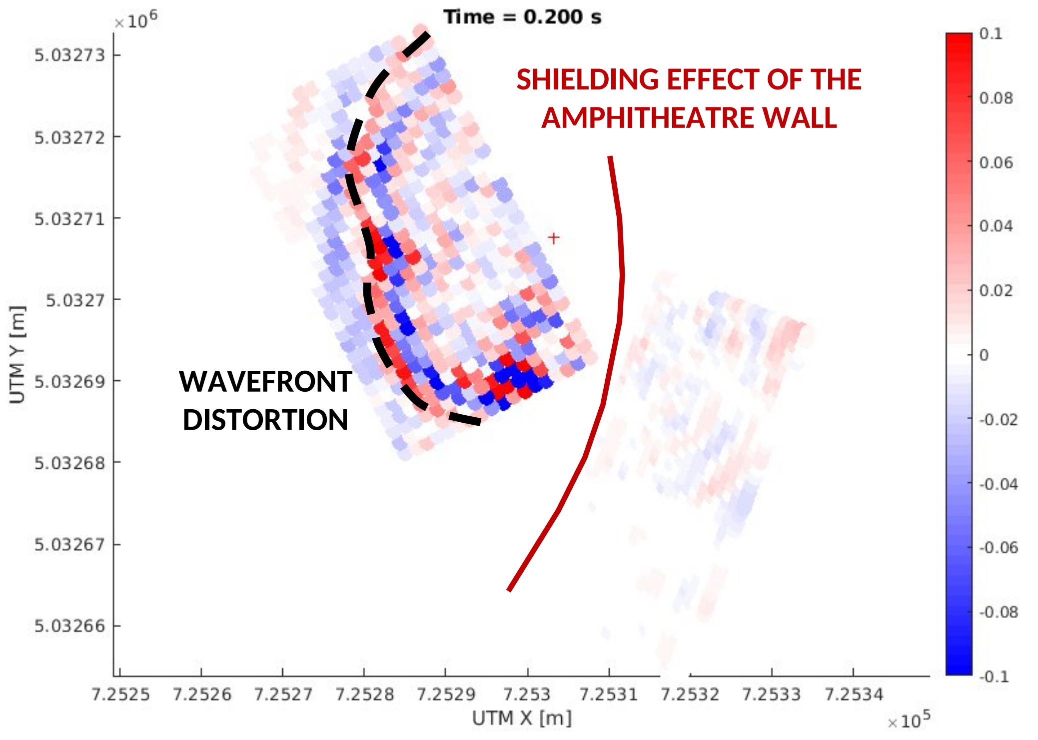
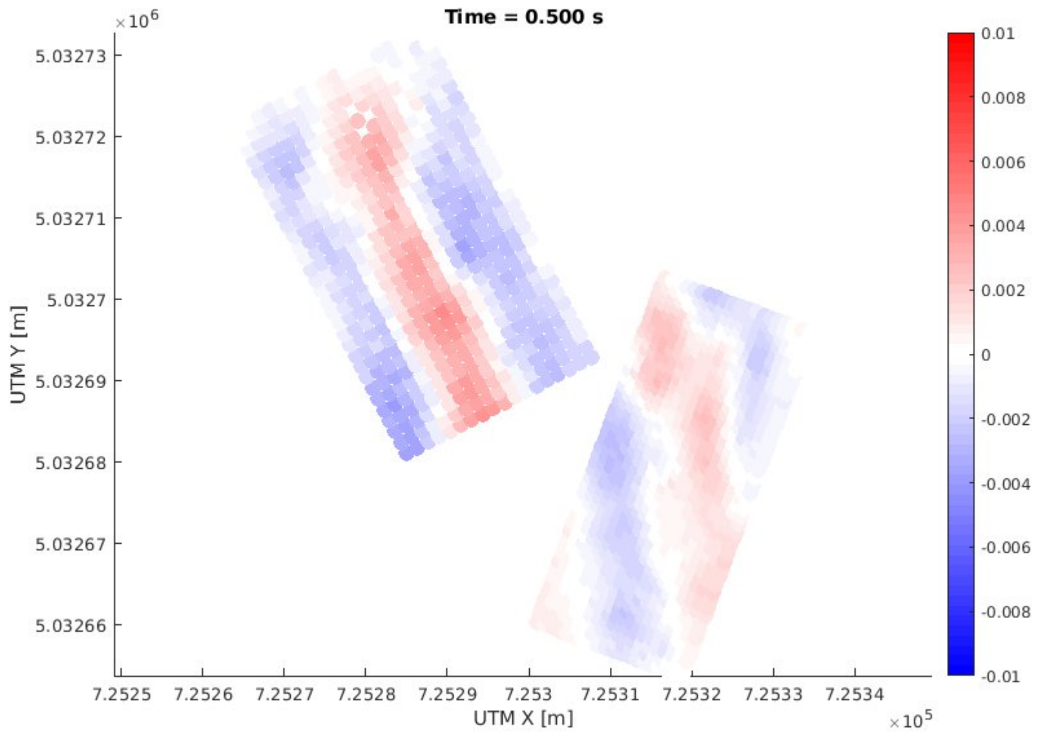


Engineering scale study – the Scrovegni Chapel





Engineering scale study – the Scrovegni Chapel

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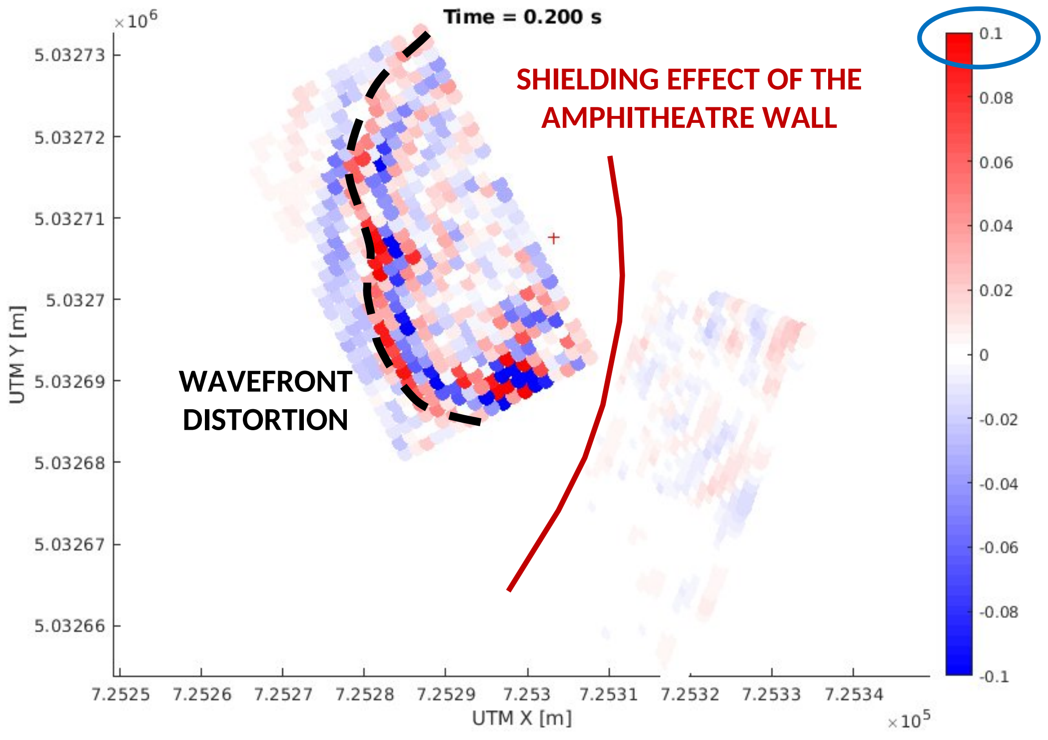

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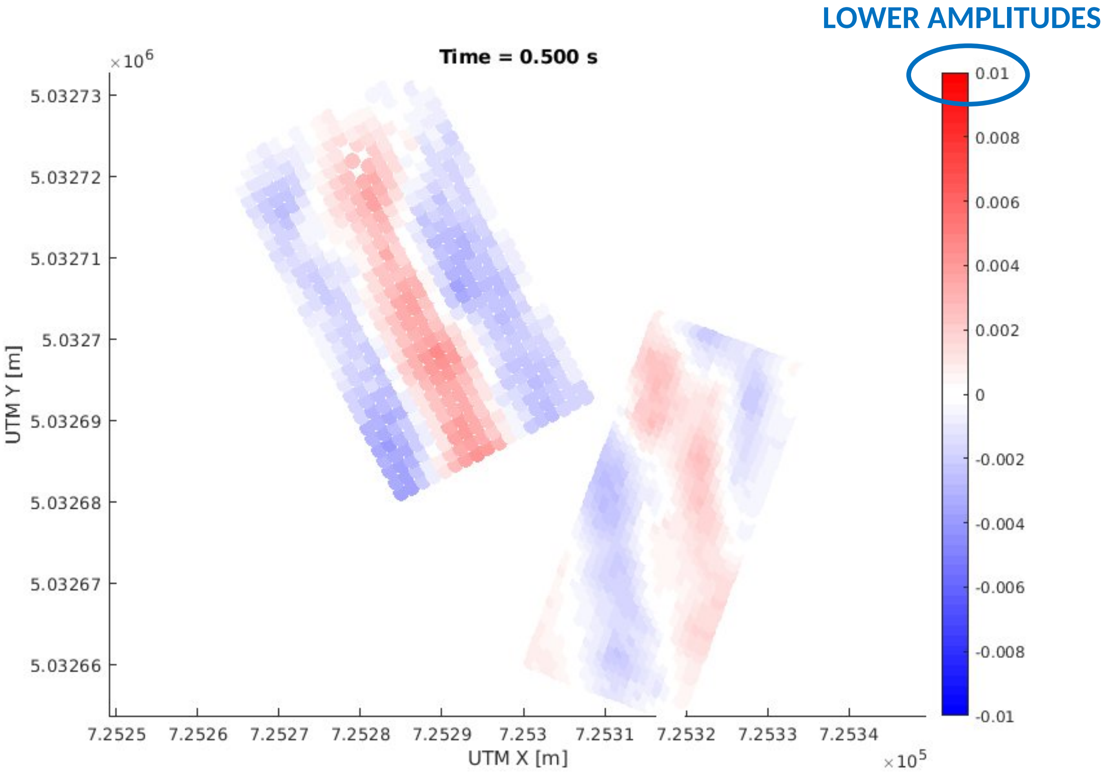

Engineering scale study – the Scrovegni Chapel

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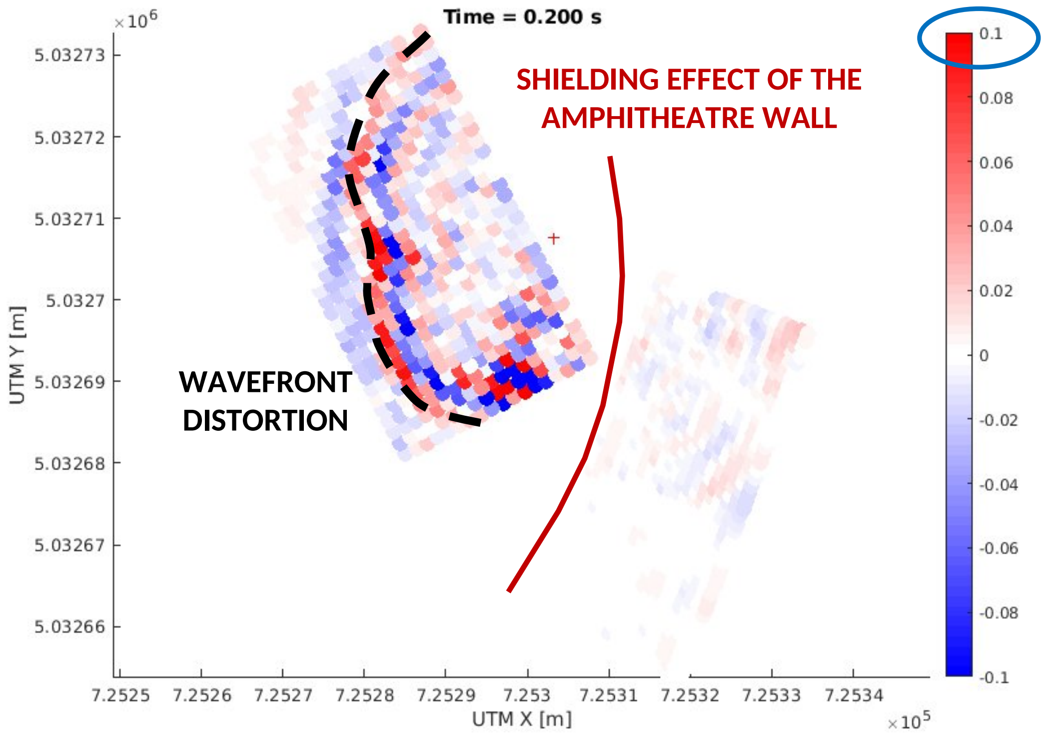

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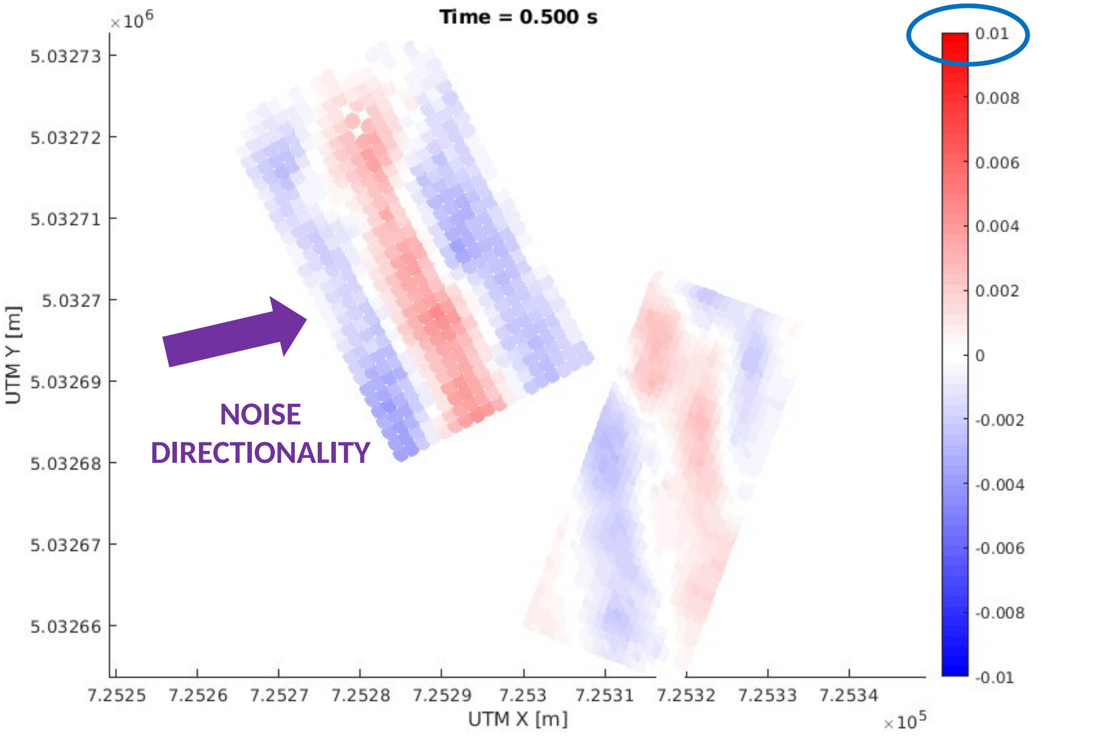
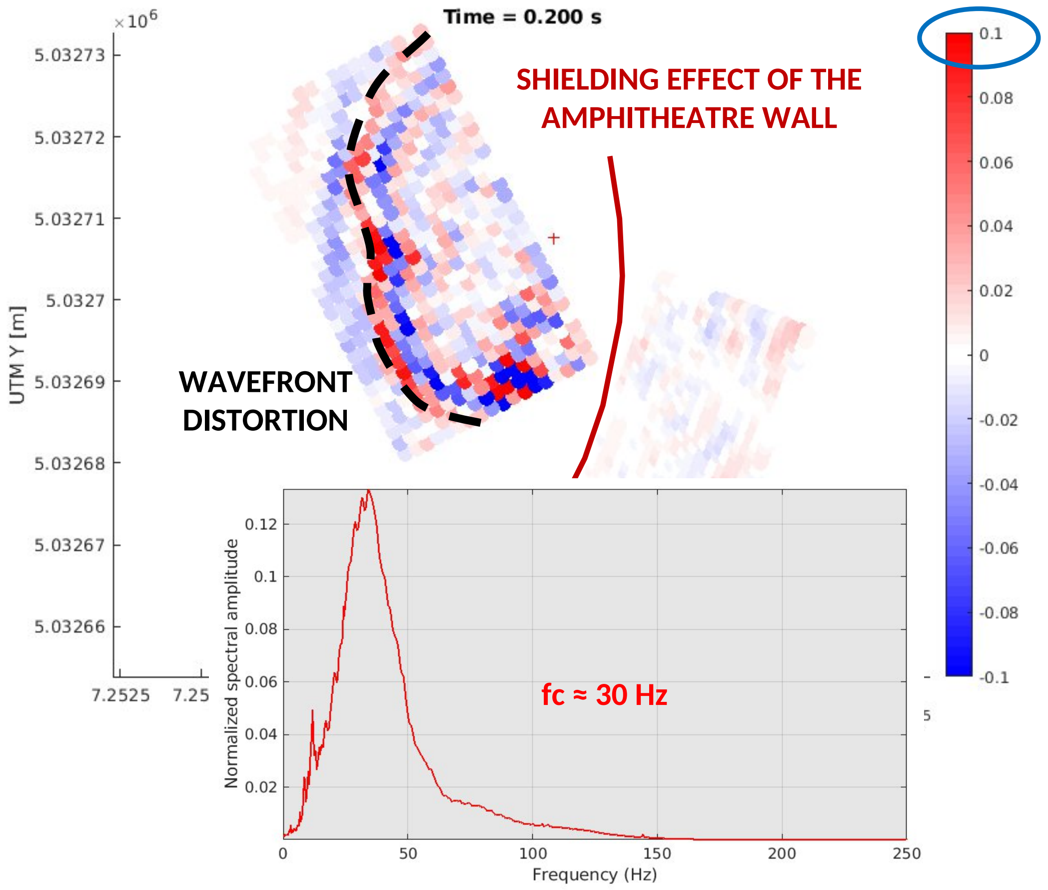


Engineering scale study – the Scrovegni Chapel

ACTIVE SHOT RECORD



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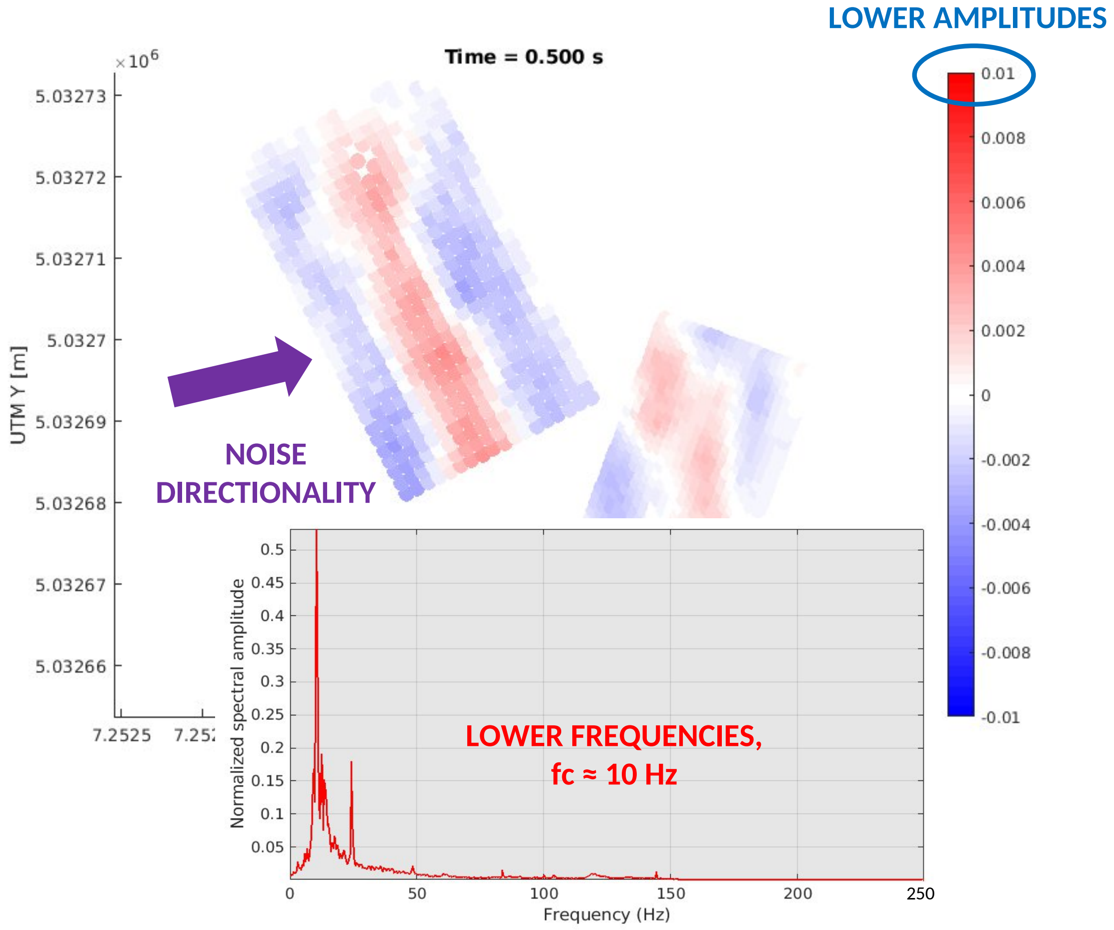
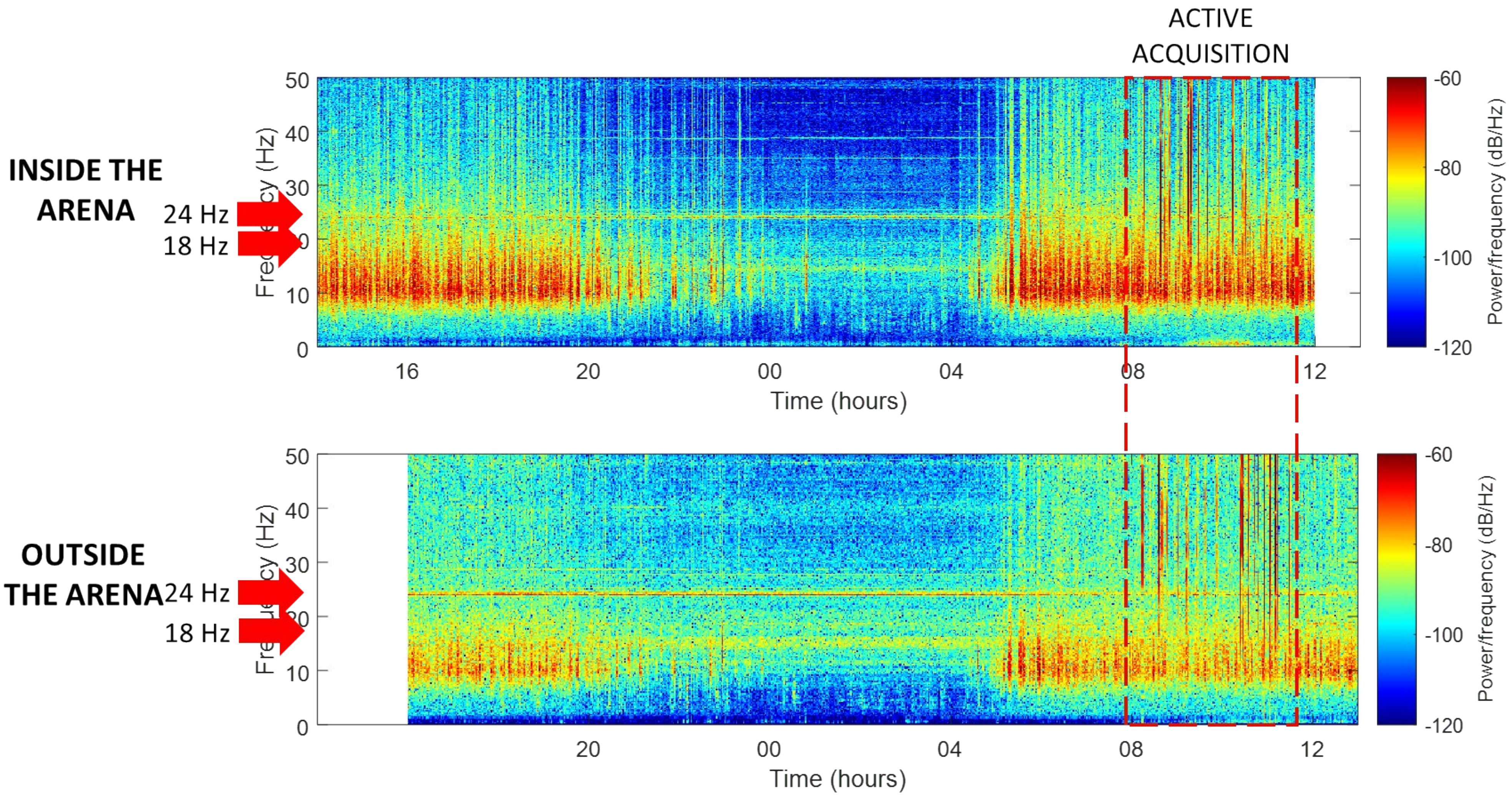


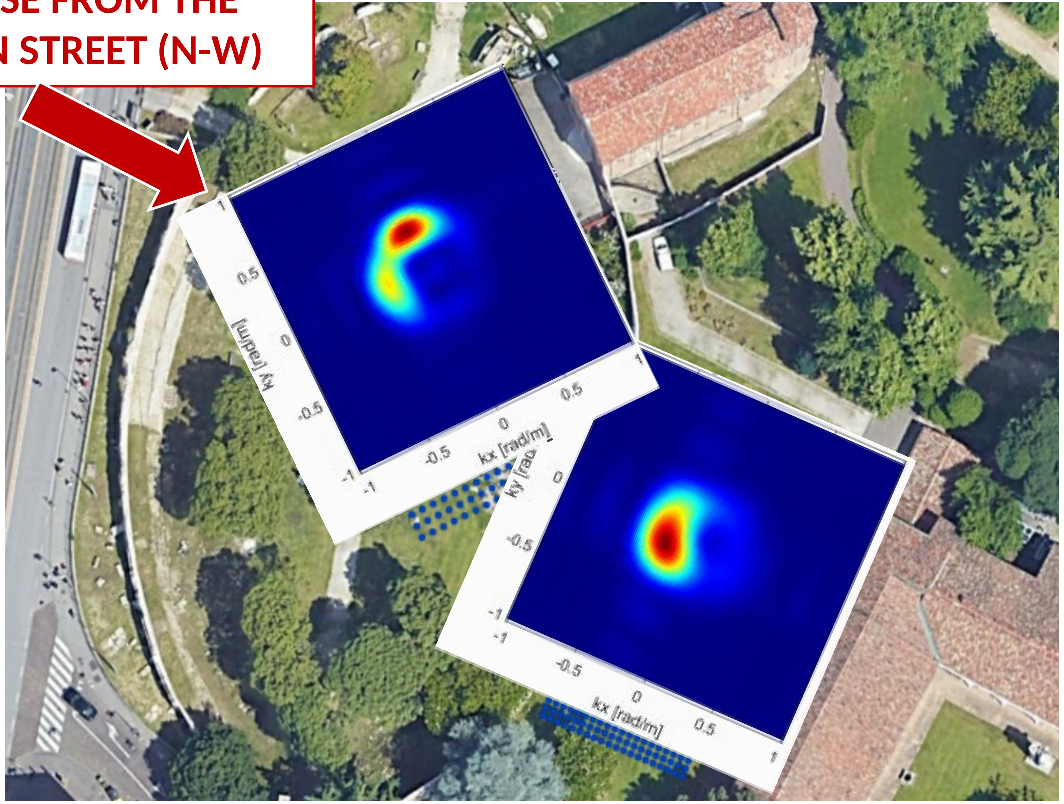
Engineering scale study – the Scrovegni Chapel



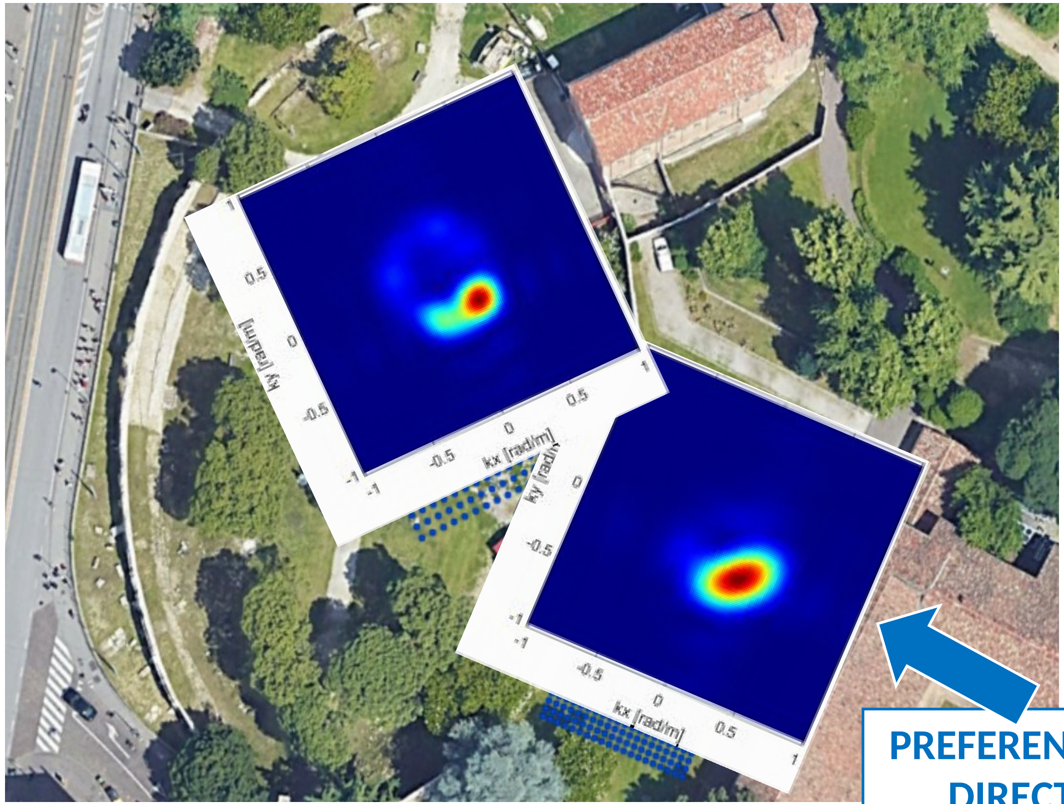
Engineering scale study – the Scrovegni Chapel

DAYTIME (1 hour) – 10 Hz

NOISE FROM THE MAIN STREET (N-W)



NIGHT TIME (1 hour) – 10 Hz

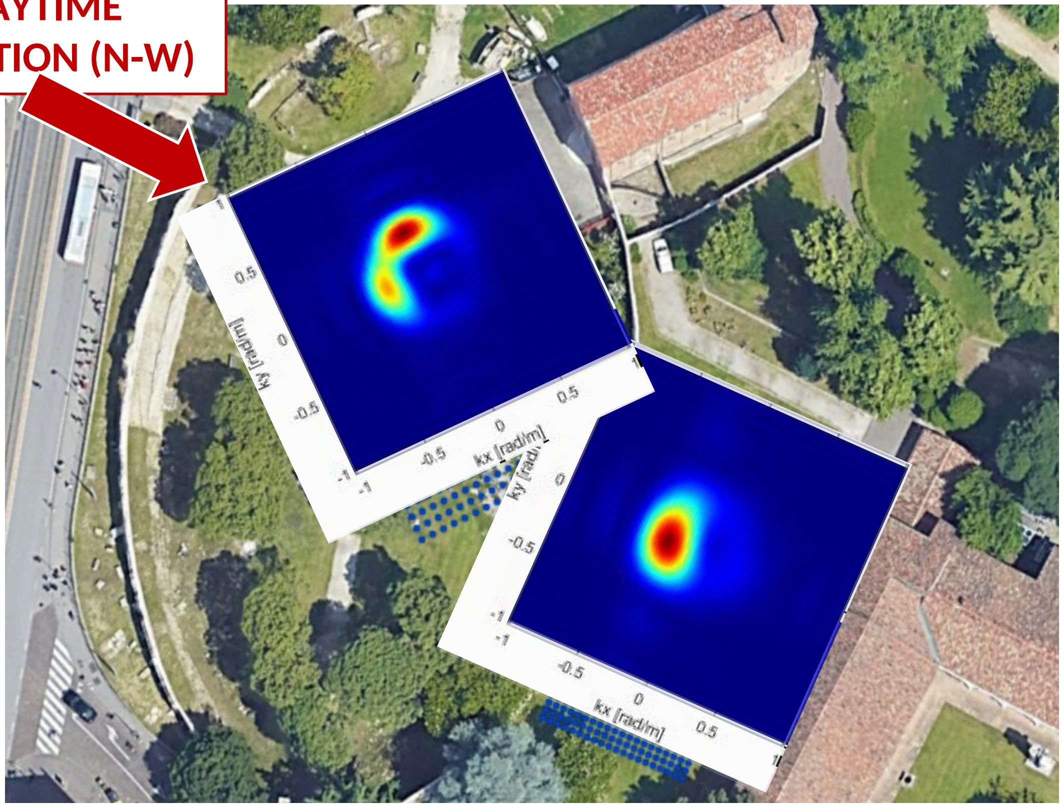


PREFERENTIAL NOISE DIRECTION S-E

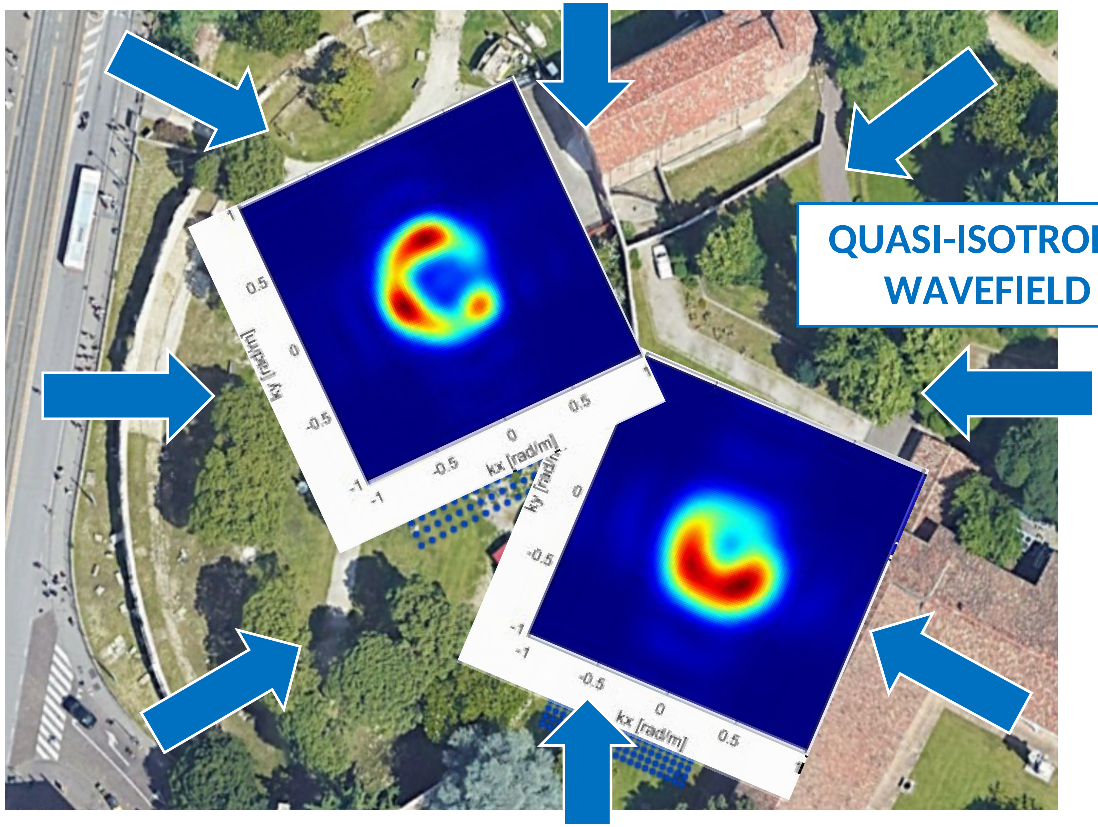
Engineering scale study – the Scrovegni Chapel

PREDOMINANT DAYTIME DIRECTION (N-W)

22 hours – 10 Hz



22 hours with spectral normalization – 10 Hz

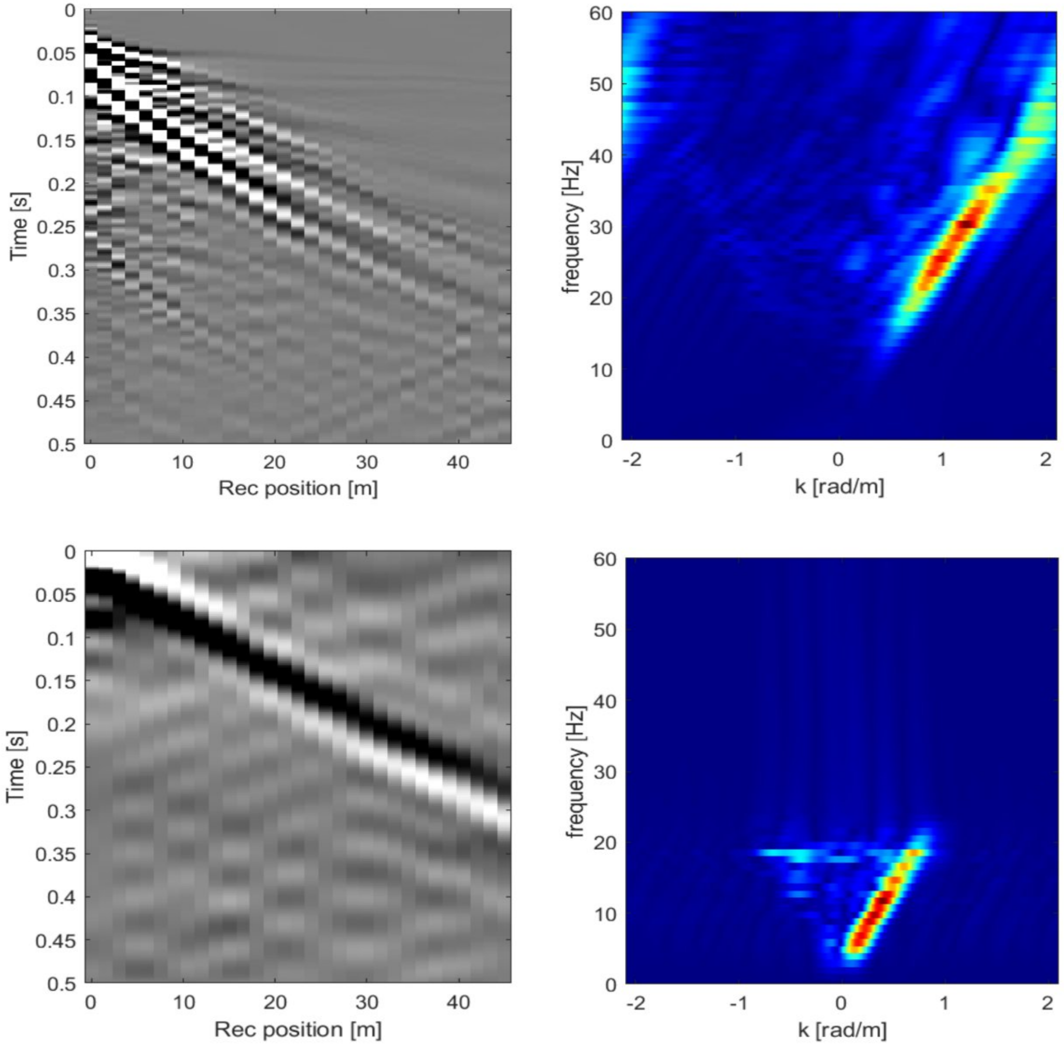


QUASI-ISOTROPIC WAVEFIELD

Engineering scale study – the Scrovegni Chapel

ACTIVE GATHER

PASSIVE GATHER



SELECTION OF 5 s WINDOWS

↓

BANDPASS FILTER (5-20 Hz)

↓

SPECTRAL WHITENING

↓

CROSS-CORRELATION

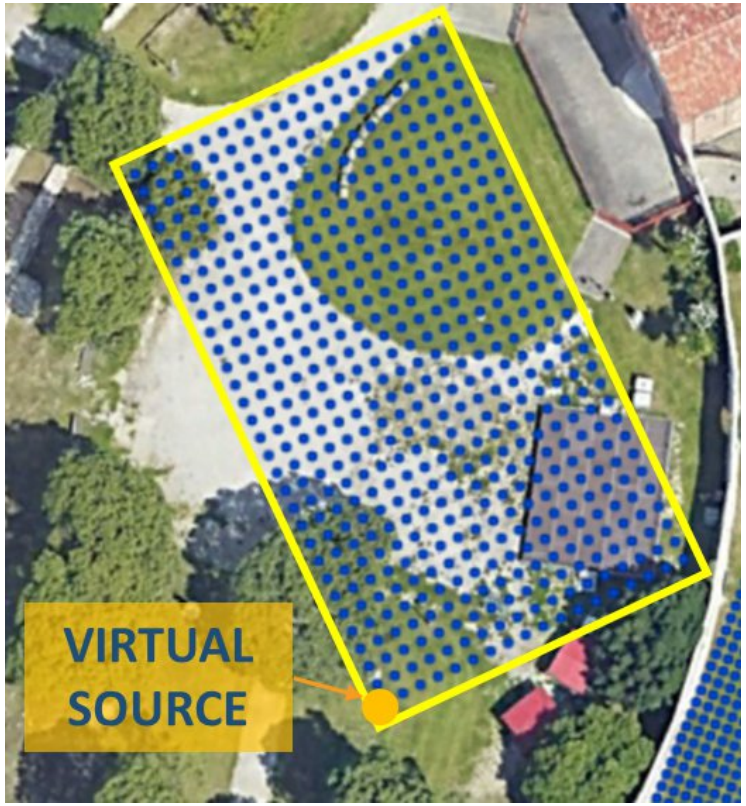
↓

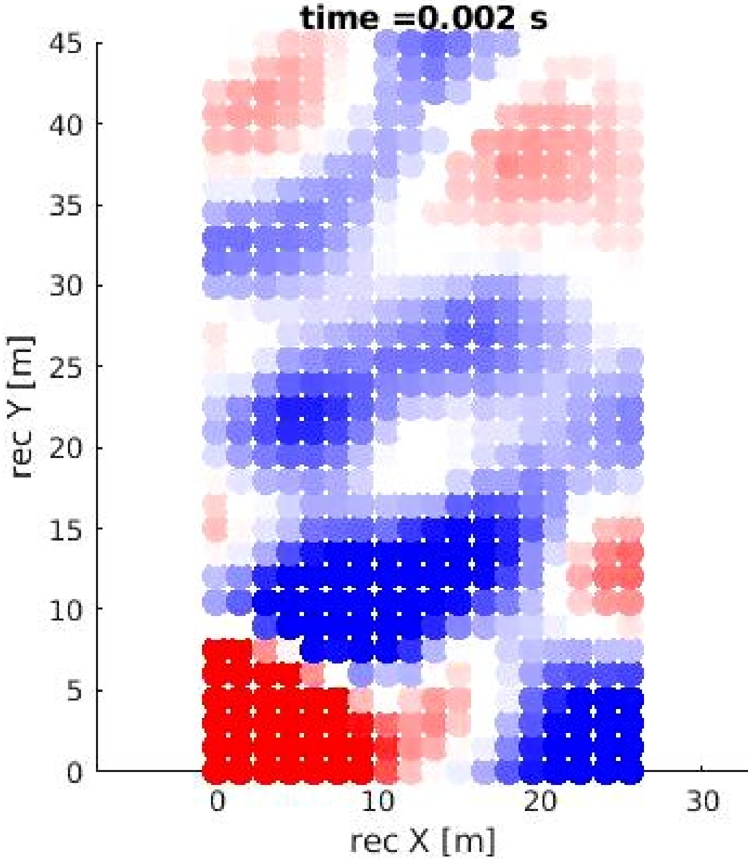
STACK OVER DIFFERENT WINDOWS

↓

POSITIVE-LAG AND NEGATIVE-LAG AVERAGE

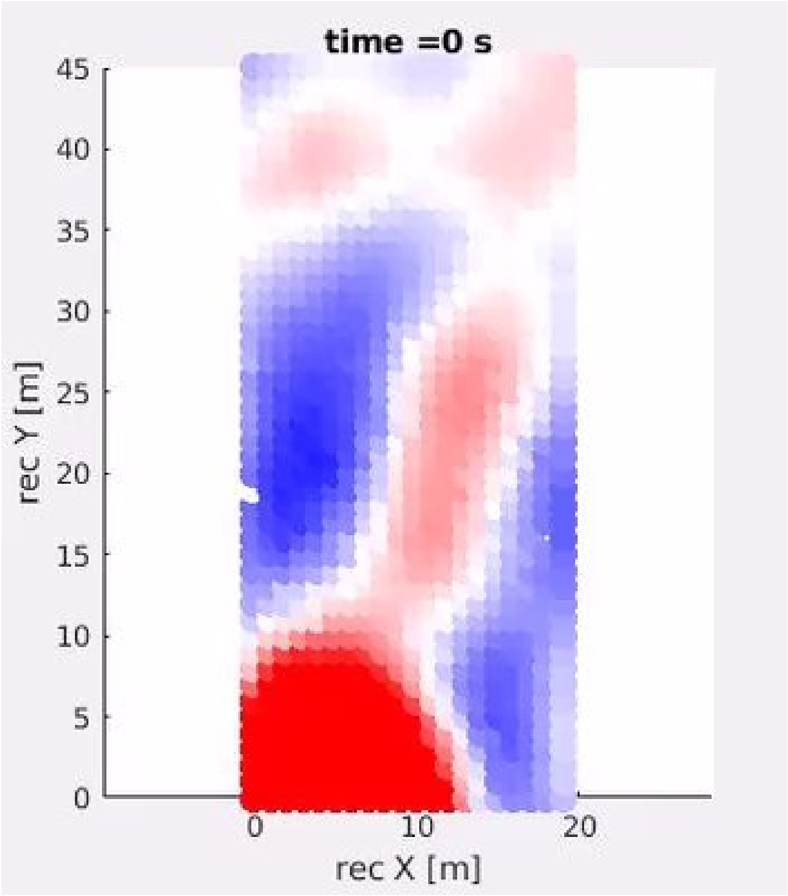
Engineering scale study – the Scrovegni Chapel

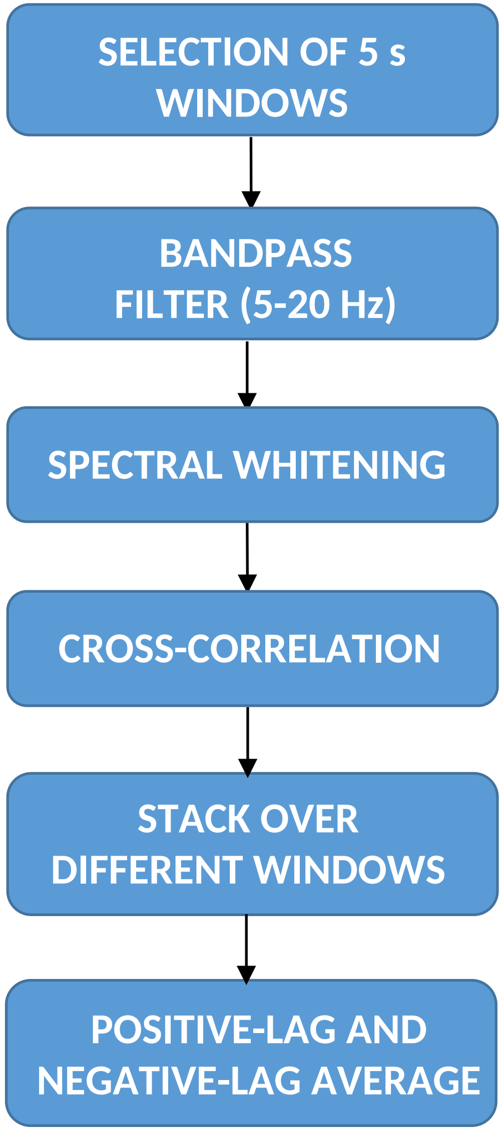




- SELECTION OF 5 s WINDOWS
- BANDPASS FILTER (5-20 Hz)
- SPECTRAL WHITENING
- CROSS-CORRELATION
- STACK OVER DIFFERENT WINDOWS
- POSITIVE-LAG AND NEGATIVE-LAG AVERAGE

Engineering scale study – the Scrovegni Chapel

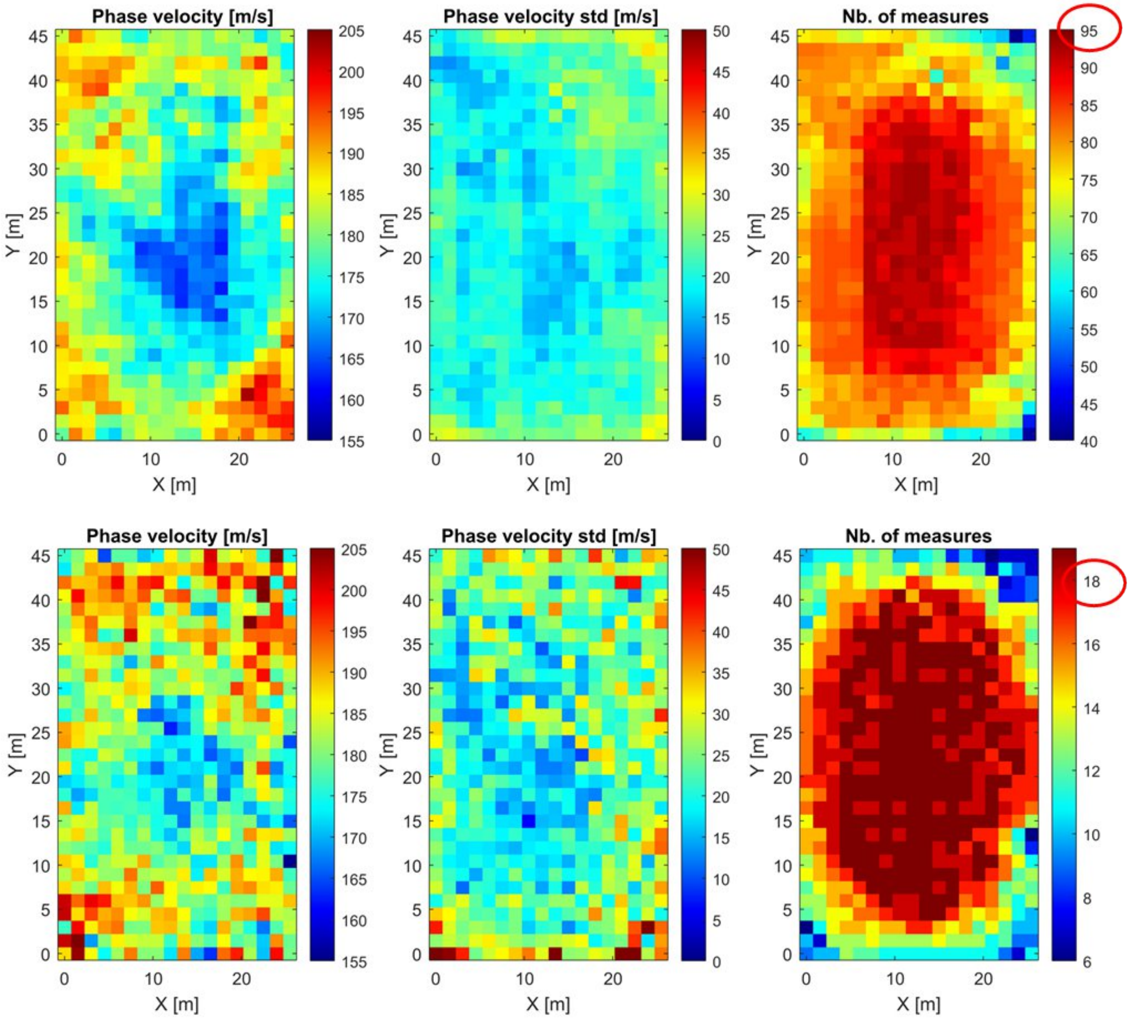


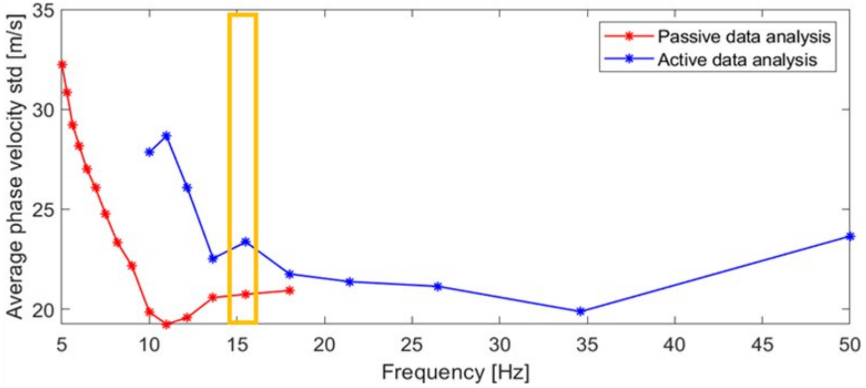


Engineering scale study – the Scrovegni Chapel

PASSIVE ANALYSIS
f = 15.5 Hz

ACTIVE ANALYSIS
f = 15.5 Hz

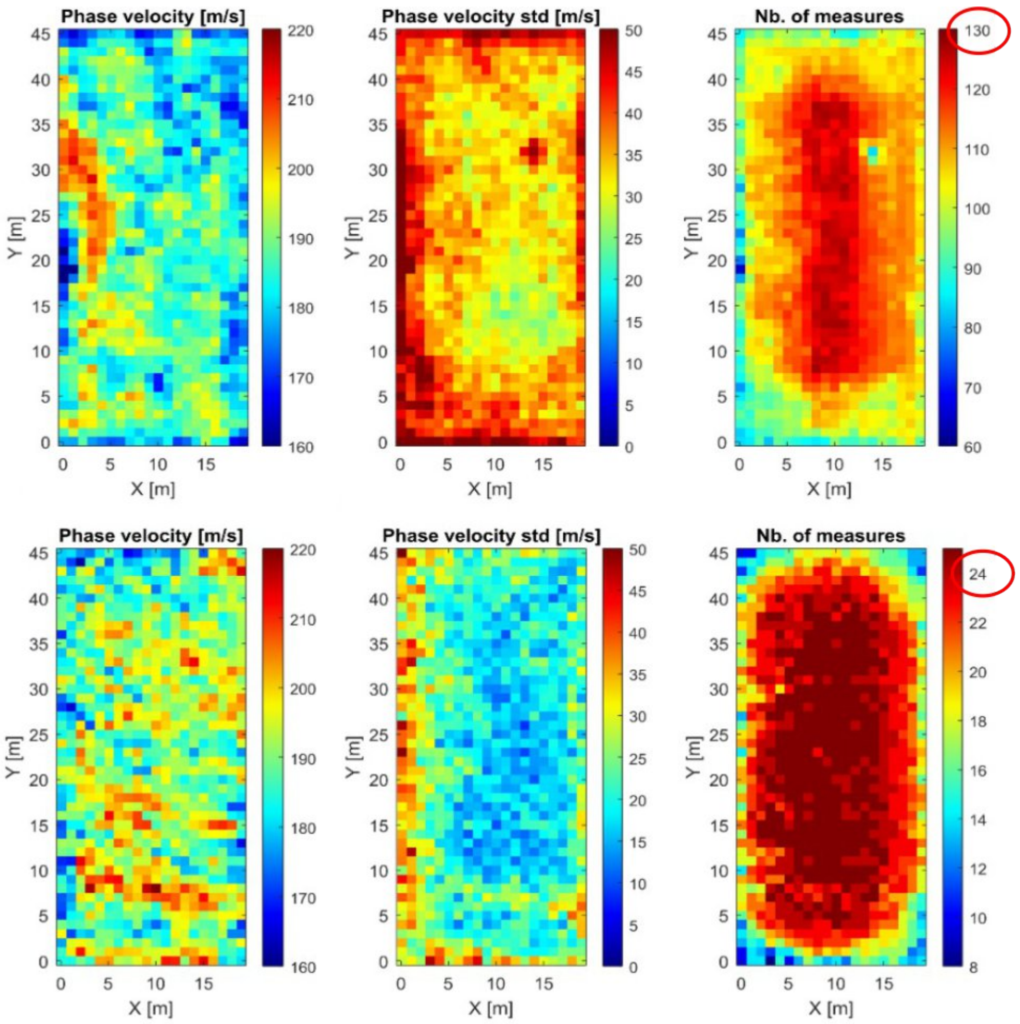




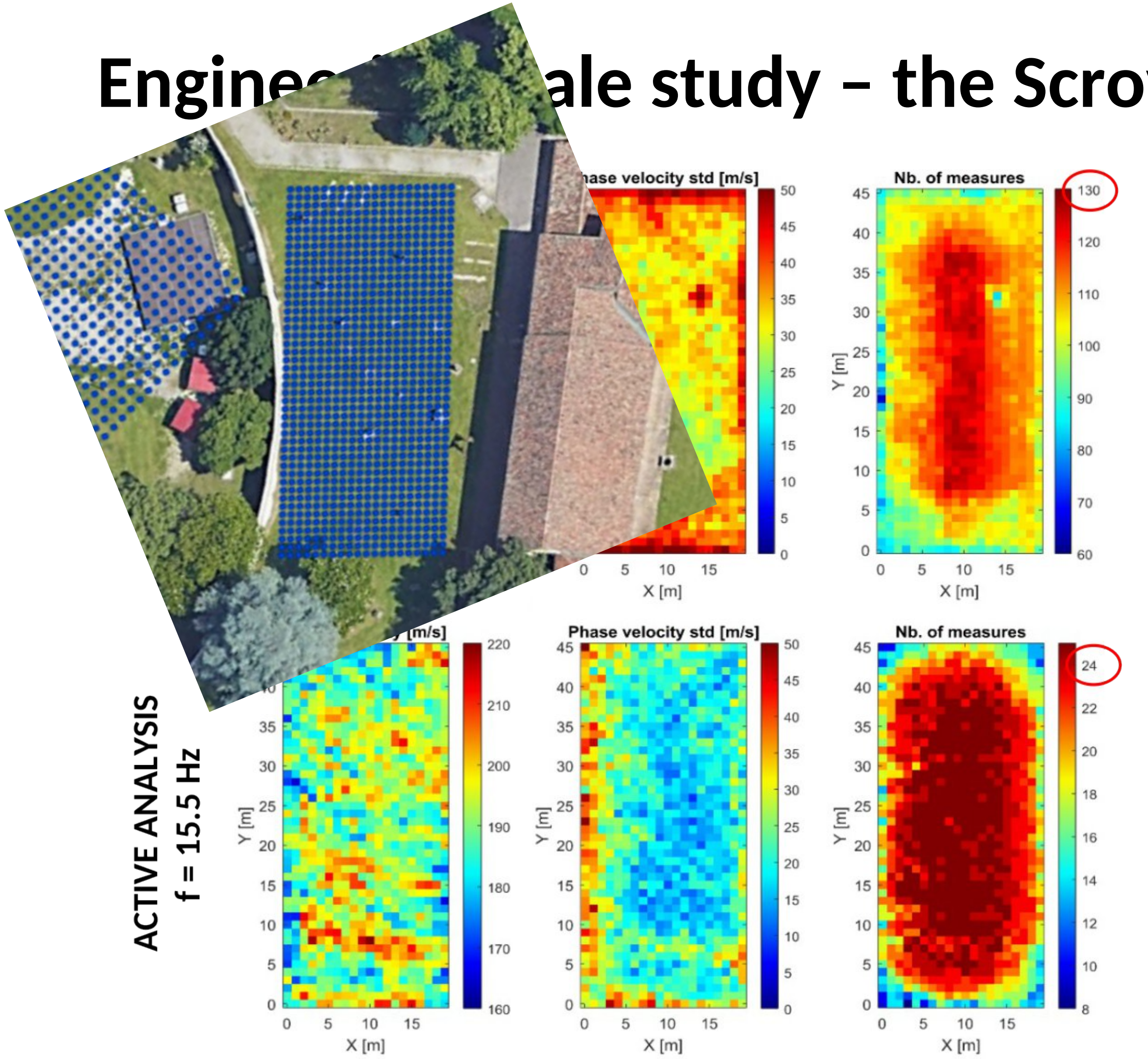
Engineering scale study – the Scrovegni Chapel

PASSIVE ANALYSIS
f = 15.5 Hz

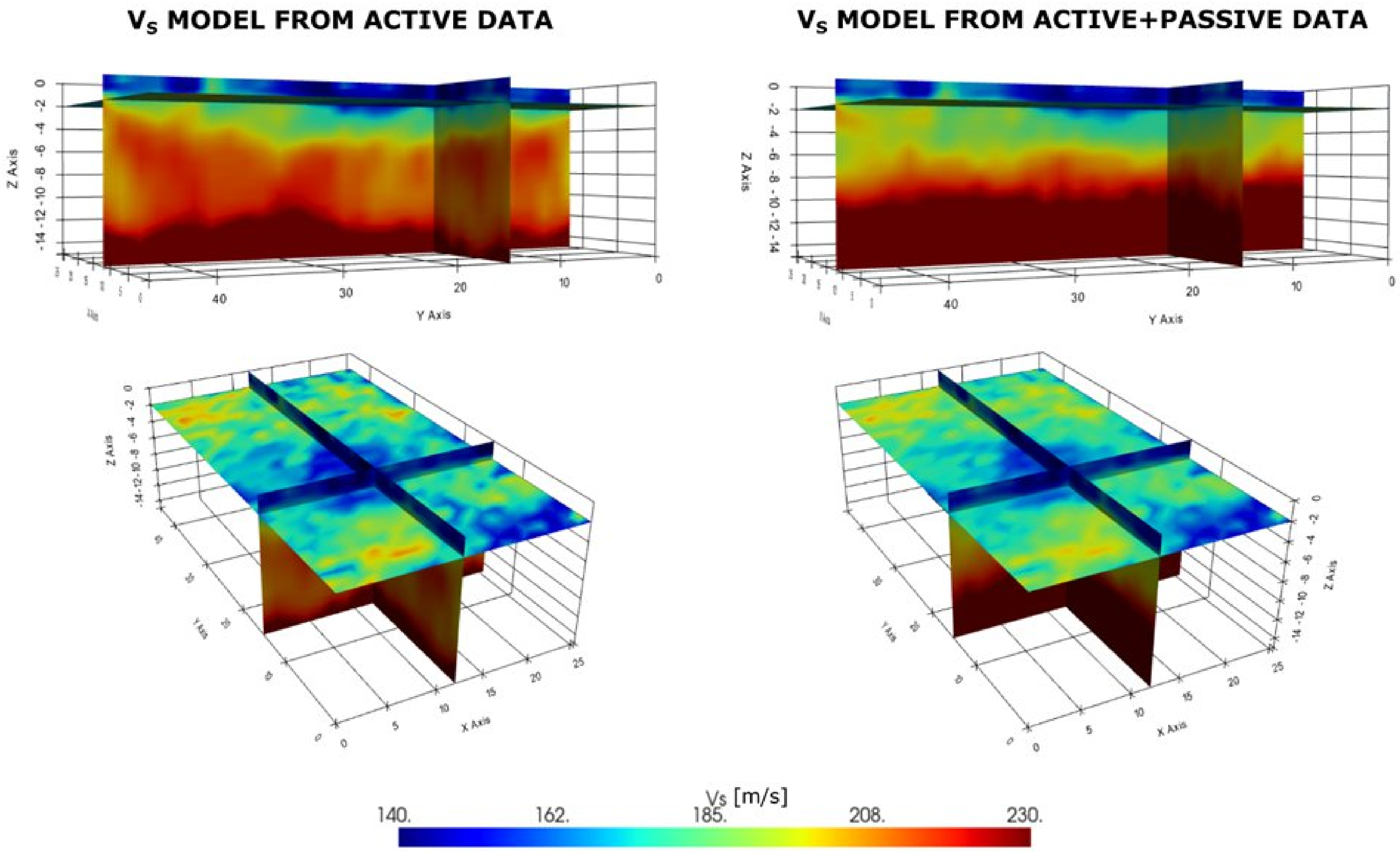
ACTIVE ANALYSIS
f = 15.5 Hz



Engine ale study – the Scrovegni Chapel



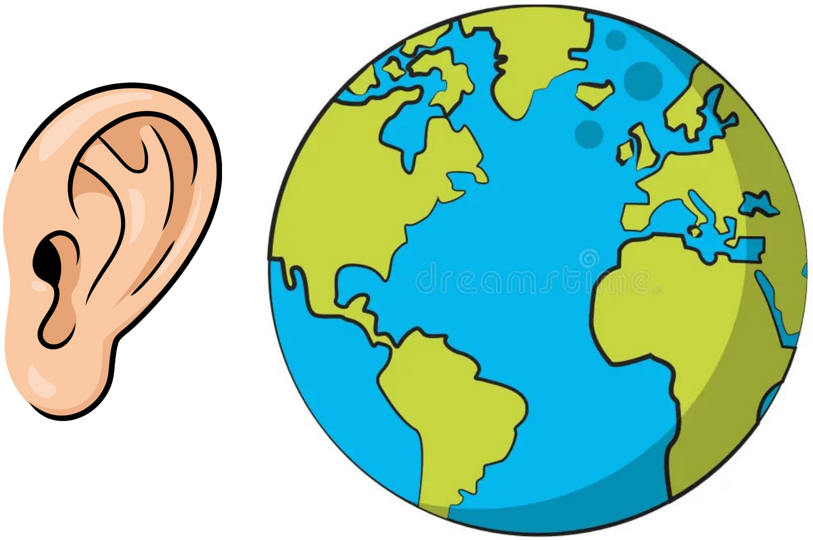
Engineering scale study – the Scrovegni Chapel



Conclusions

- Passive seismic methods are a **cheap alternative** or a **good complement** to active seismic methods.
- The main application of passive seismic methods is the **reconstruction of surface waves**, for the retrieval of **3D Vs models**.
- It is also possible to reconstruct reflections and to perform dynamic analysis.
- Pre-requisites are **distant uncorrelated sources**, with an **isotropic distribution in azimuth**.
- A good processing should include:
  - A preliminary noise characterization
  - Time and/or frequency domain normalizations
  - Stacking over a sufficiently long period.

… All we have to do is to listen to the Earth!



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Thank you for your attention!