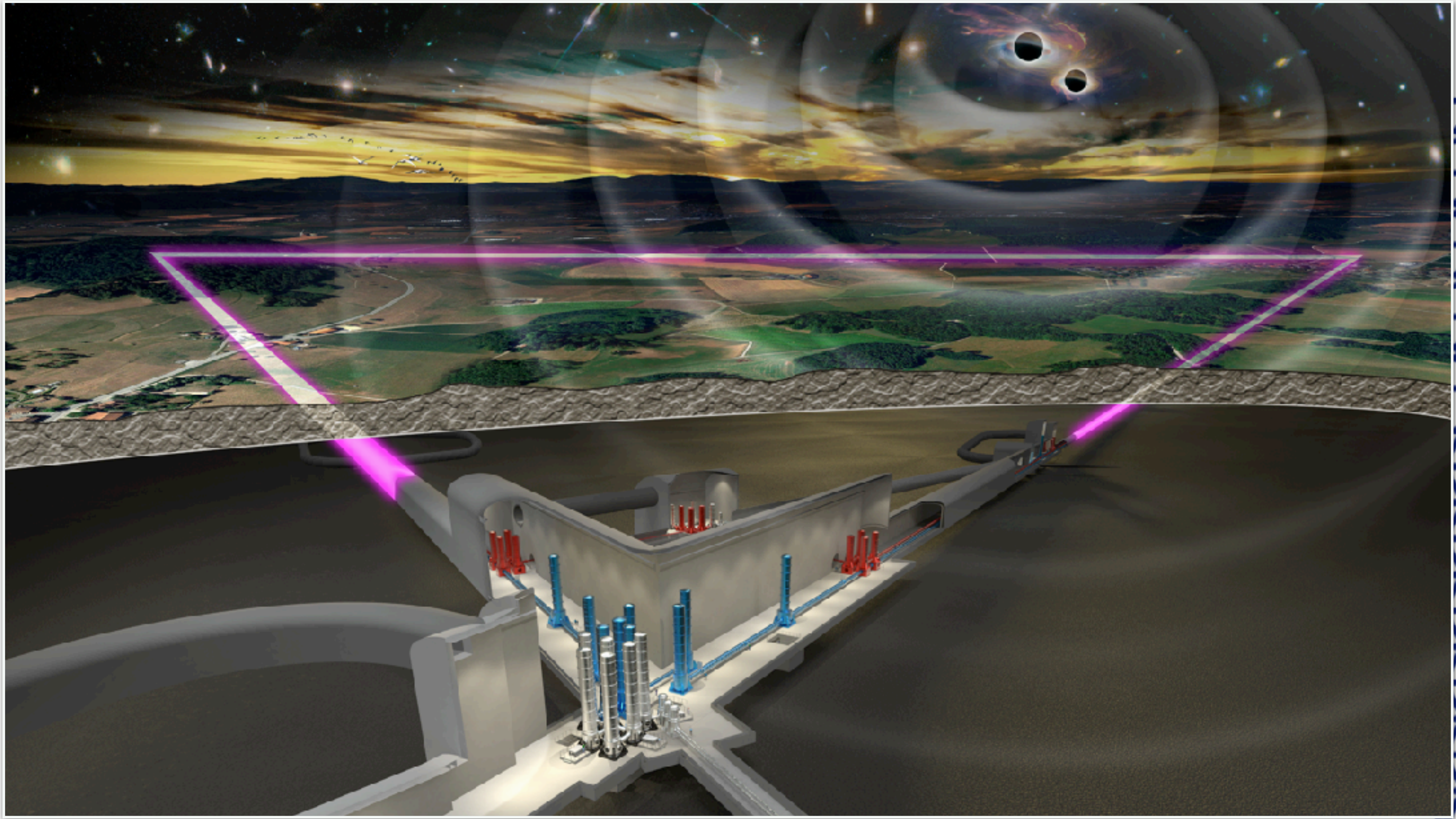

TOWARDS AN IMPROVED ANALYTICAL FRAMEWORK FOR UNDERSTANDING NEWTONIAN NOISE - EMR REGION

Stan Bentvelsen - Croatia, November 12, 2025
on behalf of EMR Newtonian Noise Working Group
(ULiège, RWTH, Maastricht, Nikhef, Ghent, Hamburg, KULeuven)

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Newtonian Noise

We evaluate the ongoing discussions on NN

- EMR demands, and develops, adequate noise modeling that suits the region

We develop numerical framework(s) to compute NN to account for arbitrary heterogeneities and sources distribution

  - i.e. finite elements for the seismic wavefield to integrate the NN on FE mesh

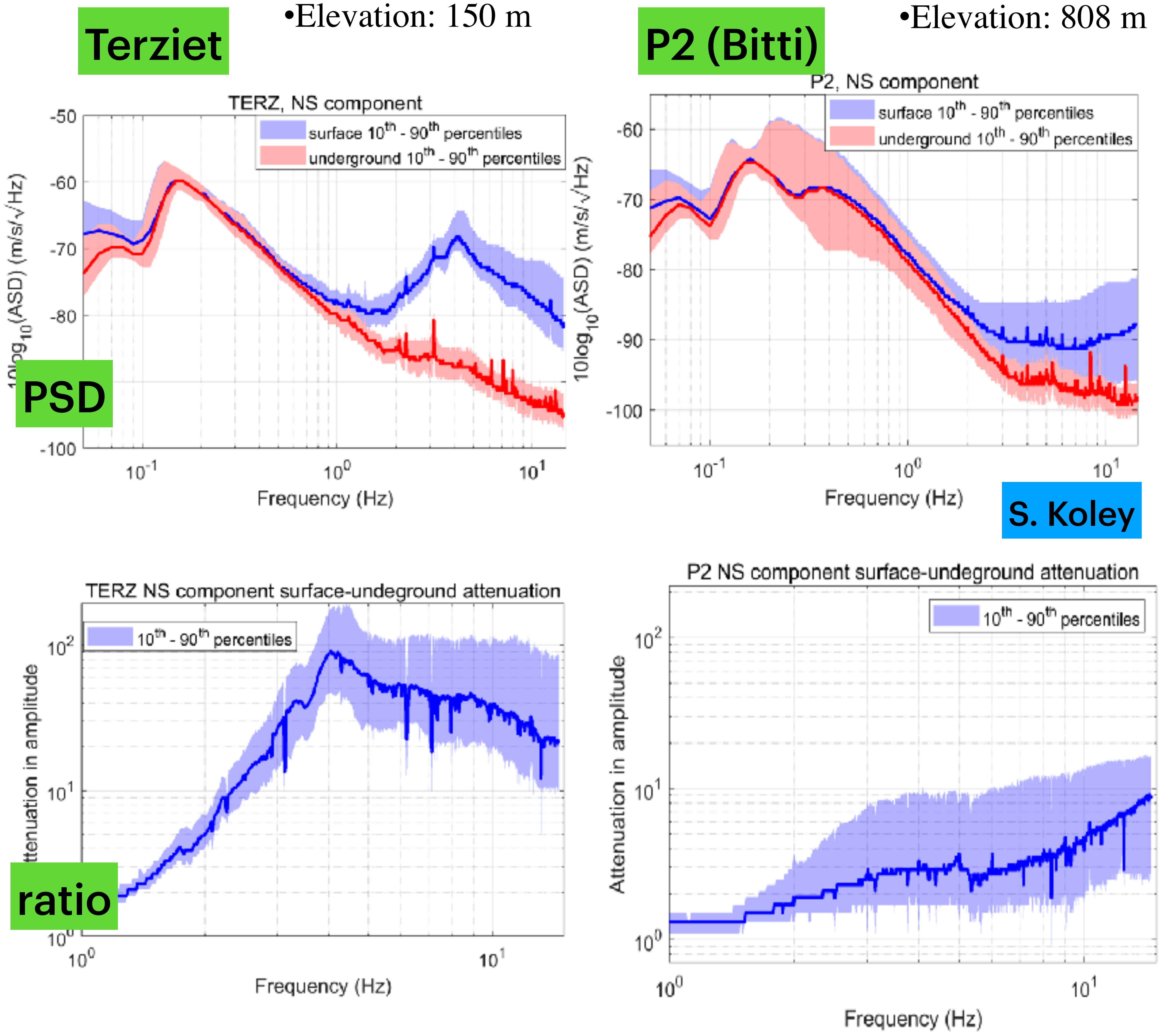
- Suitable for any geology - and applicable to EMR
  - So far, NN predictions are based on homogeneous geology
- Suitable for adequate geometries/topographies
  - So far only very simplistic geometries considered (Harms et al. Eur. Phys. J. Plus (2022) 137)
- Suitable for variety of noise sources and mitigation effects
  - So far magnetic and electric disturbance have not been considered

Specific geology

Comparing surface with subsurface

•Local depth: 250 m
•Elevation: 150 m

•Local dept: 264 m
•Elevation: 808 m



Geology challenges

- EMR has special geological environment where infrastructure is ‘protected’ by soft layers on top
  - Vertical attenuation is much larger compared to other sites

EMR is relatively insensitive to future changes in surface activities

- This robustness is an important aspect for an infrastructure that will run for >50 years!

Unfortunately we have a delay in collecting new subsurface sensor data -

Active working group NN - EMR area

See presentation of Valentin Tempel

NP1: Analytic understanding of NN

- Analytical calculations for simplified geometry and geology

NP2: Validation of the numerical tools

- Compare to analytic calculations, increasing complexity: layered geology and realistic geometries

No new data to show, unfortunately

NP3: (Preparation for) sub-surface measurements

- Understanding of surface and sub-surface measurements
- Development noise model for of NN calculations

NP4: Mitigation strategy and results

- Generation of ideas and development of tools to mitigate NN

See presentation of Patrick Schillings
and poster of Tim Kuhlbush

NP2: Tools for Newtonian Noise & mitigation

Agreement with ISB and SCB on development of tools for NN and mitigation

- The list of NN and mitigation modeling/design tools has been collected

These tools will have to be reviewed and tested by July 2026

- Other tools might still be added later, but for sure this is an excellent starting point.

1. **Newtonian Noise optimizations** - Francesca Badaracco
2. **NewtonForge-3D** - Tomislav Andric
3. **SeisNN** - Andreas Rietbrock
4. **pySeis1DNN and pySeis3DNN** - Soumen Koley
5. **Prediction of environmental vibration due to anthropogenic sources and computation of Newtonian Noise** - Geert Degrande
6. **FraNC** - Tim Kuhlbusch
7. **ParaArrayOpt** - Johannes Erdmann

Focus on these → (items 4–7)

Numerical 3d evaluation on FE mesh

The 9th European Congress on Computational Methods in Applied Sciences and Engineering
ECCOMAS Congress 2024
3–7 June 2024, Lisboa, Portugal

Expertise and work done at KULeuven

- Georgia Kuci, Pieter Reumers, Stijn Francois, Geert Derange
- Theory of elasticity and plasticity, dynamics of structures, wave propagation and vibration in the built environment, and non-linear structural analysis.

Ambition to create a full 3d numerical simulation of the EMR area to assess the NN

- Numerical model in which the soil domain surrounding the cavity geometry is discretized with finite elements
- Gaussian quadrature to numerically evaluate the volume integrals quantifying the NN
- Full implementation of wave scattering by the cavity and geology layers

Seismic Newtonian Noise: numerical evaluation

Implementing NN governing equations - validation steps

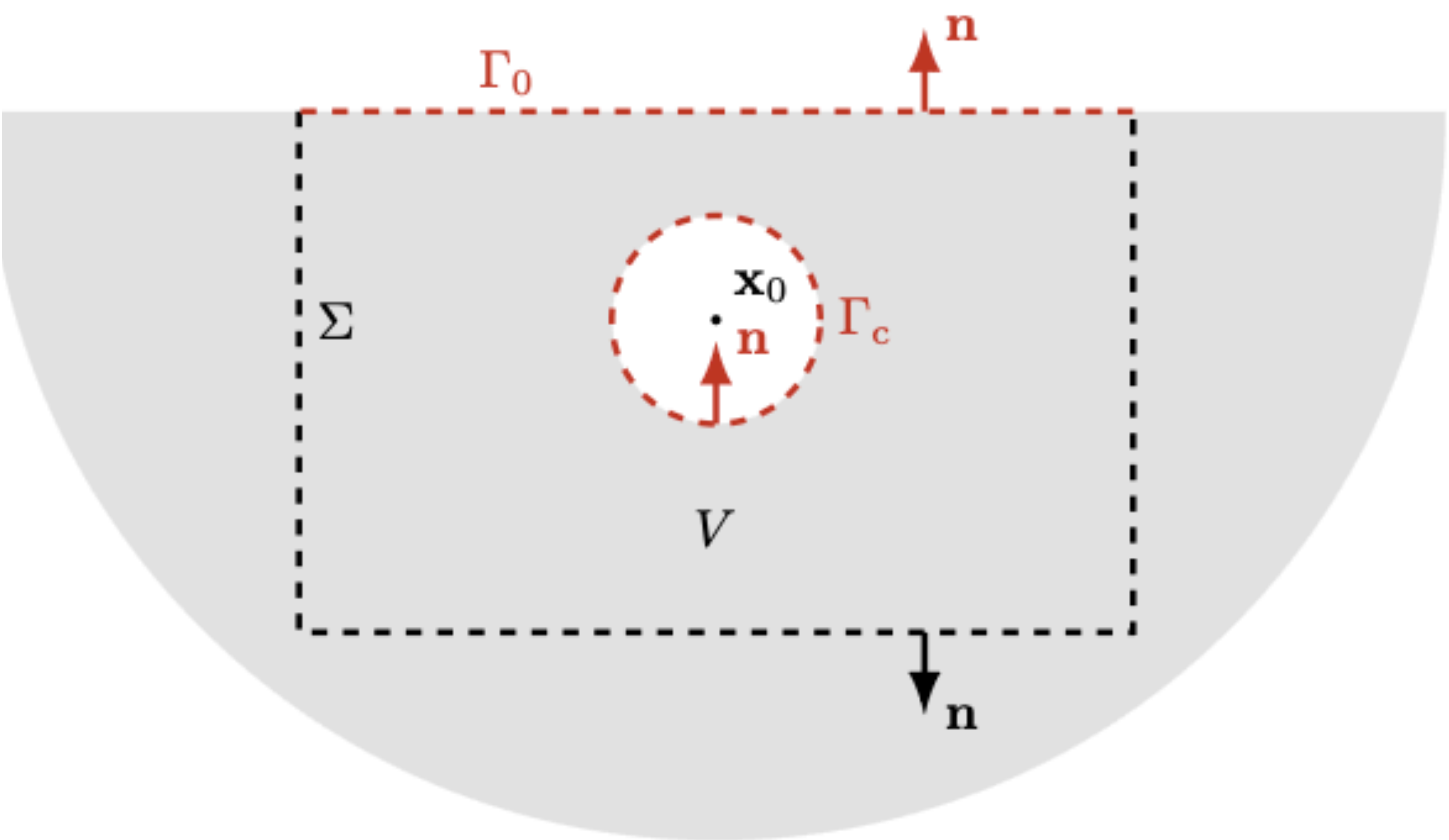
- Perturbation $\delta a(x_0)$ [$m/s^2/Hz$] in the gravitational acceleration $\delta a(x_0)$ at the mirror position x_0 due to the seismic displacement field $u(x)$:

$$\begin{aligned}
\delta\hat{\mathbf{a}}(\mathbf{x}_0) &= -\nabla_0 \delta\hat{\phi}(\mathbf{x}_0) \\
&= -G \int_V \rho(\mathbf{x}) \nabla_0 \left(\hat{\mathbf{u}}(\mathbf{x}) \cdot \boldsymbol{\chi}(\mathbf{x}, \mathbf{x}_0)\right) \mathrm{d}V \\
&= +G \int_V \rho(\mathbf{x}) \frac{1}{|\mathbf{x}-\mathbf{x}_0|^3} \left[\hat{\mathbf{u}}(\mathbf{x}) - 3\left(\mathbf{e}_r \cdot \hat{\mathbf{u}}(\mathbf{x}) \mathbf{e}_r\right)\right] \mathrm{d}V
\end{aligned}$$

$$\boldsymbol{\chi}(\mathbf{x}, \mathbf{x}_0) = \frac{\mathbf{x}-\mathbf{x}_0}{|\mathbf{x}-\mathbf{x}_0|^3}$$

$$\mathbf{e}_r = (\mathbf{x}-\mathbf{x}_0)/|\mathbf{x}-\mathbf{x}_0|.$$

- Bulk and surface contributions
  - Make sure these terms are implemented correctly
    - Homogeneous medium with density ρ_0 occupying a volume V and free surface S(Γ_0 on surface and Γ_c on cavity).



Seismic Newtonian Noise: numerical evaluation

Governing equations

- Perturbation δa(x_0) [m/s²/Hz] in the gravitational acceleration or total Newtonian Noise δa(x_0) at the mirror position x_0 due to the seismic displacement field u(x):

$$\begin{aligned}\delta\hat{\mathbf{a}}(\mathbf{x}_0) &= -\nabla_0\delta\hat{\phi}(\mathbf{x}_0)\\ &= -G\int_V \rho(\mathbf{x})\nabla_0\left(\hat{\mathbf{u}}(\mathbf{x})\cdot\boldsymbol{\chi}(\mathbf{x},\mathbf{x}_0)\right)\mathrm{d}V\\ &= +G\int_V \rho(\mathbf{x})\frac{1}{|\mathbf{x}-\mathbf{x}_0|^3}\left[\hat{\mathbf{u}}(\mathbf{x})-3\left(\mathbf{e}_r\cdot\hat{\mathbf{u}}(\mathbf{x})\mathbf{e}_r\right)\right]\mathrm{d}V\end{aligned}$$

$$\boldsymbol{\chi}(\mathbf{x},\mathbf{x}_0) = \frac{\mathbf{x}-\mathbf{x}_0}{|\mathbf{x}-\mathbf{x}_0|^3}$$

$$\mathbf{e}_r = (\mathbf{x}-\mathbf{x}_0)/|\mathbf{x}-\mathbf{x}_0|.$$

Computation of NN on an FE mesh

Valuable existing expertise at KULeuven

- Finite element discretization of the total Newtonian Noise δa(x_0) at the mirror position x_0 due to the seismic displacement field u(x), using n_e finite elements with volume V_e and nodal displacements u_e(x):

$$\delta\hat{\mathbf{a}}(\mathbf{x}_0) = -\sum_{e=1}^{n_e} G\int_{V^e} \rho^e\nabla_0\boldsymbol{\chi}(\mathbf{x},\mathbf{x}_0)\cdot\hat{\mathbf{u}}^e(\mathbf{x})\,\mathrm{d}V^e \longrightarrow \delta\hat{\mathbf{a}}(\mathbf{x}_0) = \mathbf{A}\underline{\hat{\mathbf{u}}}$$

Seismic Newtonian Noise: numerical evaluation

NN calculation as
large 3x3n matrix product for n_e nodes

The 3 ×3n matrix A contains FE information
- the geology
- the geometry of the caverns
- the topography

and has to be computed once for a geometry
It yields the contribution of the nodal displacements u_e of element *e* to the total NN

Displacement acceleration

$$\delta\hat{\mathbf{a}}(\mathbf{x}_0) = \sum_{e=1}^{n_e} \mathbf{A}_s^e \underline{\hat{\mathbf{u}}}^e = \mathbf{A}_s \underline{\hat{\mathbf{u}}}$$

The vector u is contains the seismic noise model
Raleigh, bulk waves with sources
Matched to the surface and subsurface seismic measurements

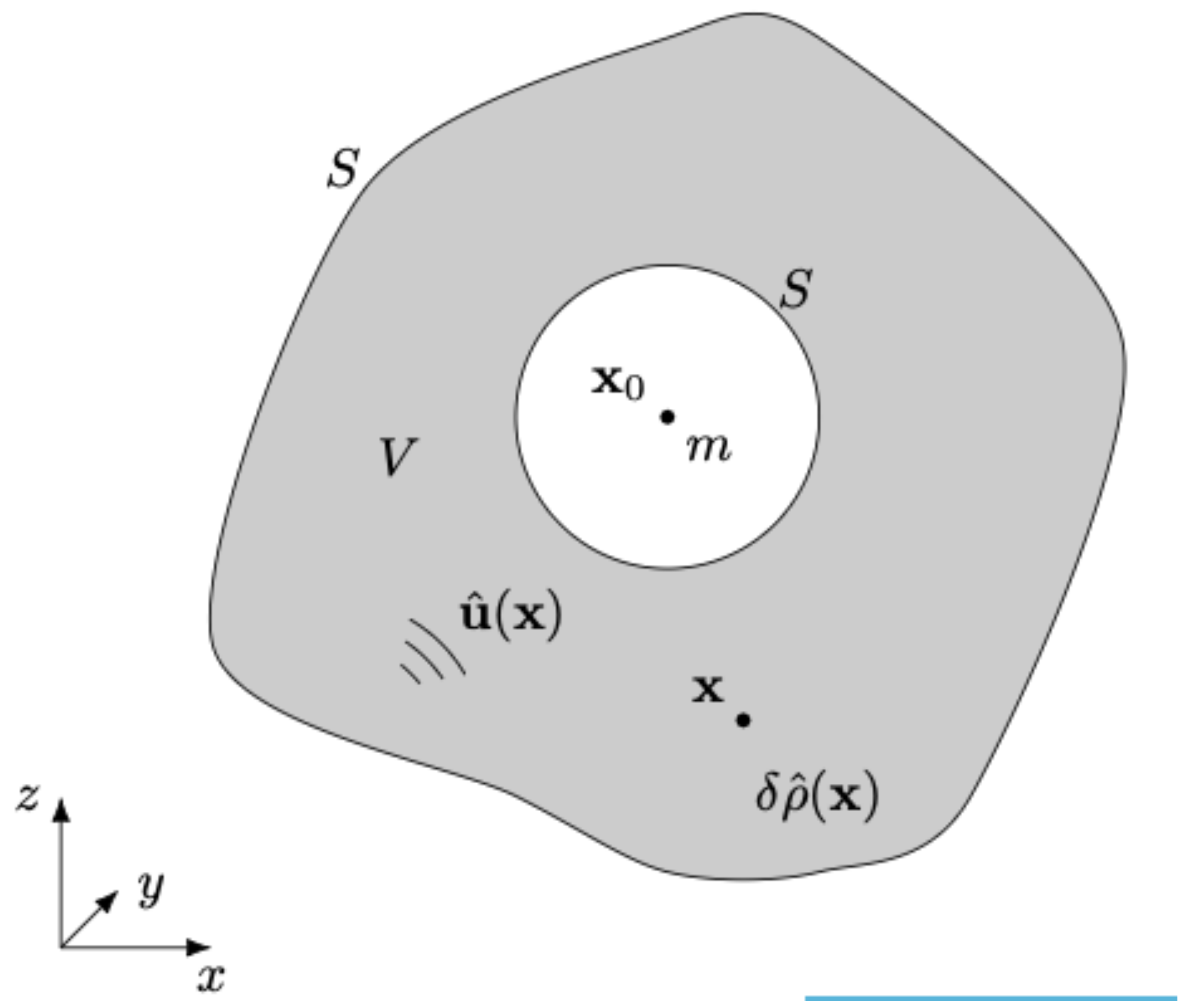
- Derivation involves transformation from global coordinates x to local mesh coordinates ξ

$$\delta\hat{\mathbf{a}}(\mathbf{x}_0) \simeq \sum_{e=1}^{n^e} \left[G \int_{-1}^{+1}\int_{-1}^{+1}\int_{-1}^{+1} \rho^e \left(\sum_{k=1}^{n} \boldsymbol{\chi}_k \otimes \nabla N_k^e(\boldsymbol{\xi}) \right) \cdot \mathbf{N}^e(\boldsymbol{\xi}) \det(\mathbf{J}^e)\, \mathrm{d}\xi_1\, \mathrm{d}\xi_2\, \mathrm{d}\xi_3 \right] \underline{\hat{\mathbf{u}}}^e$$

Validating numerical tool

Setting up FE mesh criteria (short-cut here)

- Truncation for the bulk and surface contributions
  - Typically impose tolerance (ε= 0.01) for each bulk and surface contributions, for which is needed: $R_{bulk} \approx 16\lambda_p$, $R_{surf} \approx 48\lambda_p$.



- Wavelength resolution: To resolve wave propagation, the maximum element size is chosen as

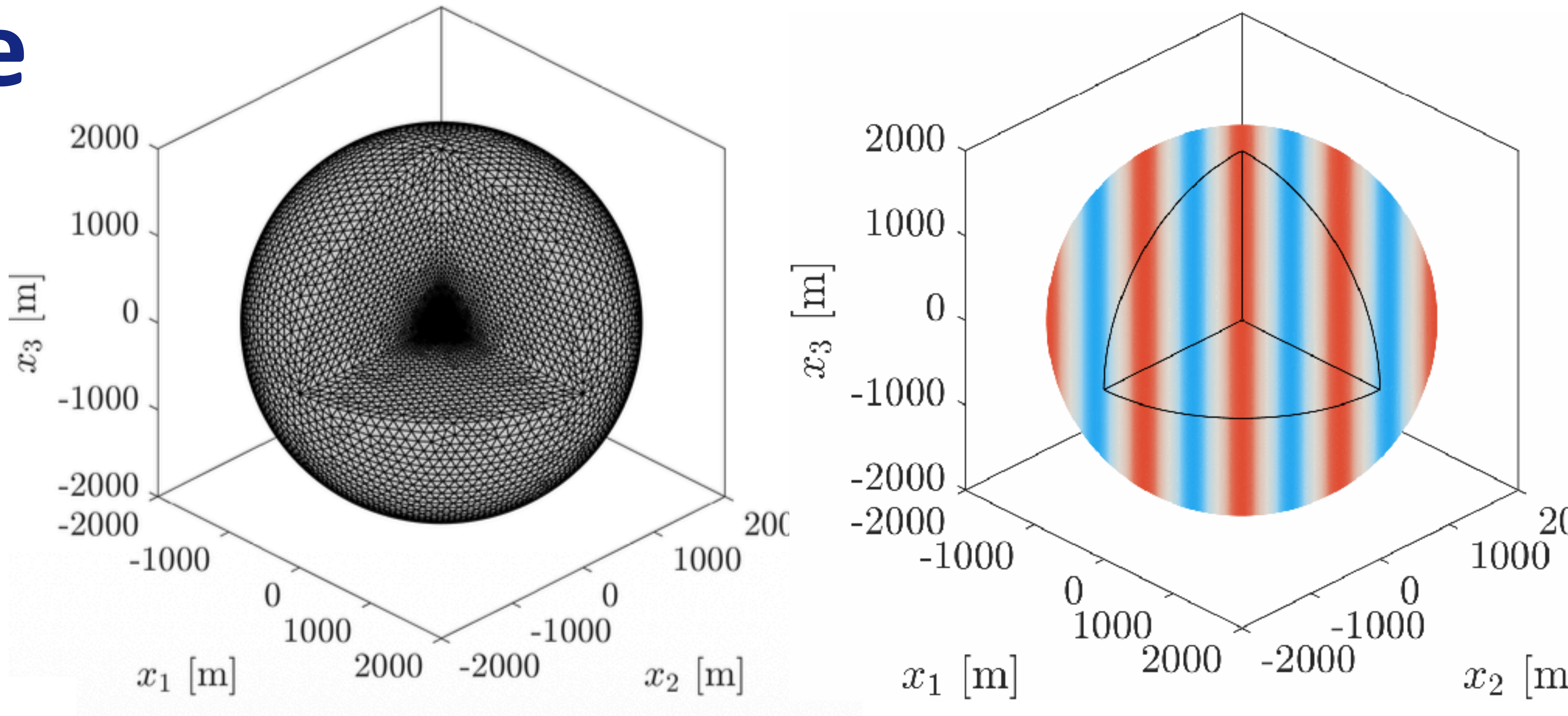
$$\ell_e = \frac{C_s}{n f_{\max}}, \qquad n = 4, 6, 8, \ldots \text{elements per wavelength}$$

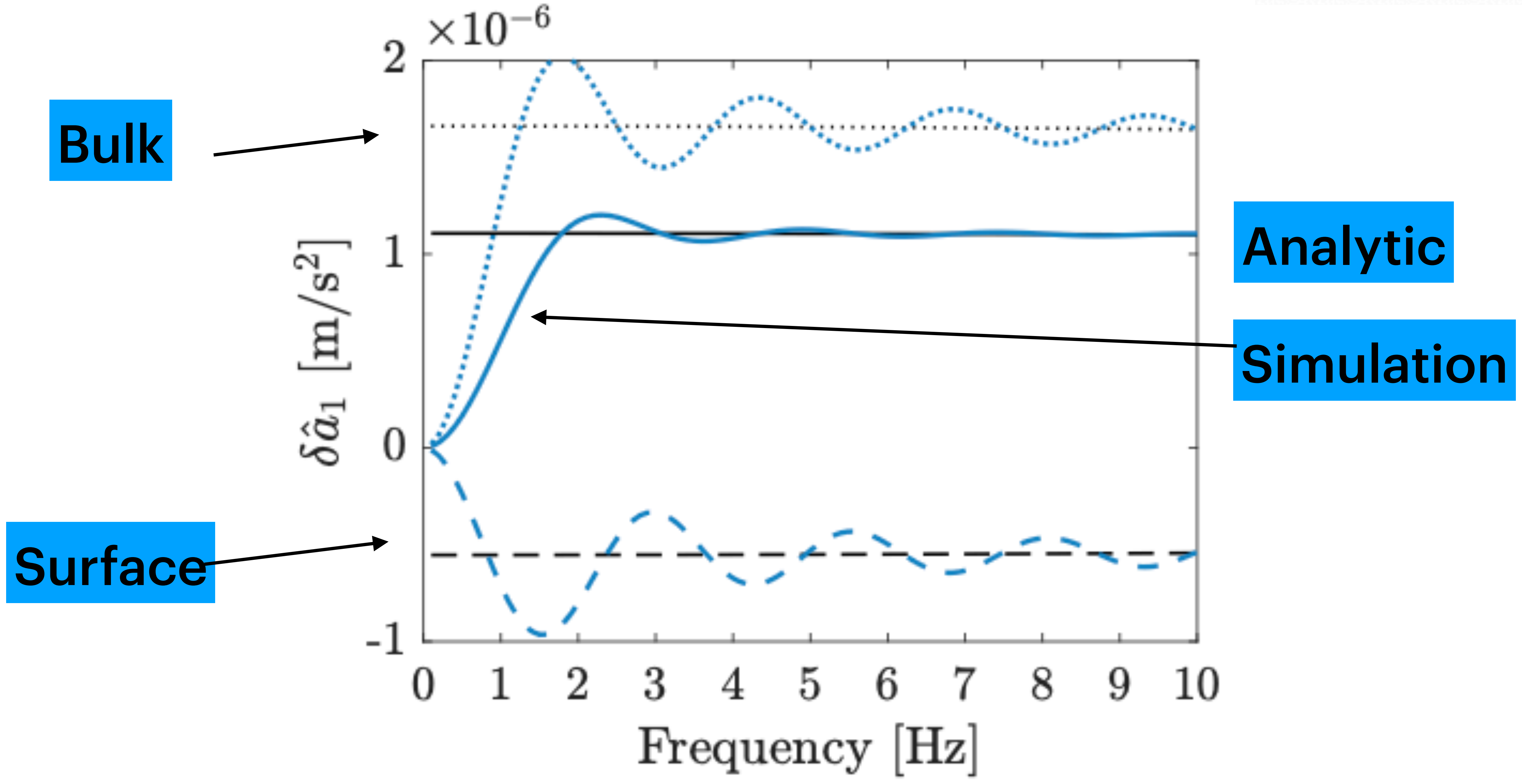
- Further refine mesh element sizes to ensure fine resolution where needed and coarser elements away from the cavity, balancing accuracy and computational cost.

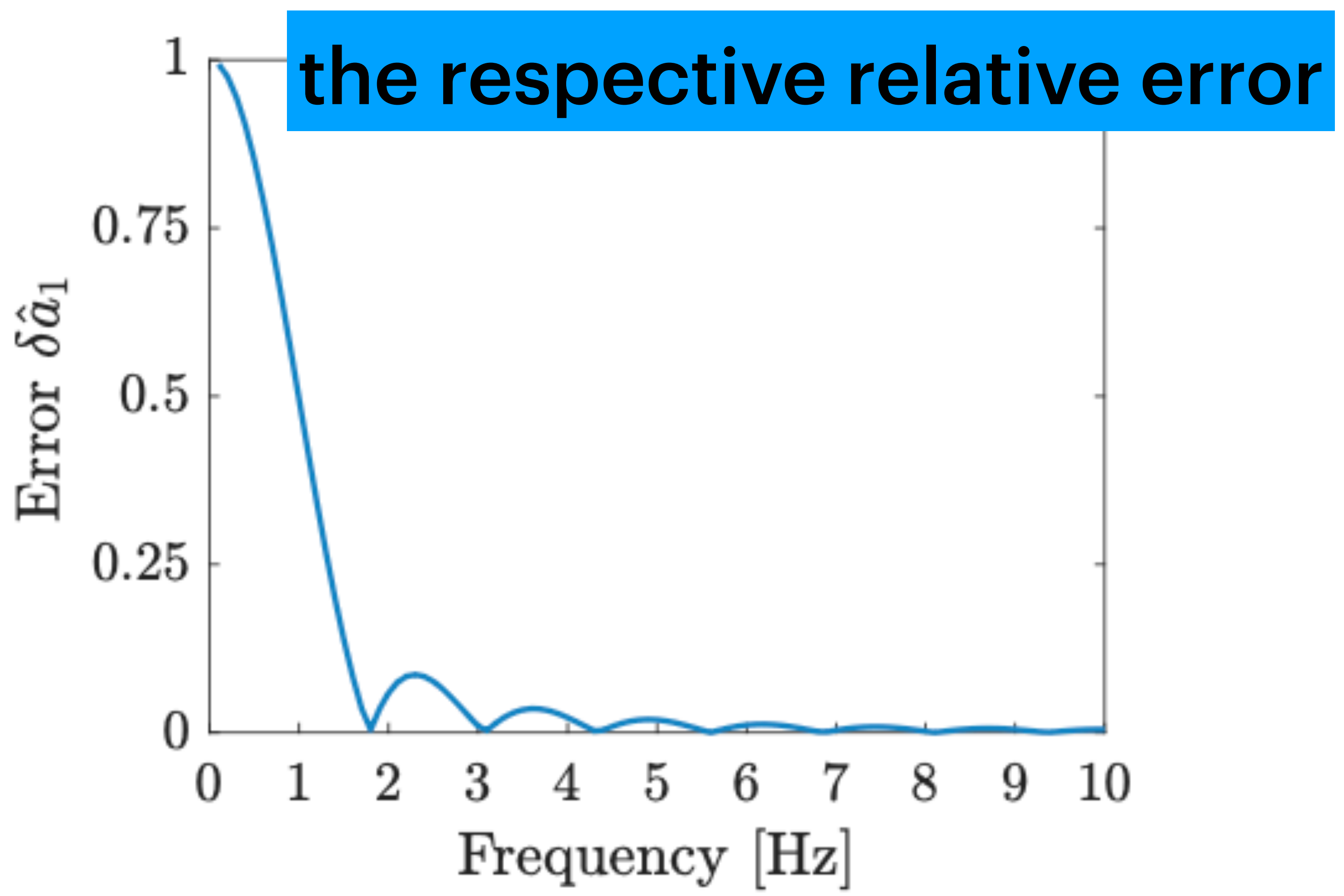
Validating full space

NN for a plane P-wave
with unit amplitude - 5 Hz

- Fullspace (R= 2000m) with cavity (r_0 = 20 m).
- $\delta a(x_0)$ computed analytically and numerically



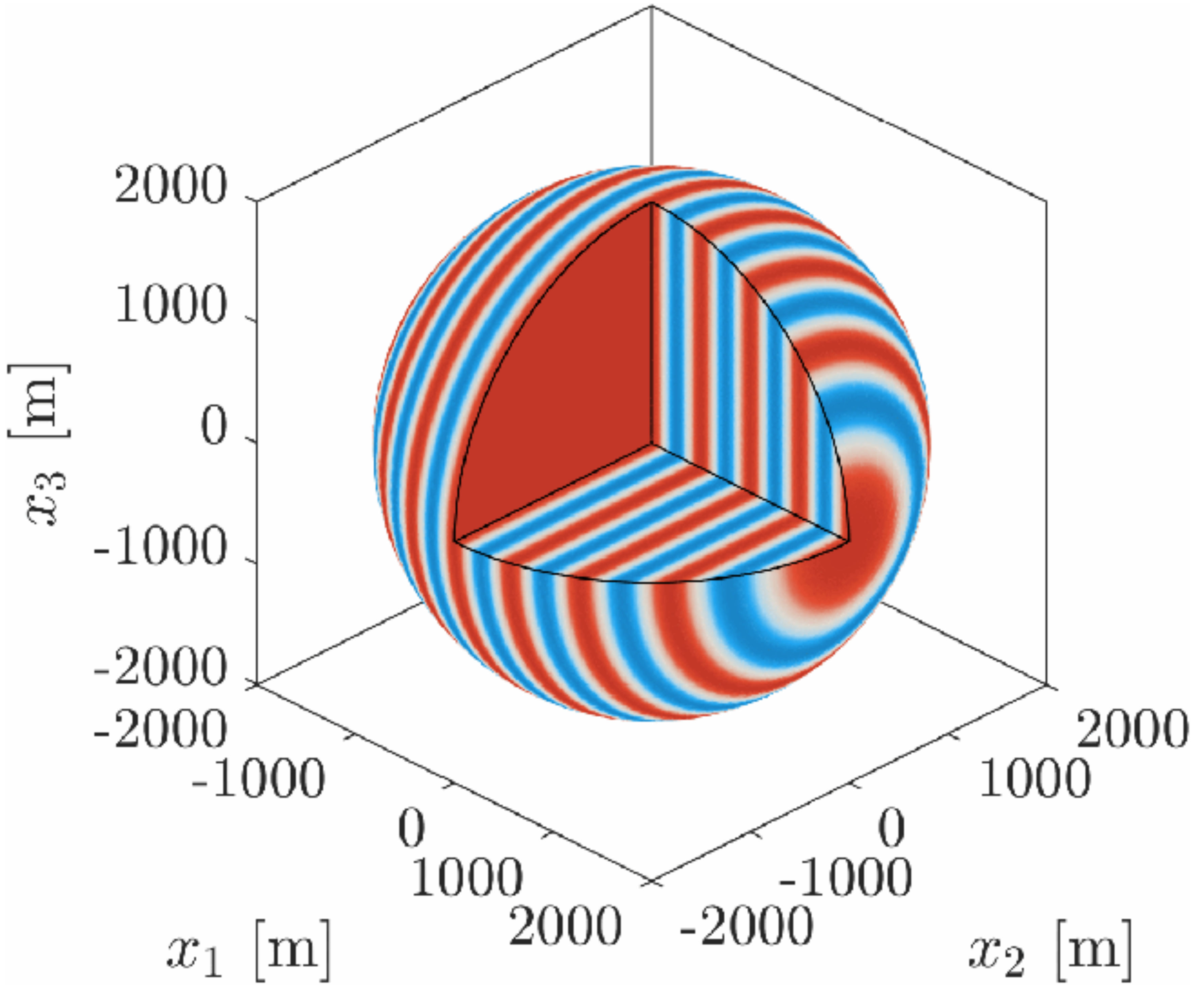


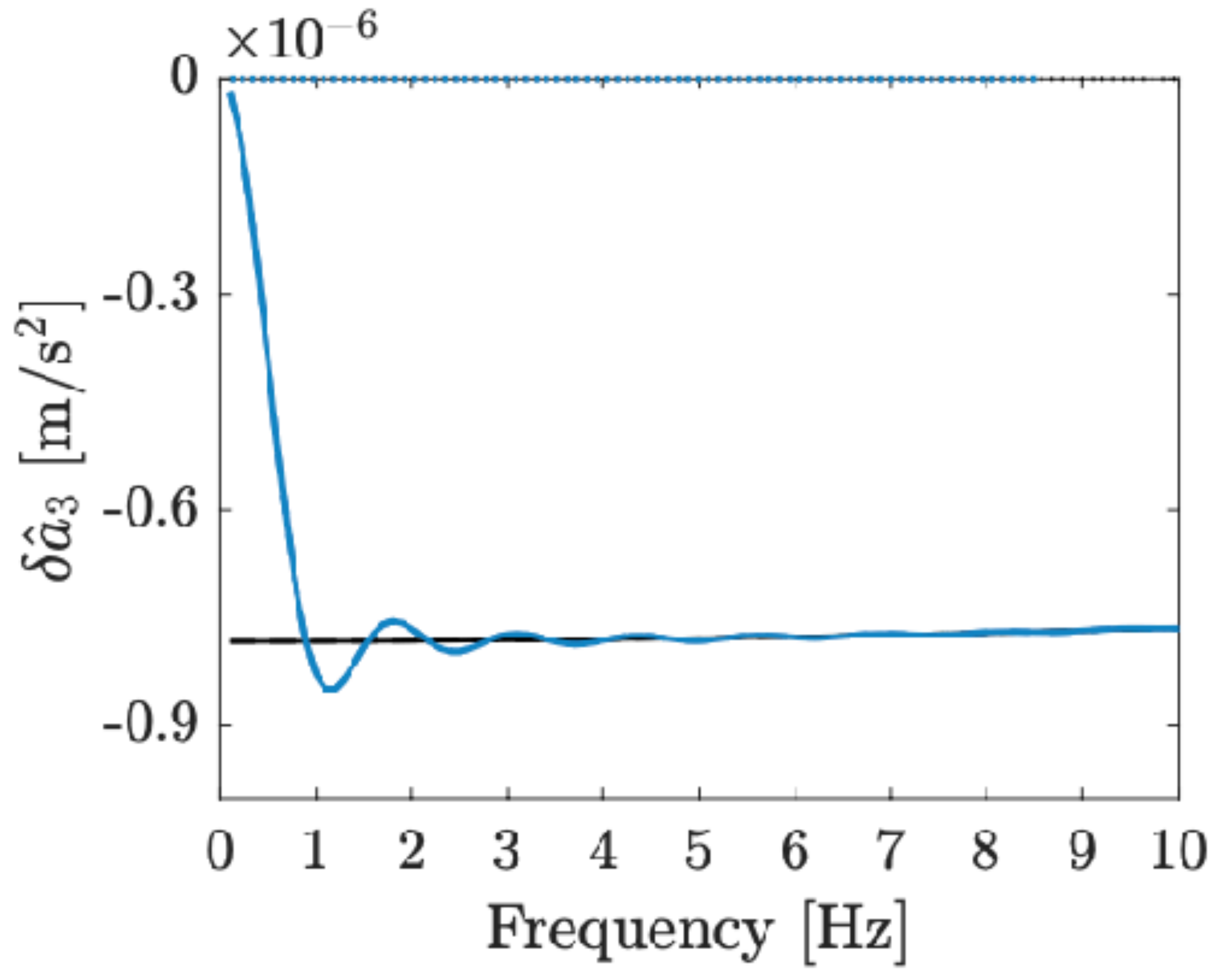


Validating full space

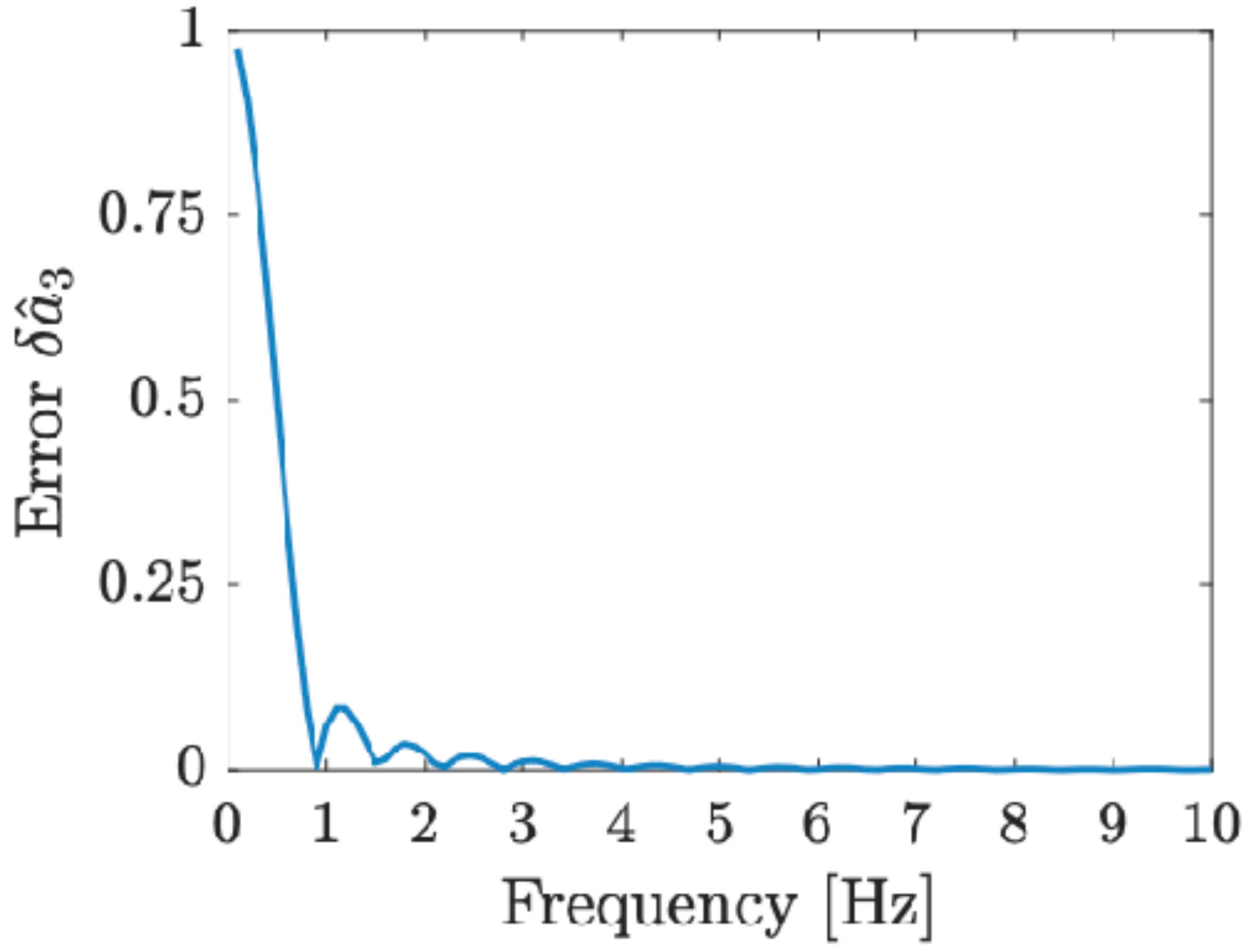
Validation: plane S-wave

- Newtonian noise $\delta a_3(x_0)$ under S-wave excitation computed analytically and with the numerical model





(b)

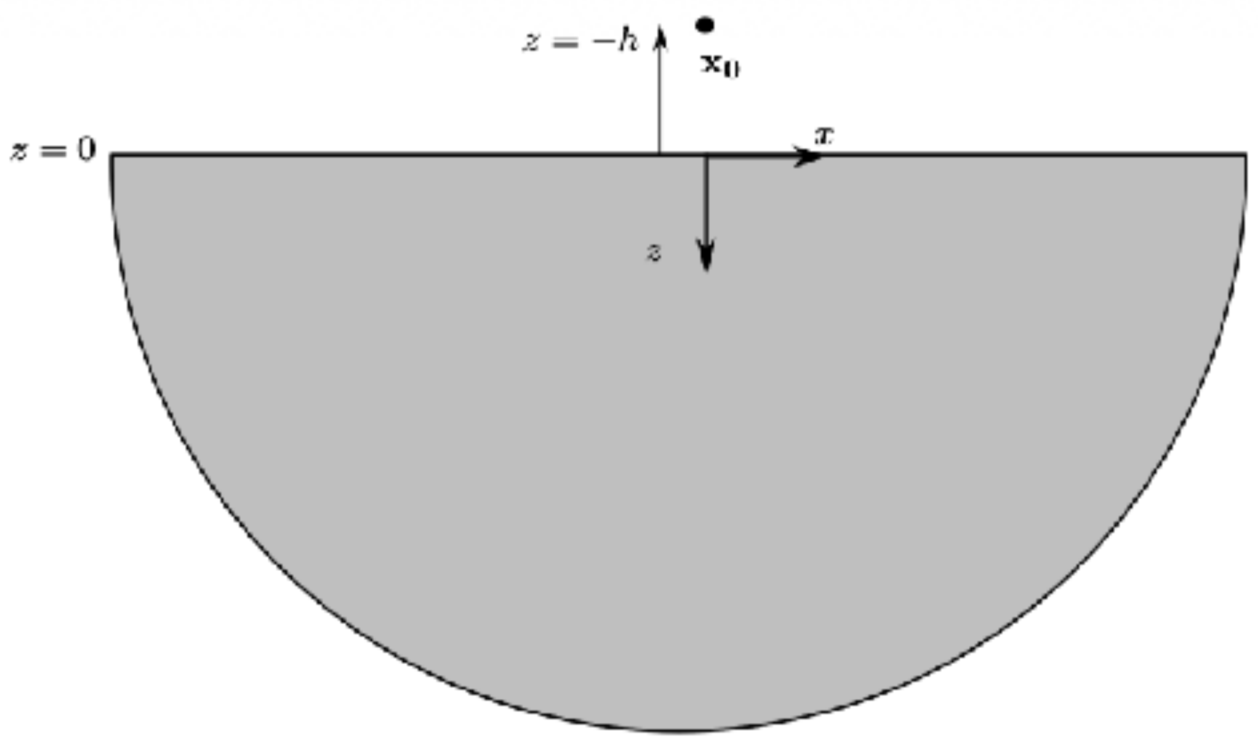


Analytic result:

$$\delta \hat{\mathbf{a}}(\mathbf{x}_0) \quad = \quad -4\pi\rho_1 G \frac{j_1(k_s r_0)}{k_s r_0} \hat{\mathbf{u}}(\mathbf{x}_0)$$

Uniform full-space validated

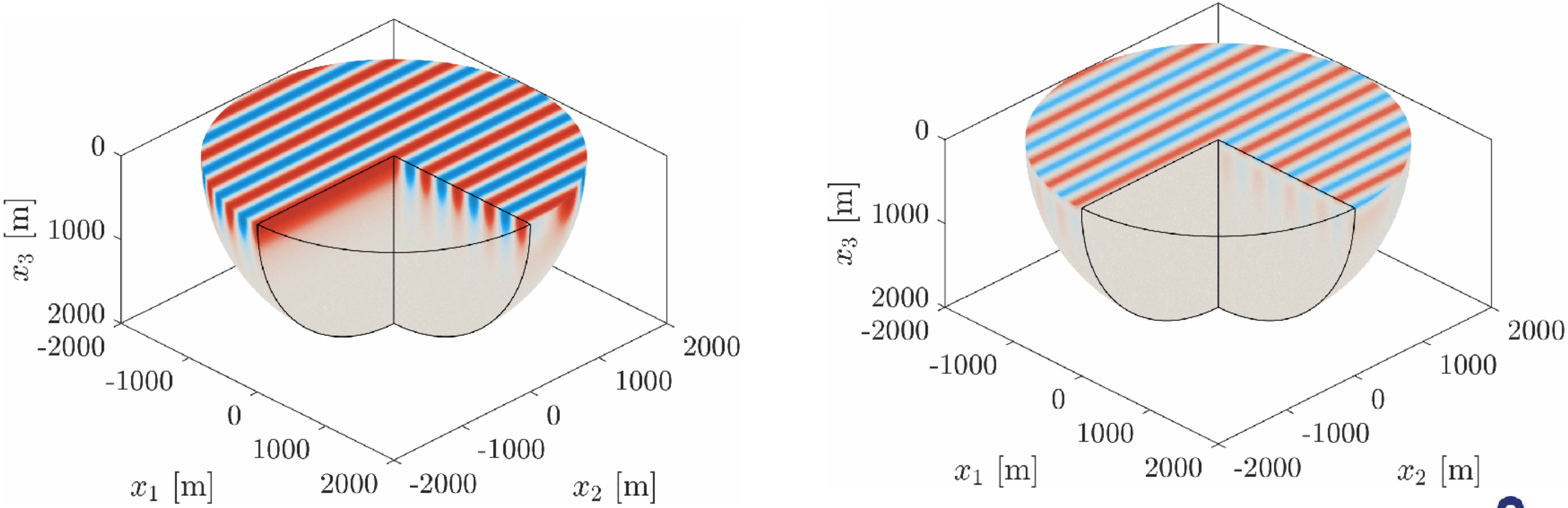
Numerical results half-sphere



Raleigh waves in homogeneous halfspace

- Test mass at distance z=−h above free surface.
  - Half-space: C_s = 2500 m/s, C_p = 5000 m/s, ρ= 2800 kg/m³
  - Wave at 5 Hz

.

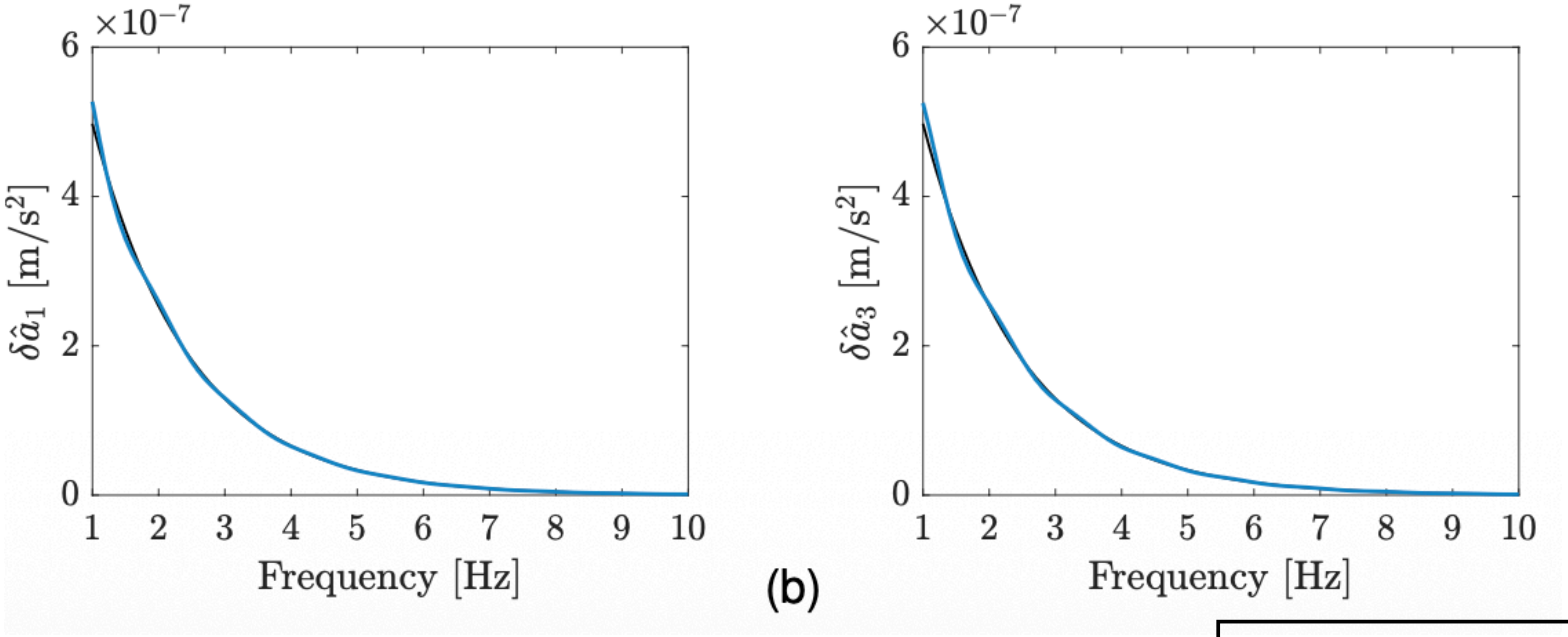


Seismic displacements $u_1(x)$ and $u_3(x)$

Numerical results half-sphere

Newtonian noise for a Rayleigh wave in a halfspace with test mass at distance $z_0 = -h$ above free surface:

- Computed analytically and with the numerical model



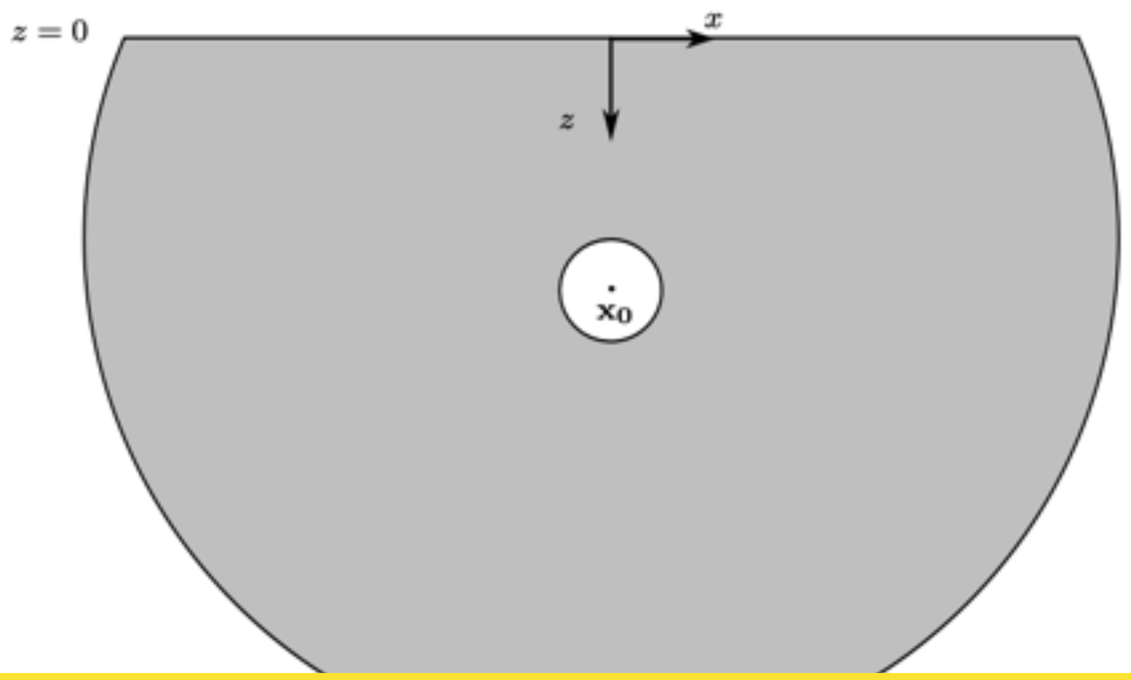
Half-space with Raleigh waves validated ✔

Analytic result:

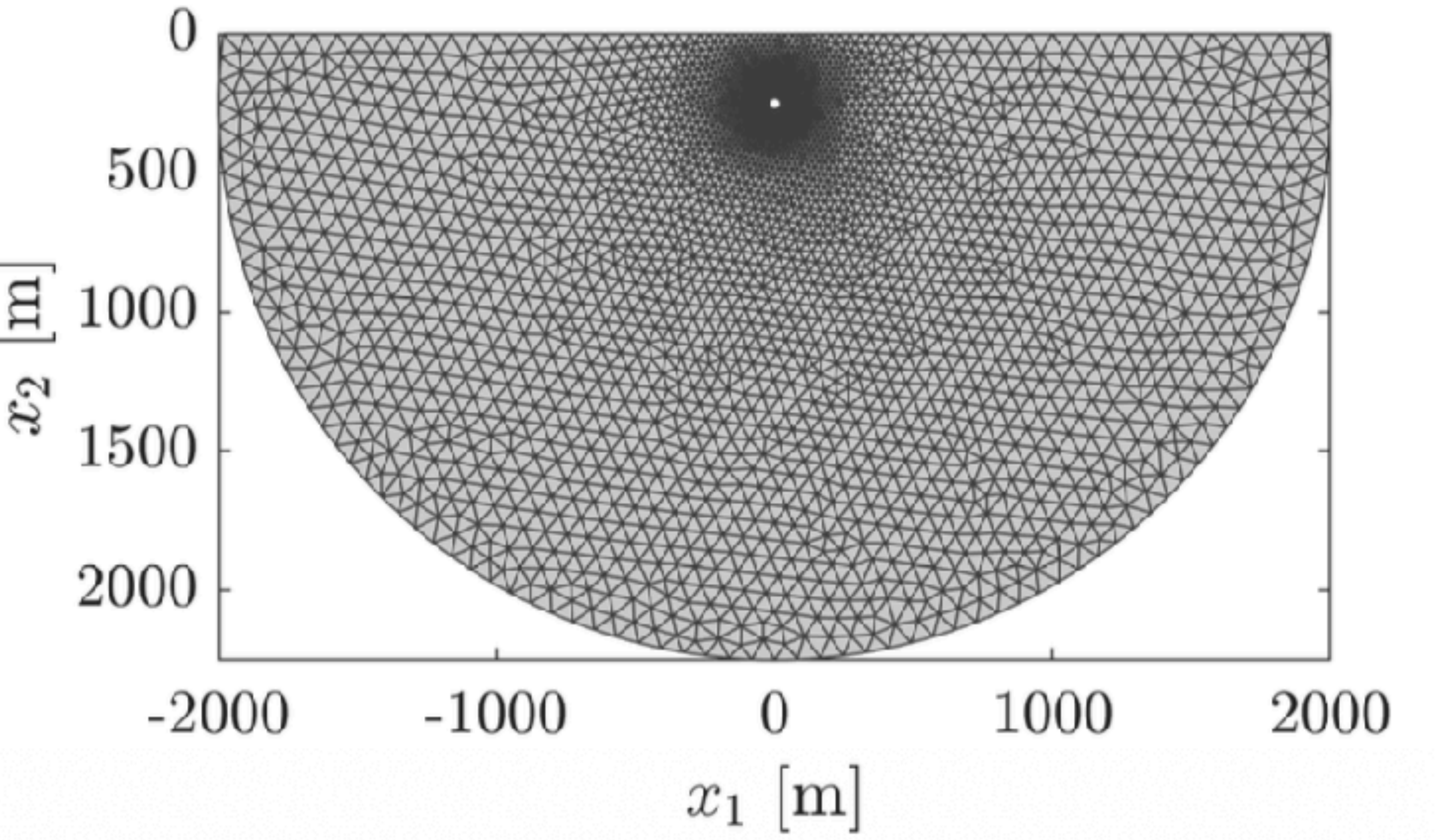
$$\delta\hat{\mathbf{a}}(\mathbf{x}_0) = 2\pi G\rho e^{-k_{\mathrm{R}}h}\frac{k_{\mathrm{R}}\left(1-\sqrt{k_{z\mathrm{p}}/k_{z\mathrm{s}}}\right)}{\mathrm{i}k_{z\mathrm{p}}-k_{\mathrm{R}}\sqrt{k_{z\mathrm{p}}/k_{z\mathrm{s}}}}\left(-\mathrm{i}\mathbf{e}_{\parallel}-\mathbf{e}_z\right)\exp\left(-\mathrm{i}k_{\mathrm{R}}\mathbf{e}_{\parallel}\cdot\mathbf{x}_{0\parallel}\right).$$

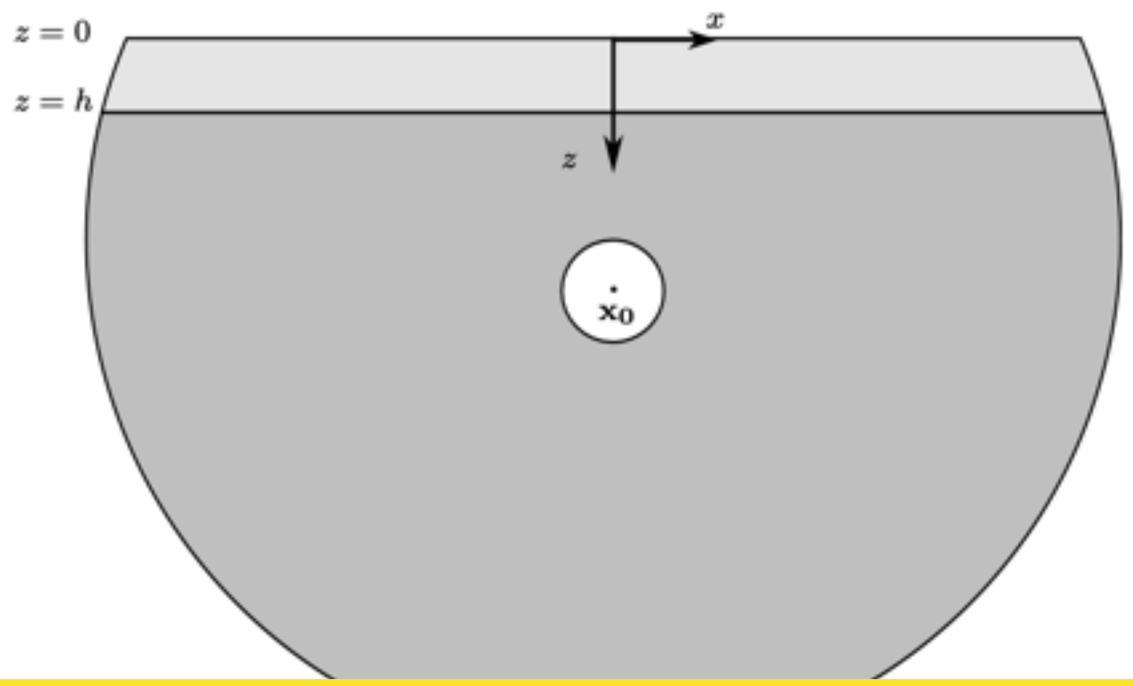
Future plans

Half-space with subsurface cavern; results soon!

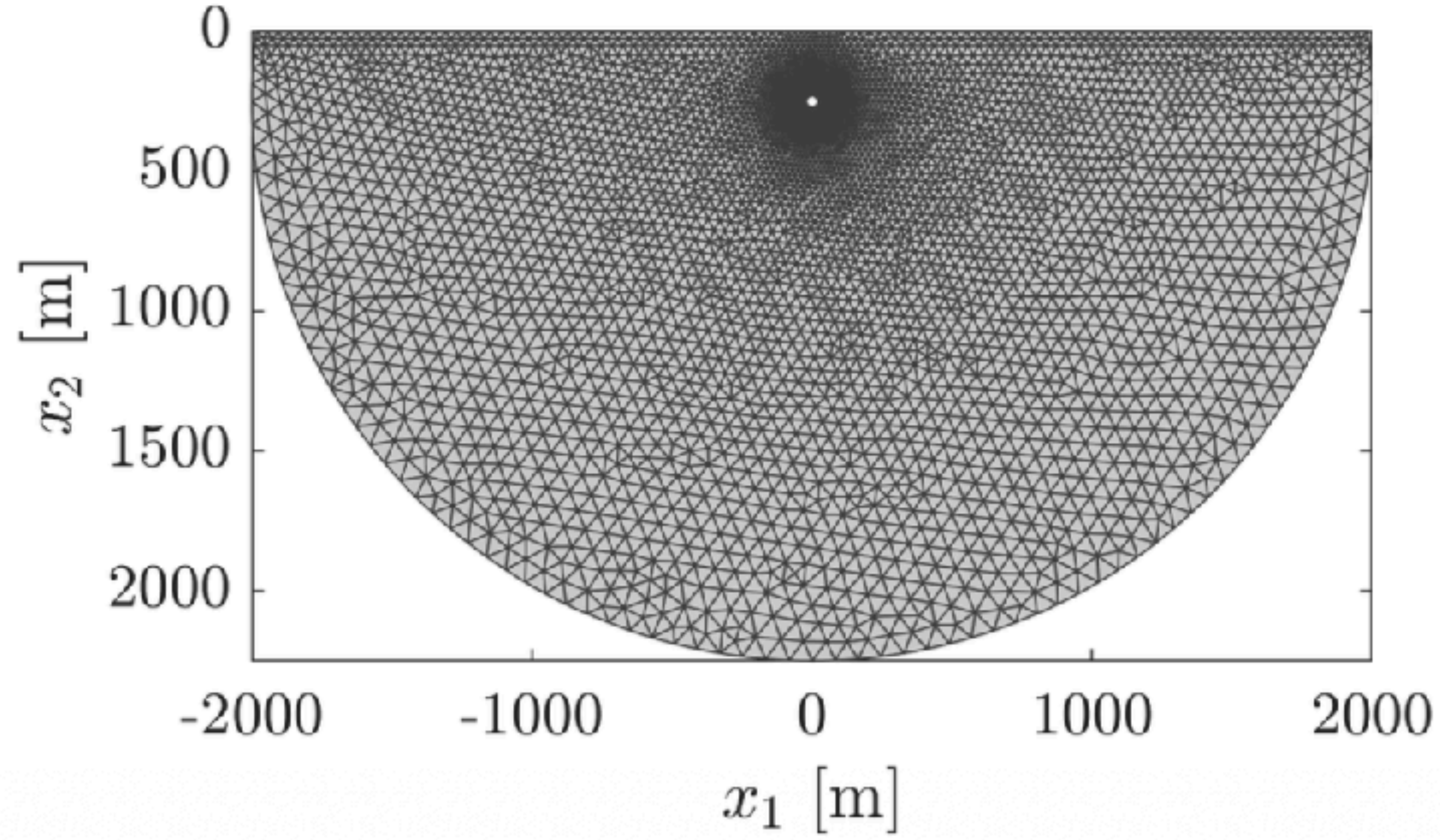


Homogeneous geology



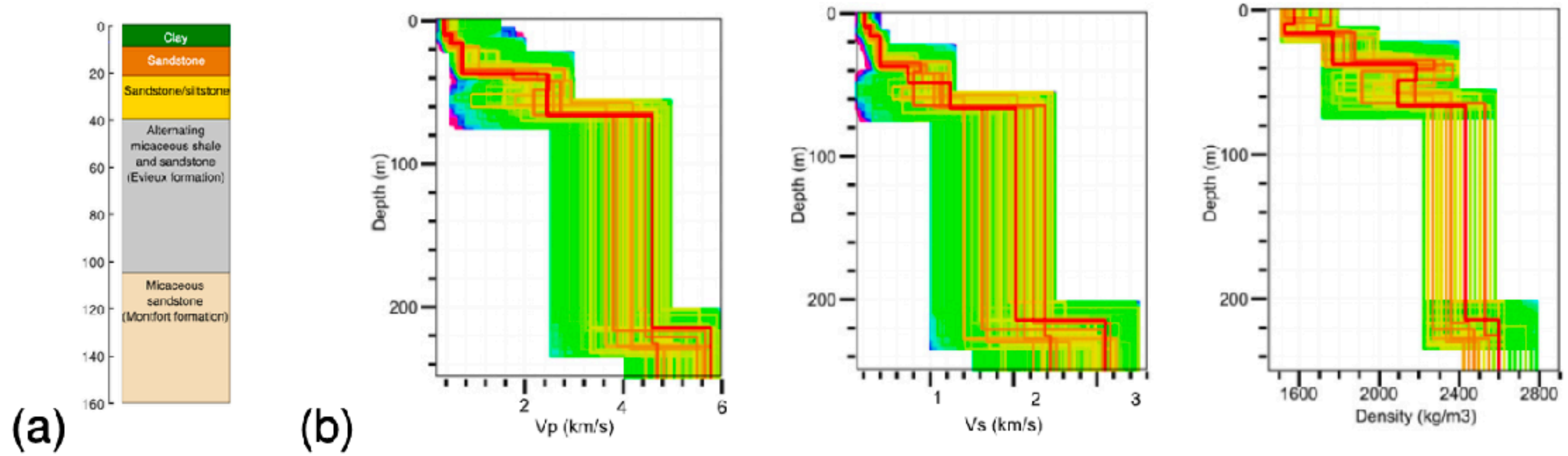


2-layer geology; different velocities



Outlook
Soil layering and properties for Terziet

- Experimental campaign in Terziet (The Netherlands) [Bader et al. (2022); Koley et al. (2022)]:
  - Borehole samples: lithology
  - Resistivity, sonic and gamma-ray logging: lithology, density ρ, shear and dilatational wave velocities C_s and C_p
  - Beamforming (two seismic arrays): shear wave velocity C_s
  - Refraction tomography: dilatational wave velocity C_p
- (a) Lithology and (b) P-wave, S-wave and density models [Koley et al. (2022)].



- Dynamic soil characteristics [Bader et al. (2022)].

Layer	Description	h [m]	C_s [m/s]	C_p [m/s]	ρ [kg/m^3]	β_s [-]	β_p [-]
1	Clay	5.7	165	385	1950	0.020	0.020
2	Sandstone/siltstone	10.2	270	445	2250	0.010	0.010
3	Sandstone/siltstone	18.9	335	685	2500	0.010	0.010
4	Quartzite/shales	58.2	1240	2810	2800	0.005	0.005
5	Silcified shales	∞	2430	4050	2800	0.005	0.005

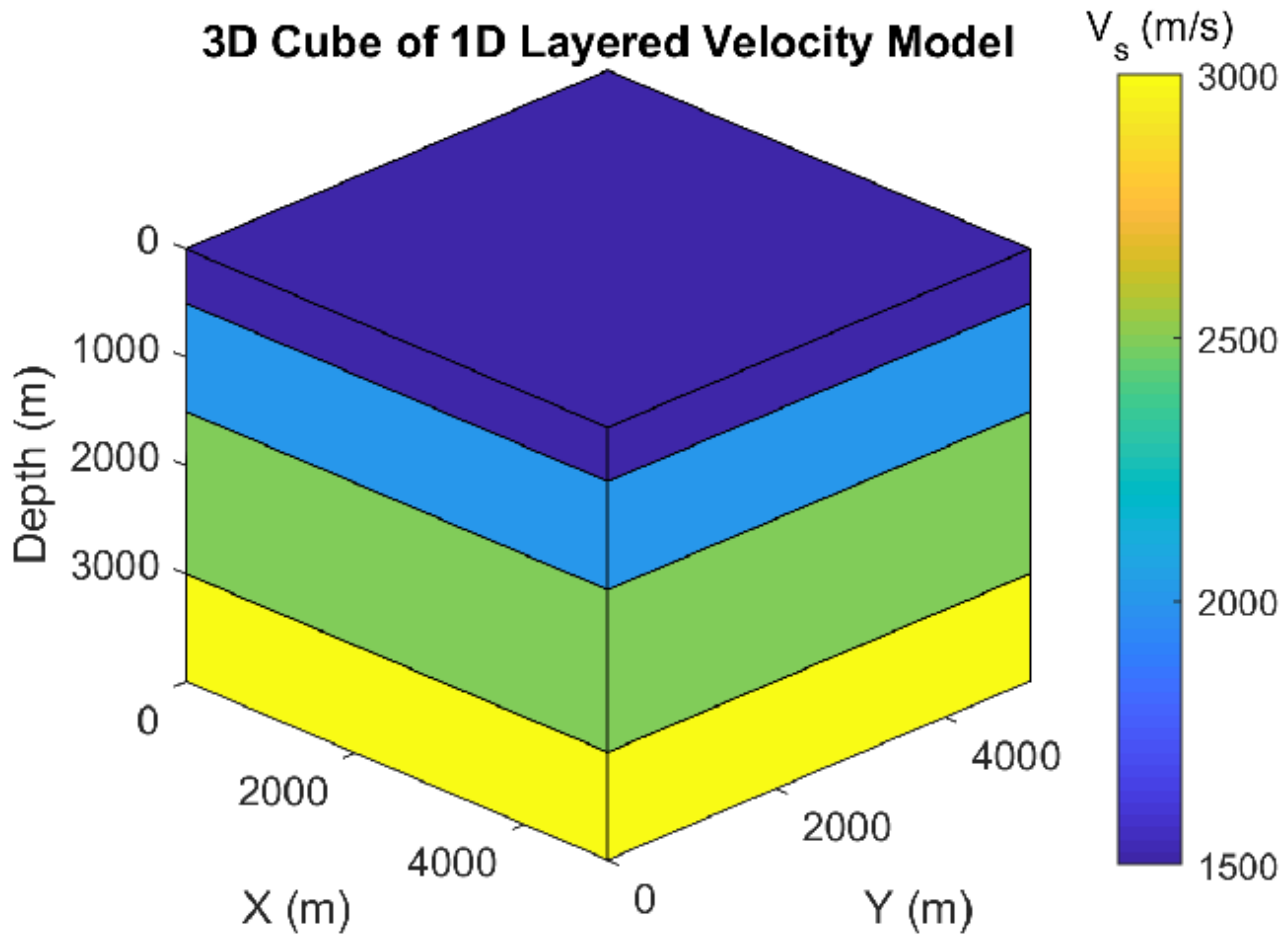
KU LEUVEN

pySeis1DNN: Modeling tools for Newtonian noise

ULiege: Koley, Michel et al.

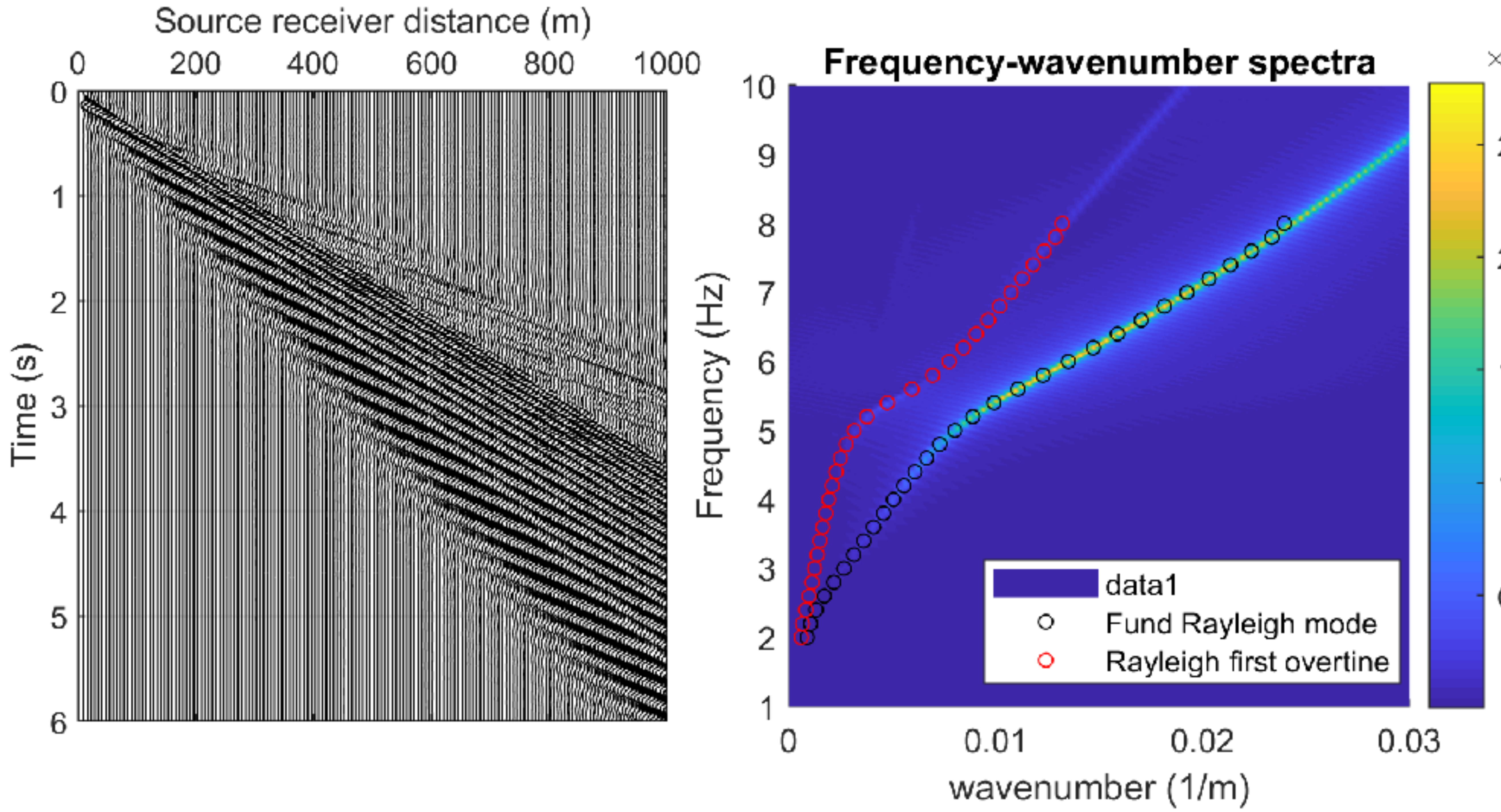
Modeling Newtonian noise in 1D elastic medium – pySeis1DNN

- Based on displacement simulation using pre-computed transfer function in a 1D elastic medium
- Precompute transfer function in a layered medium for different force types and source-receiver distances and depth



An illustration of a Layered geology in a cubical simulation domain

Compute Green's function for force types



Green's function gather for a vertical force type with source and receiver spread on the surface. (right) F-K spectra of the Green's function receiver gather showing dominant energy propagating as the fundamental and the first overtone of the Rayleigh wave

pySeis1DNN: Modeling tools for Newtonian noise

Modeling NN in 1D elastic medium

- Noise sources on the surface
  - Stochastic or known sources
  - With random/predetermined source phase, amplitude and azimuth for horizontal force types
- Makes use of rotation-symmetry to compute displacements
  - At desired GL points in the layered geology – speeds up computation
- Scale amplitude of the sources
  - To match spectra on the surface and underground
- Compute Newtonian Noise
  - Integrate displacements

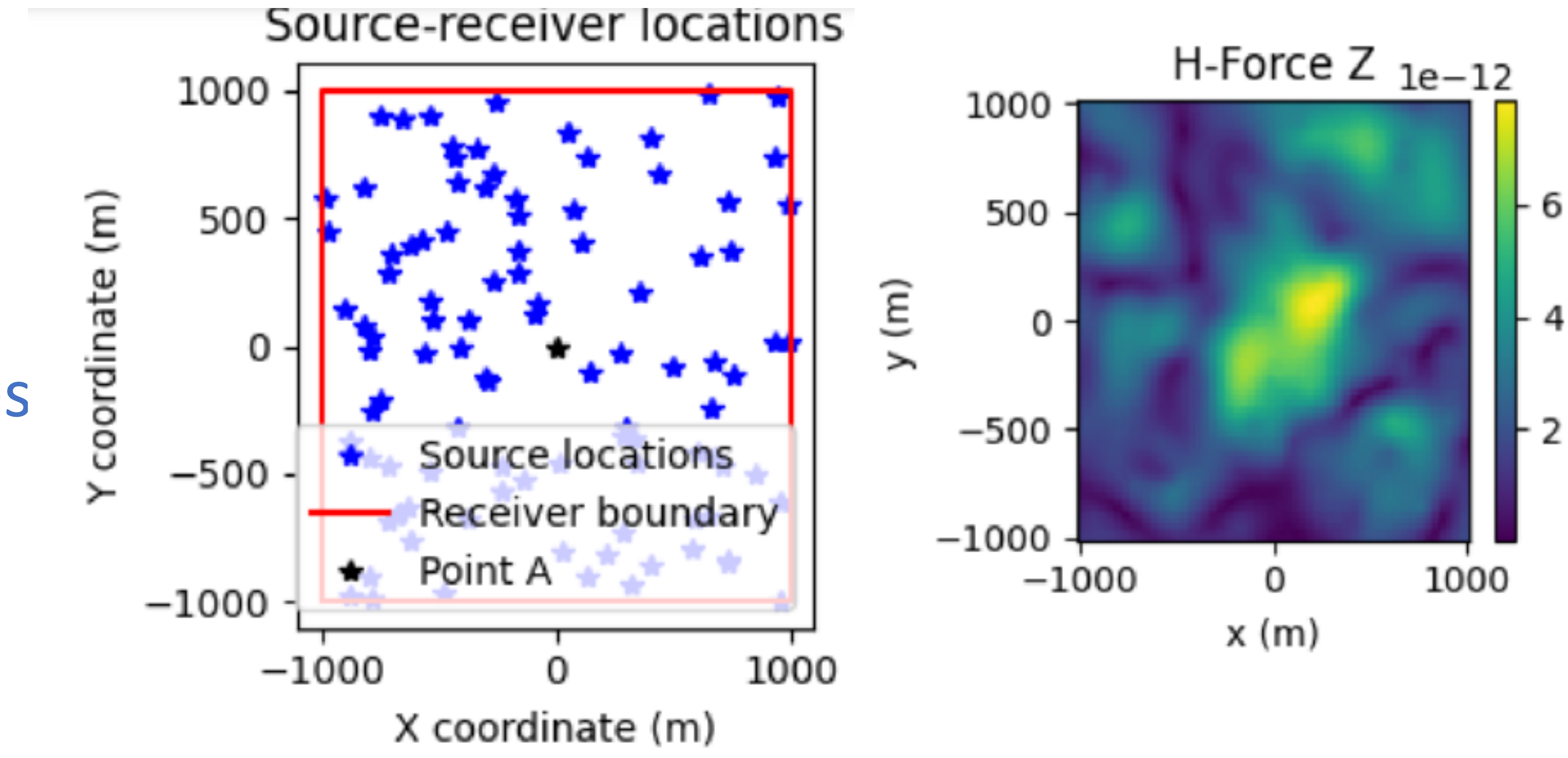


Figure showing random locations of 100 sources (one realization) within the simulation domain. (right) Vertical acceleration spectra (arbitrary units) derived from GF database at a depth of 220 m in a layered geology from horizontal forces

Cons: Cannot handle effects due to topography and undulating geology
Usage: typically for the corners points of the triangle
Try to set several limits of parameters - search for best geology model
Check for the interpolation between the measurements

pySeis3DNN: Modeling tools for Newtonian noise

Once 1d is ready then progress to 3d

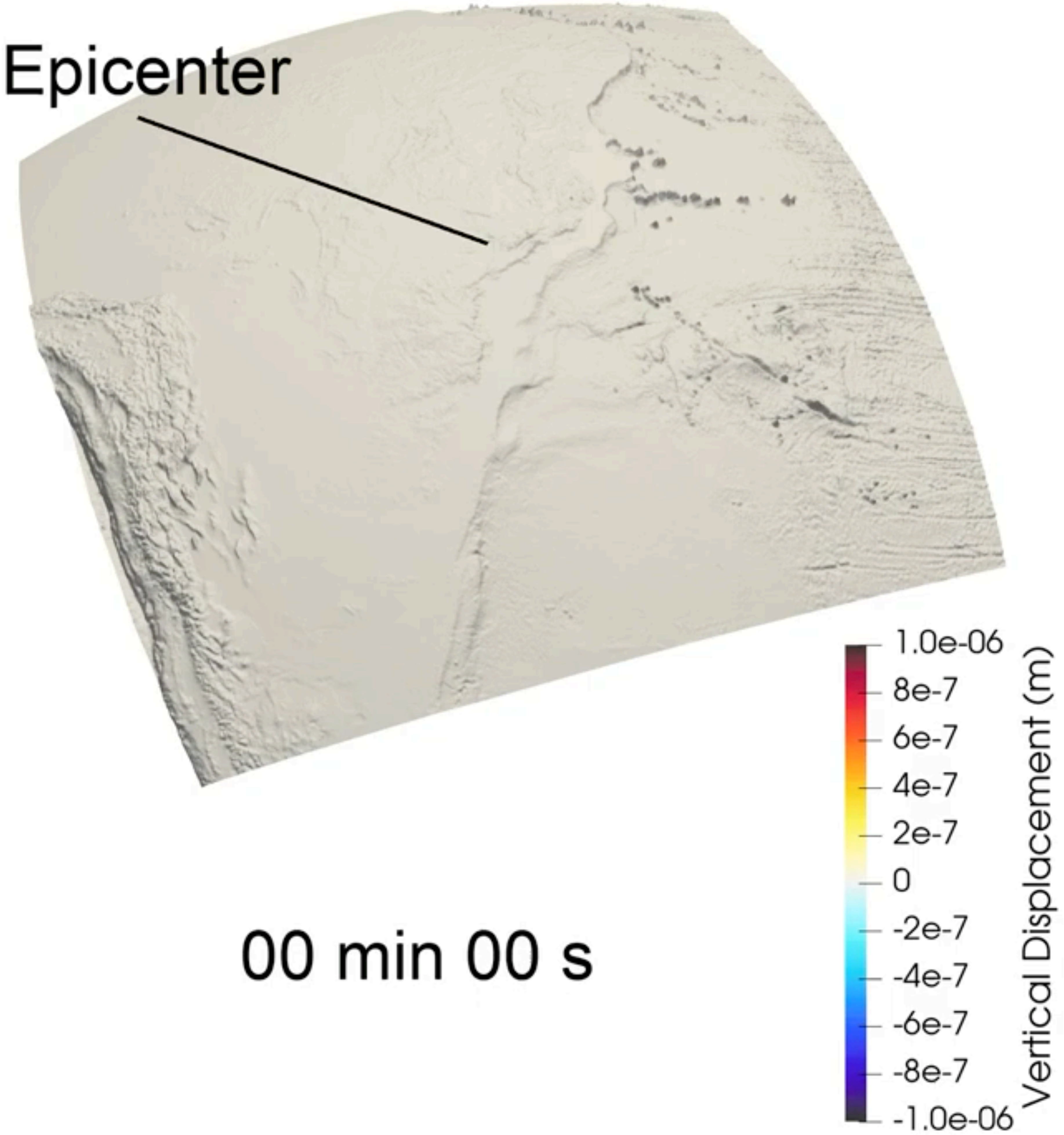
- But may take many CPU hours

SALVUS used for (very) final 3d version for EMR

- Obtaining spectra using FE method
  - Solving the elastic wave equation in hexahedral mesh
- Tomography and scattering from cavity surface
- Symmetry axes for parallization
  - It is scalable
- In-house mesh generation
  - Use CUBIT for more complicated models
- Positioning of arbitrarily sources
  - With varying source phase and amplitude

More realistic seismic displacements and NN as compared to the 1D version

- Work ongoing …



1922 Sao Paolo (Mb = 5.1) Earthquake simulation example using spectral finite element method

NP3: Preparing for measurements: surface sensors

Surface sensors campaign

Measuring the impact on the site!

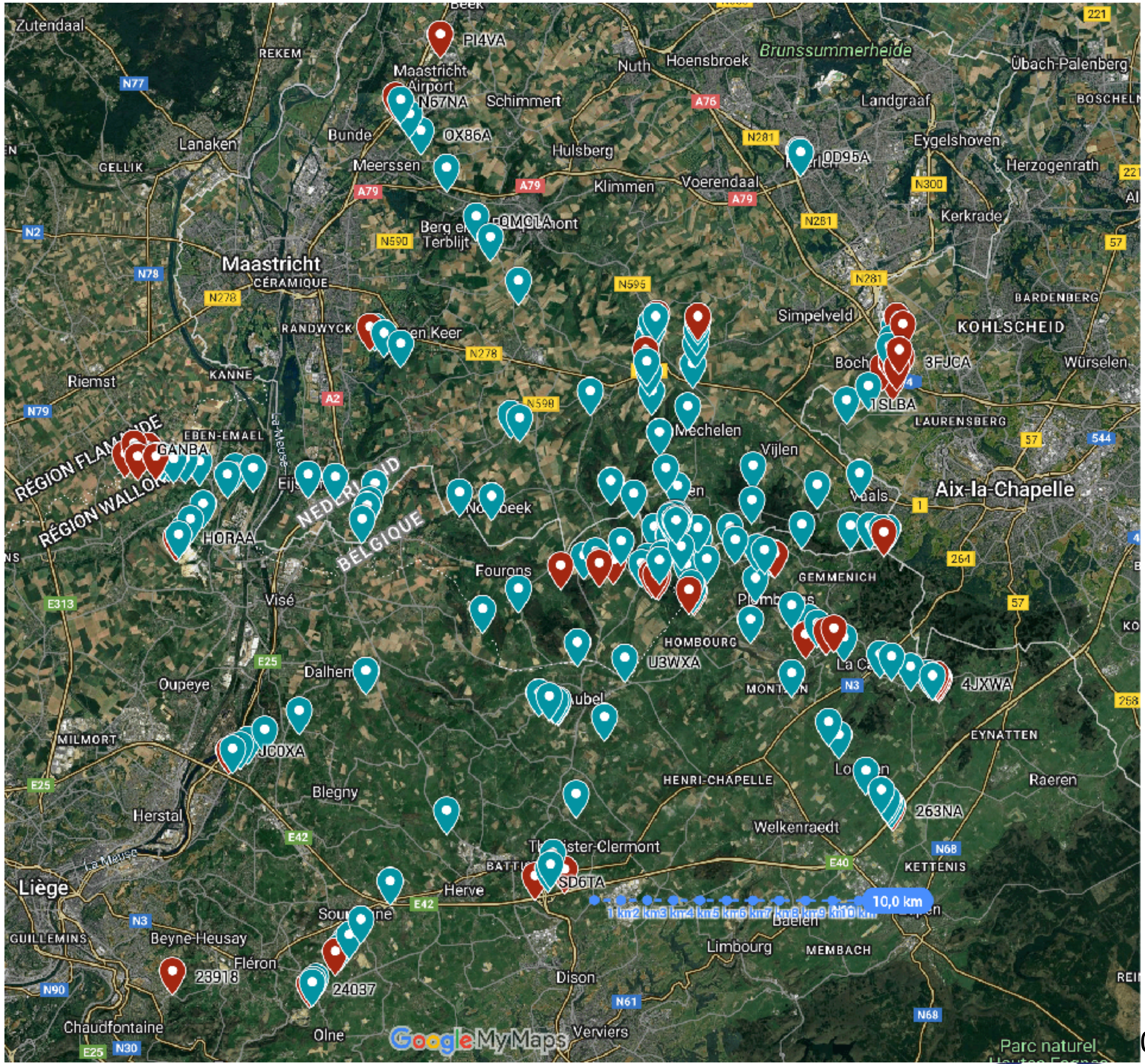
- Trying to understand as much as possible

Known and expected sources:

- Wind-turbines
- Viaducts
- Tunnels
- Industries (pumps and compressors)

DAQ – setup

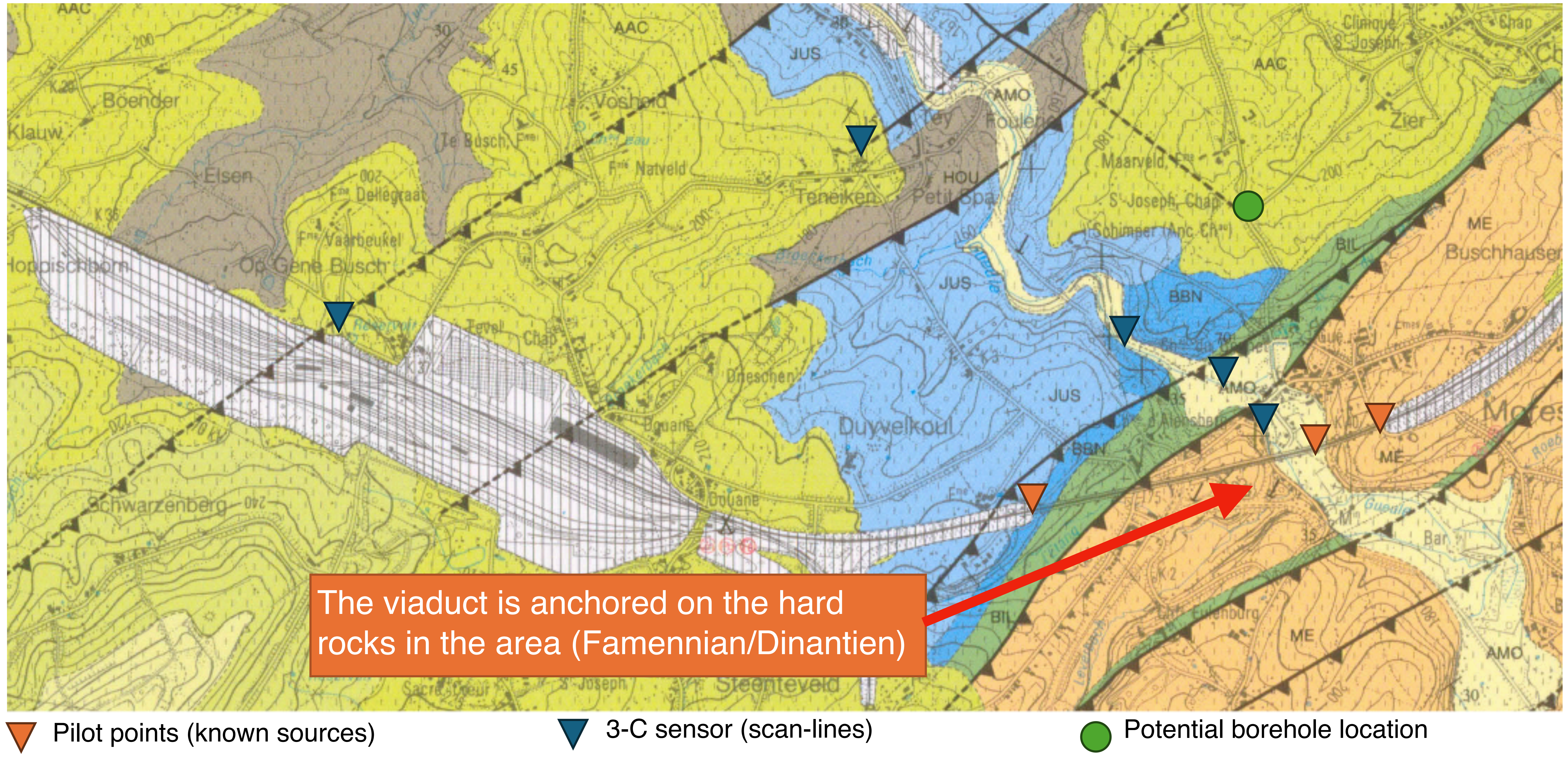
- 13 scan-lines around Terziet
- 230 Smartsolo’s IGU-16HR 3C



Surface sensors - case study

The Moresnet viaduct

- Part of the rail line 24 (Infrabel)
- Mainly used for freight trains traffic (about 2 trains per hour)



Problems for seismic noise:

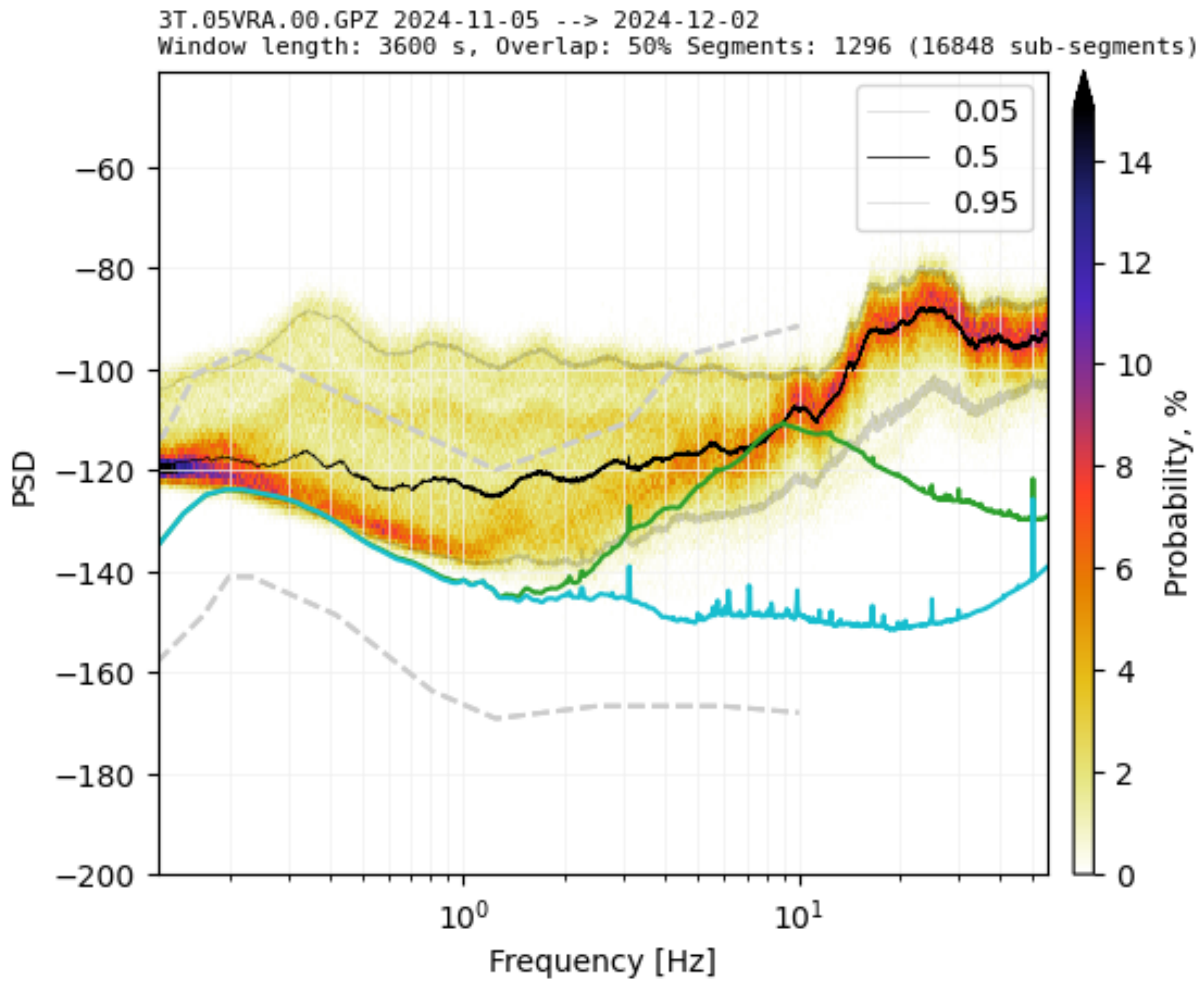
- Low resonance frequency
- Seismic source activated by trains and wind

Viaduct is anchored directly on the hard bedrock

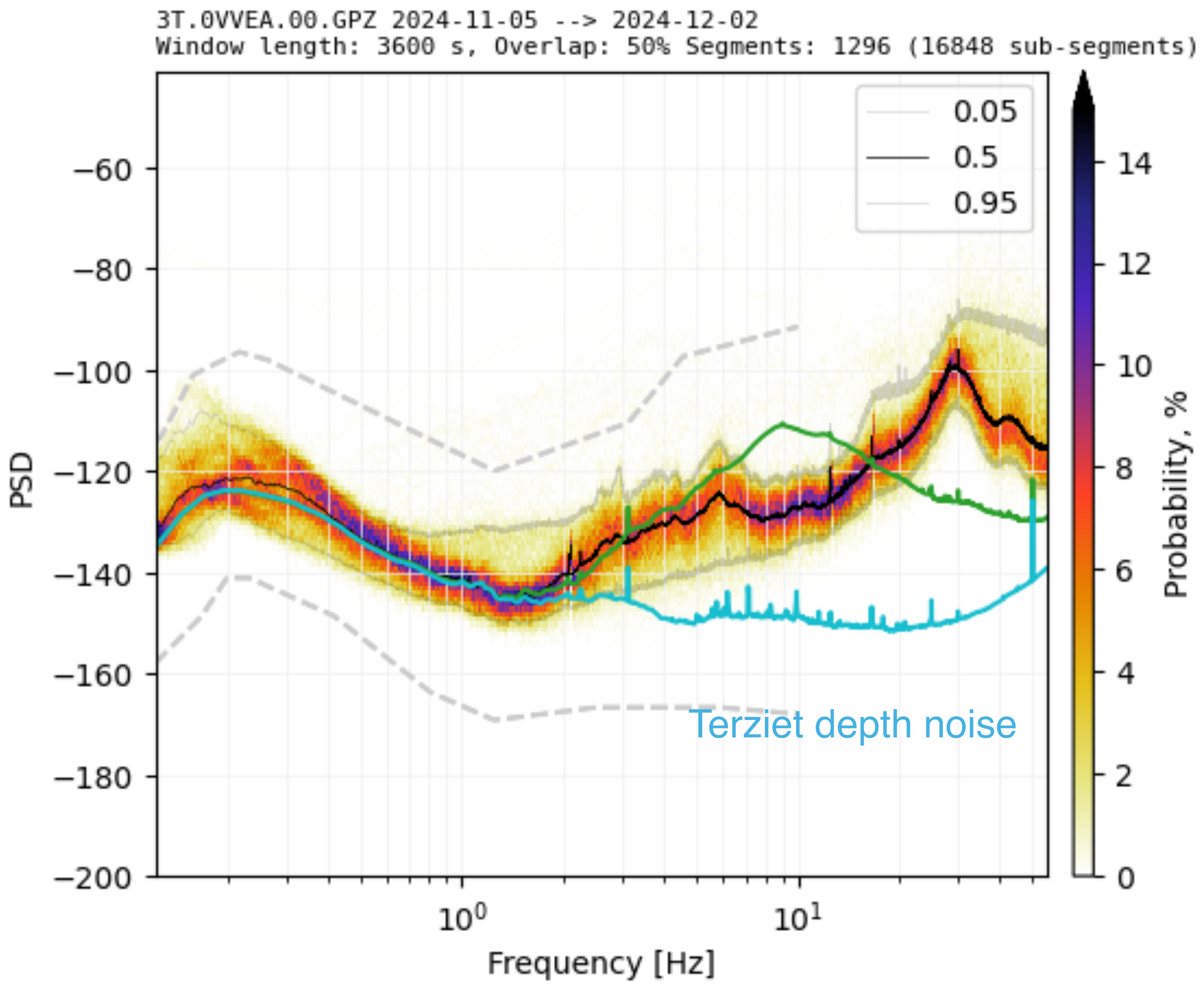
Surface sensors - case study

Viaduct can be approximated as a line-source

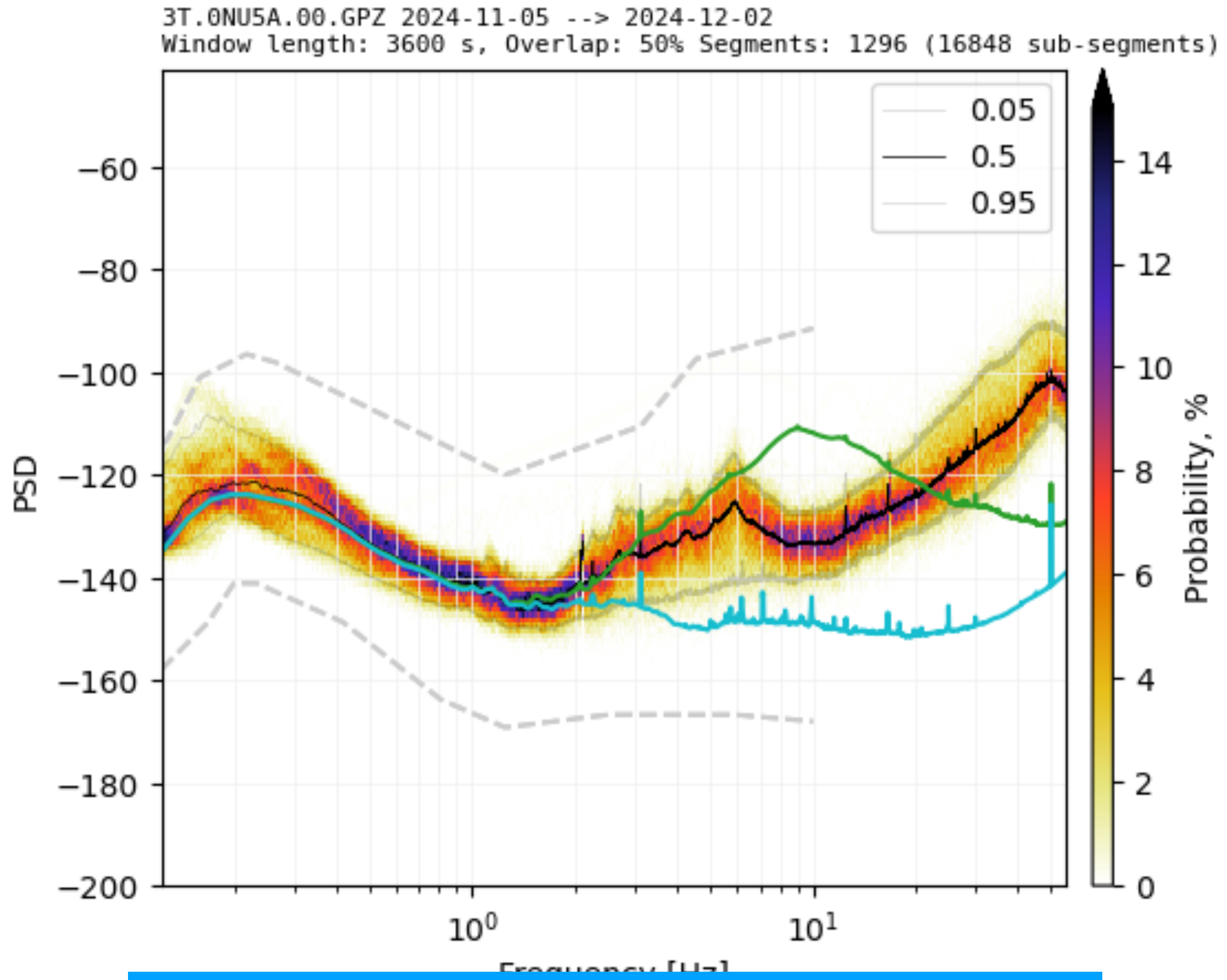
- We observe hardly any attenuation at 450m and 850m away from viaduct
  - Expect a 1/r attenuation for a line source, like body wave amplitude
  - Peak at 4.8 Hz is not changing over distance from the viaduct
- Viaduct anchored to bedrock: poor attenuation - stay away from this viaduct -



Bridge pillar (= Body wave source)

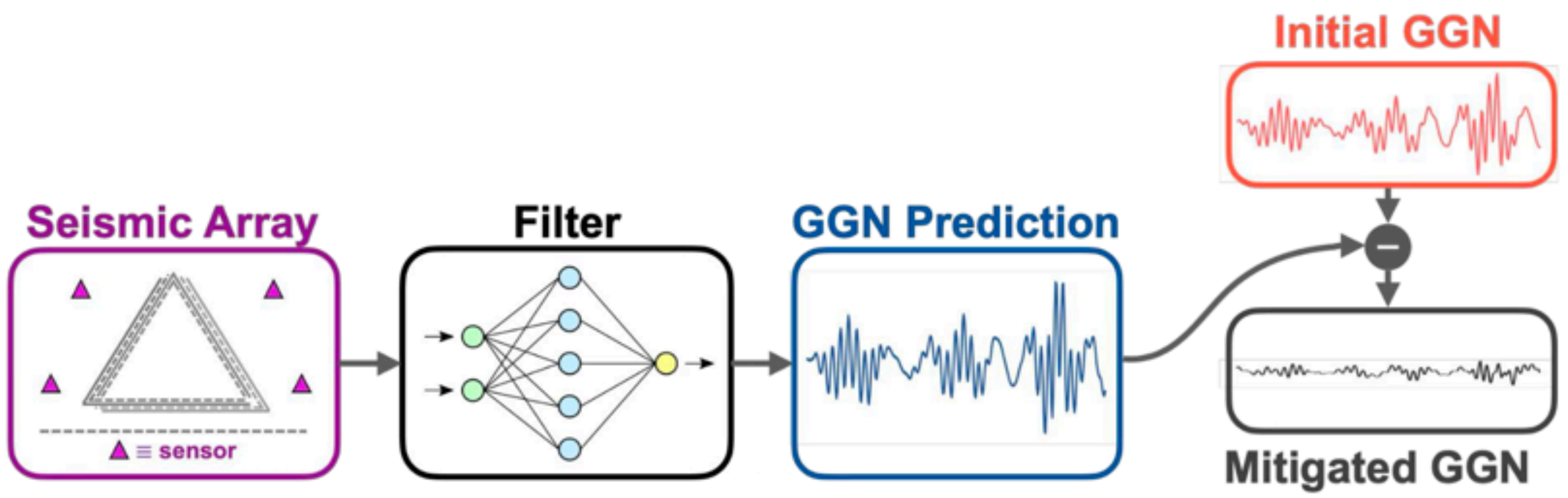


450m away from bridge



850m away from the bridge.

NP4: mitigation



FraNC

- Framework for Noise Cancellation evaluation
  - Markus Bachlechner, Johannes Erdmann, Tim Kuhlbusch
- Tool to evaluate different mitigation techniques on one defined dataset with common metrics

ParaArrayOPT

- See presentation "Towards a more realistic Seismometer Position Optimization for Newtonian Noise Mitigation"
  - Markus Bachlechner, Johannes Erdmann, Jan Kelleter, Patrick Schillings
- Conclusion
  - Effective optimization of seimometer array positioning to predict NN
  - Neural networks can outperform Wiener filters as prediction tools for NN

To conclude

Various activities ongoing:

- 1. Numerical tools have been validated - to a good extend
  - Various packages under close study
- 2. Numerical results for realistic layered geometry expected soon
  - NN predictions based on only homogeneous geology are not valid
  - We are eagerly waiting for sub-surface sensor data
    - Develop noise model that matches surface and sub-surface
- 3. Hard rock top layers are less robust for (future) surface infrastructure
  - EMR site stays away from surface bed-rock
- 4. We are successfully preparing various NN mitigation strategies

With good and reliable tools in hand,
the importance of NN is mitigated for operation of ET

Einstein
Telescope