

Seismic-driven Newtonian noise : an overview of activities for the EMR site



This research is partly funded by the Walloon region under the project ETGEO (convention number 2410081).

In a nutshell, **we work on** :

Seismic wavefield modeling inputs

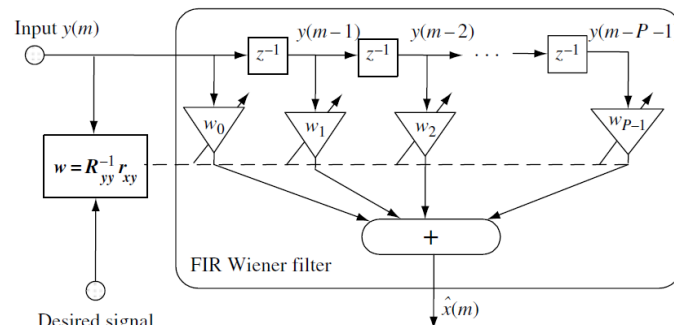
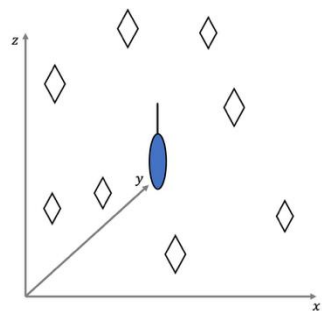
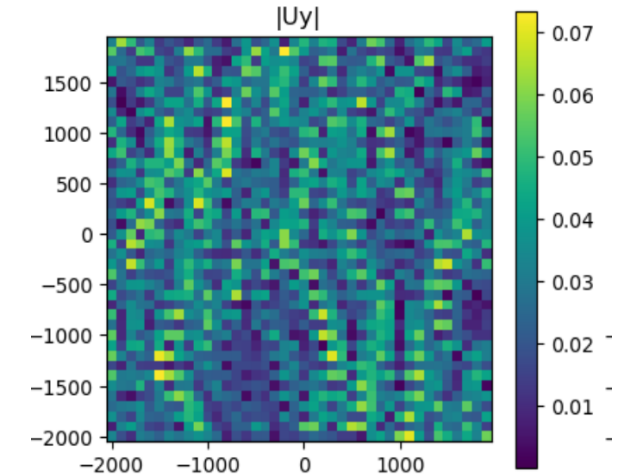
- Spatially distributed parameters like compressional, shear wave velocity, density and quality factor and caverns/tunnels geometries.
- Source mechanism and distribution.
- An efficient seismic wave equation solver
- A model able to reproduce **observed data** and determine the correlation

Newtonian noise modeling inputs

- Topography, infrastructures limits and subsurface displacement.
- Discretizing the simulation domain and integrating efficiently.

$$\delta \mathbf{a}(\mathbf{r}_0, t) = G \int \delta \rho \frac{\mathbf{r} - \mathbf{r}_0}{|\mathbf{r} - \mathbf{r}_0|^3} dV$$

Displacement amplitude at $f = 5.00$ Hz



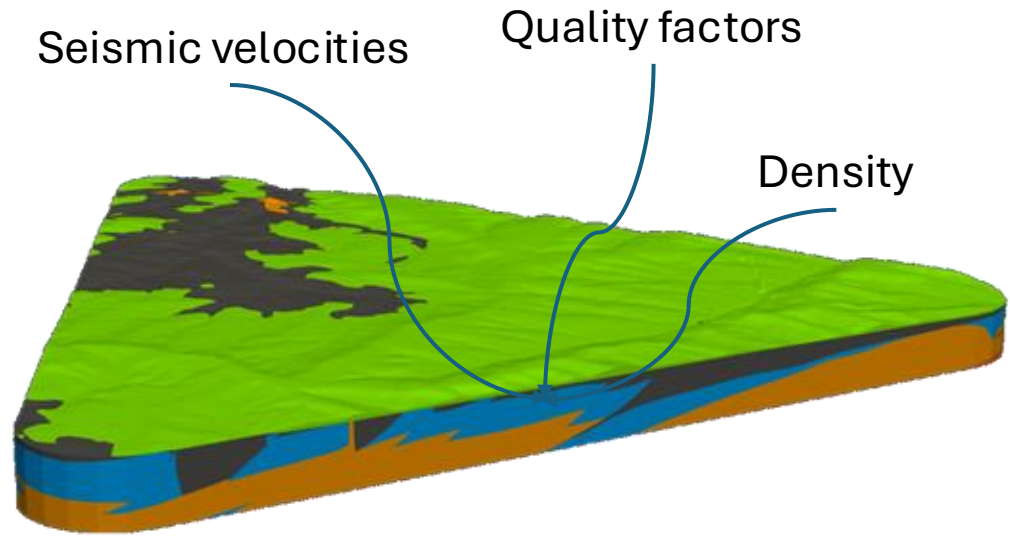
Badaracco and Harms, 2021

Newtonian noise subtraction

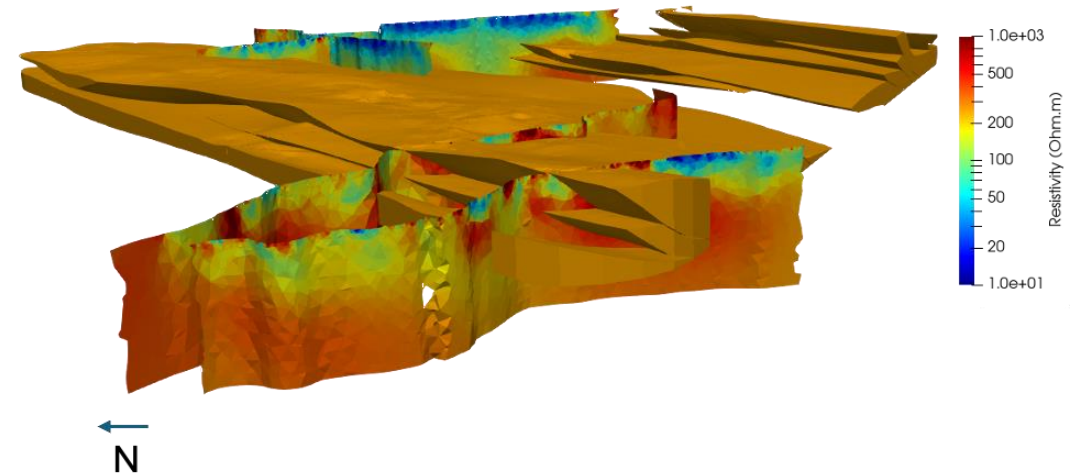
- Simulation environment to compute NN
- Dense array of sensors correlated to NN.
- Design and test subtraction schemes under realistic conditions.

What information is needed ? Models

- Spatially distributed models of bulk physical properties
- Source parameters and distribution



3D geomodel of rock type V1.0 (PO EMR)
See talk by Geert-Jan Vis and Hannes Claes.



Feeding the models

Shallow layer

Ambient seismic noise
ERT

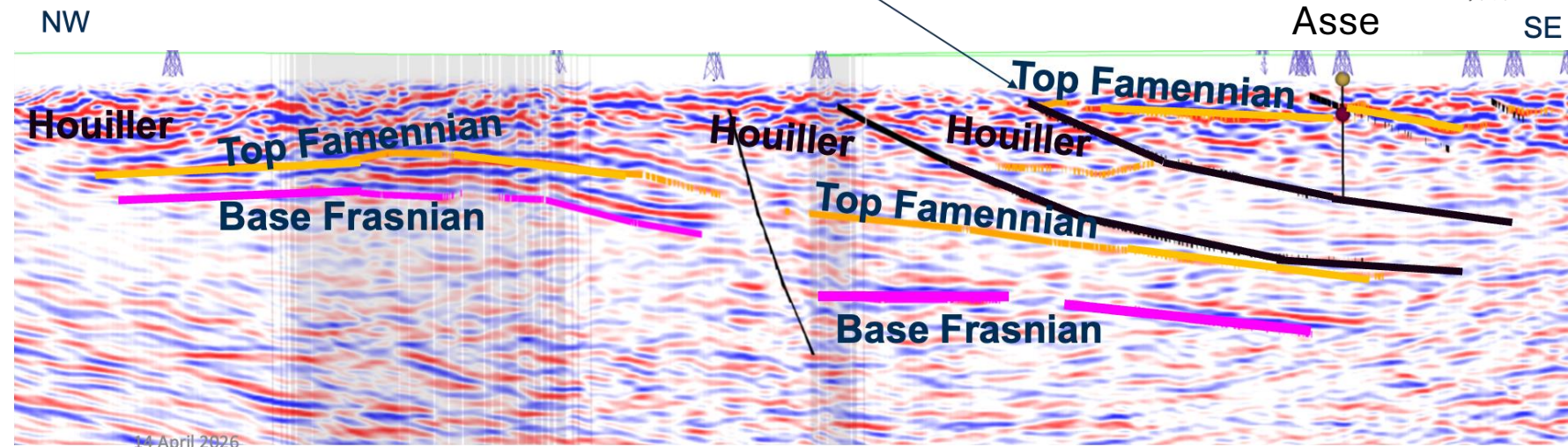
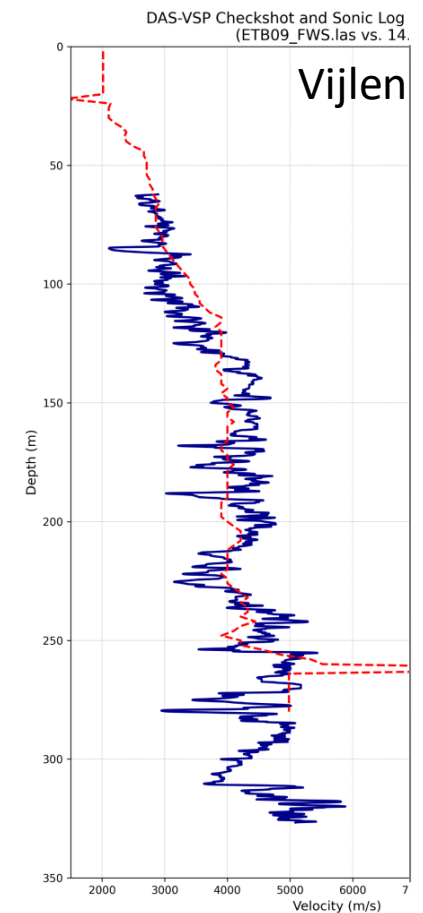
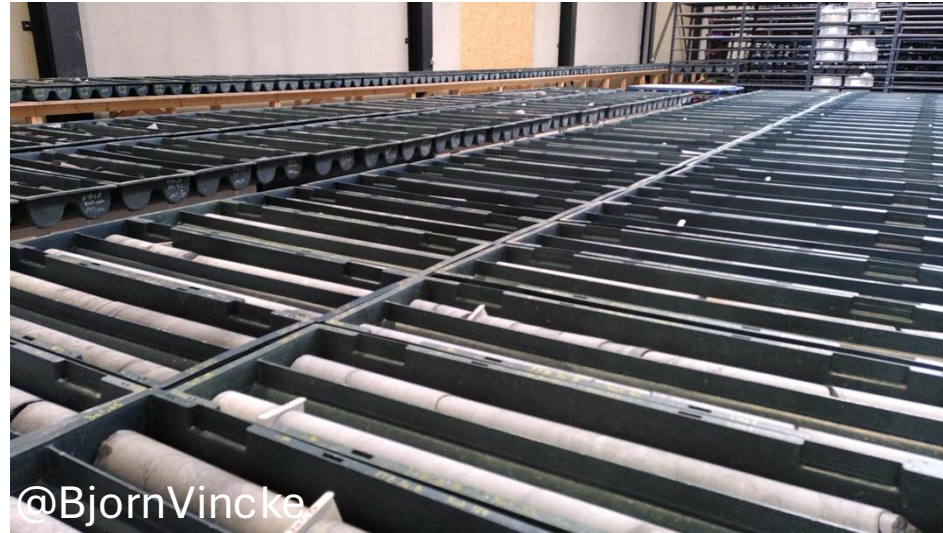
Structural model based on

Outcrops
Borehole data (24 wells with 5km of cores) incl.
BHTV & Gamma rays + 1123 legacy
Seismic (112km) to tie the wells
Gravity map and 24 km deep ERT data (faults)

Voxels properties estimated from

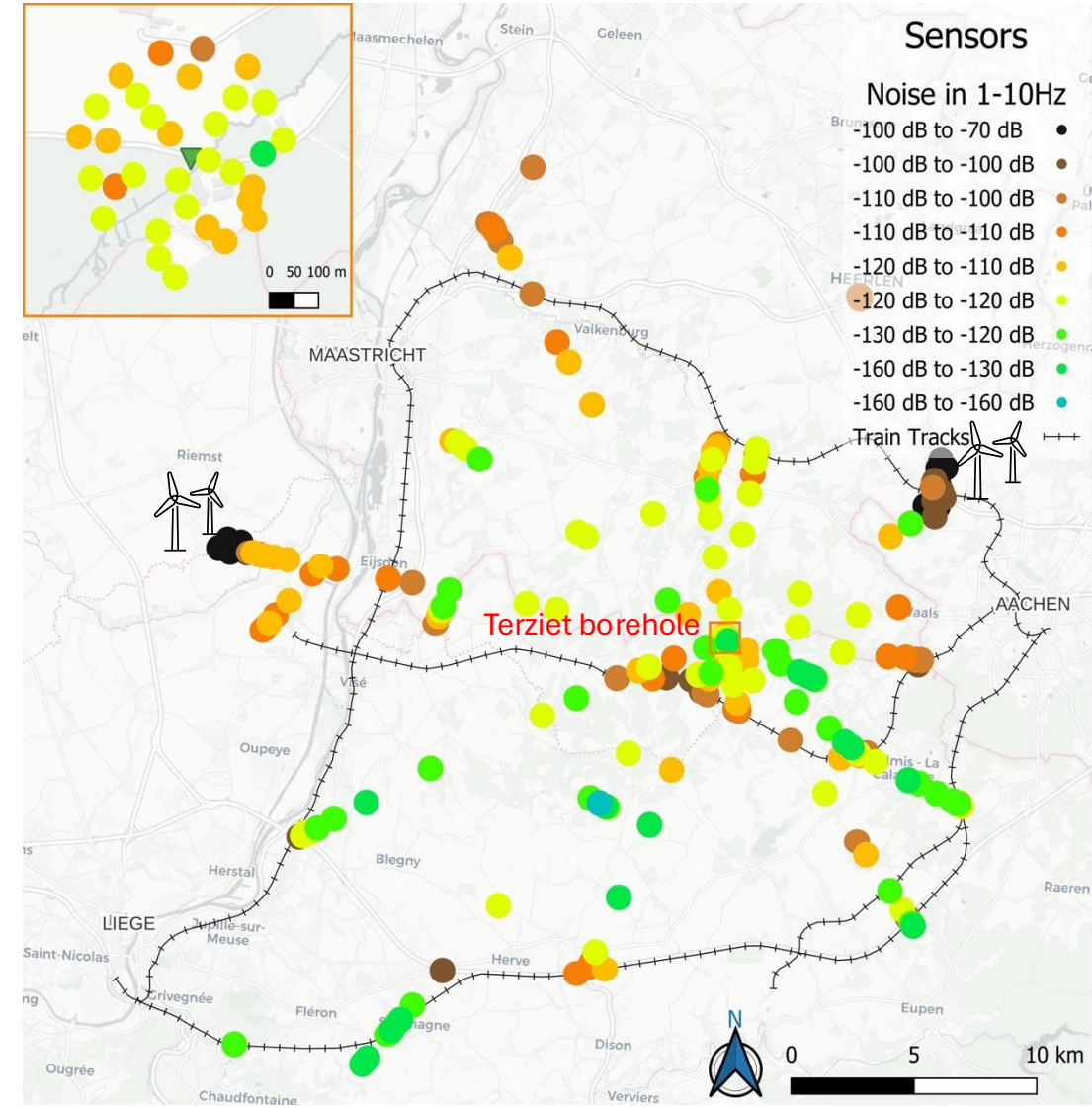
Geophysical logs (e.g. sonic logs)
5 DAS – VSP's (Q-values), pending 3
Core scale data
Fractures analysis
Geomechanical data
RQD
Empirical relationship
Tomographic information

See also G-J. Vis & H. Claes as well as M. Kiehn
& H. Michel talks



Providing data

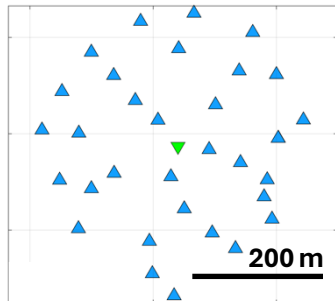
- Seismic ambient noise at
 - Surface: several hundreds sensors deployment (below array 4: 230 3C 5Hz, 1 month) XVI ET Symposium 2026 #146



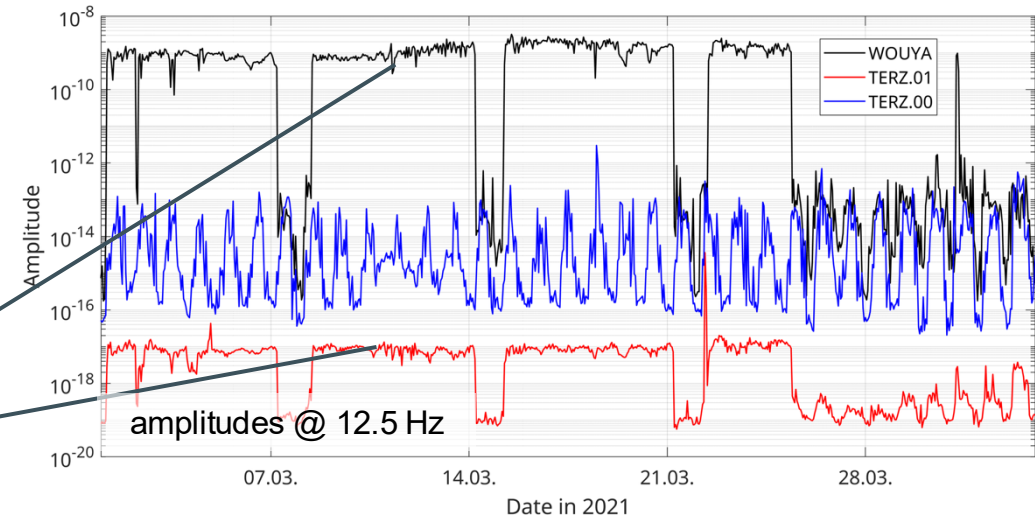
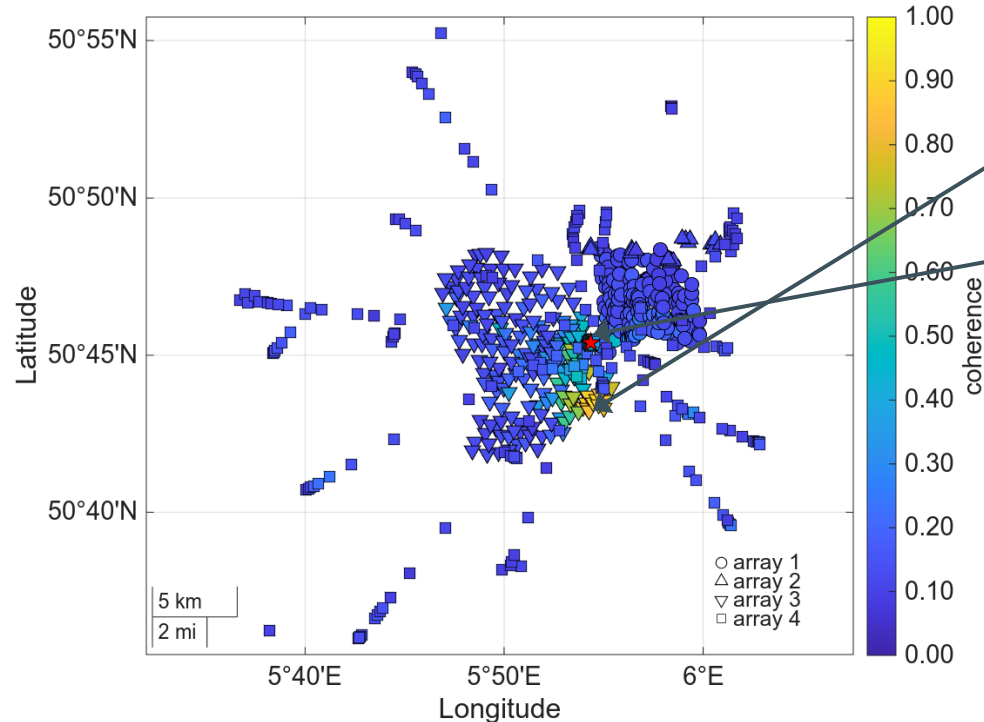
We use data from all passive seismic surface surveys to investigate sources, composition and coherence

- coherence between downhole/surface stations
- the distribution of noise source directions
- the composition of the seismic noise field
- possible noise sources from waveform coherence analysis

3C-TERZ subarray



Coherence between borehole station TERZ.01 and surface stations (10-20Hz range)



Courtesy of D. Becker (UniHamburg) and team,
Poster @EGU2026

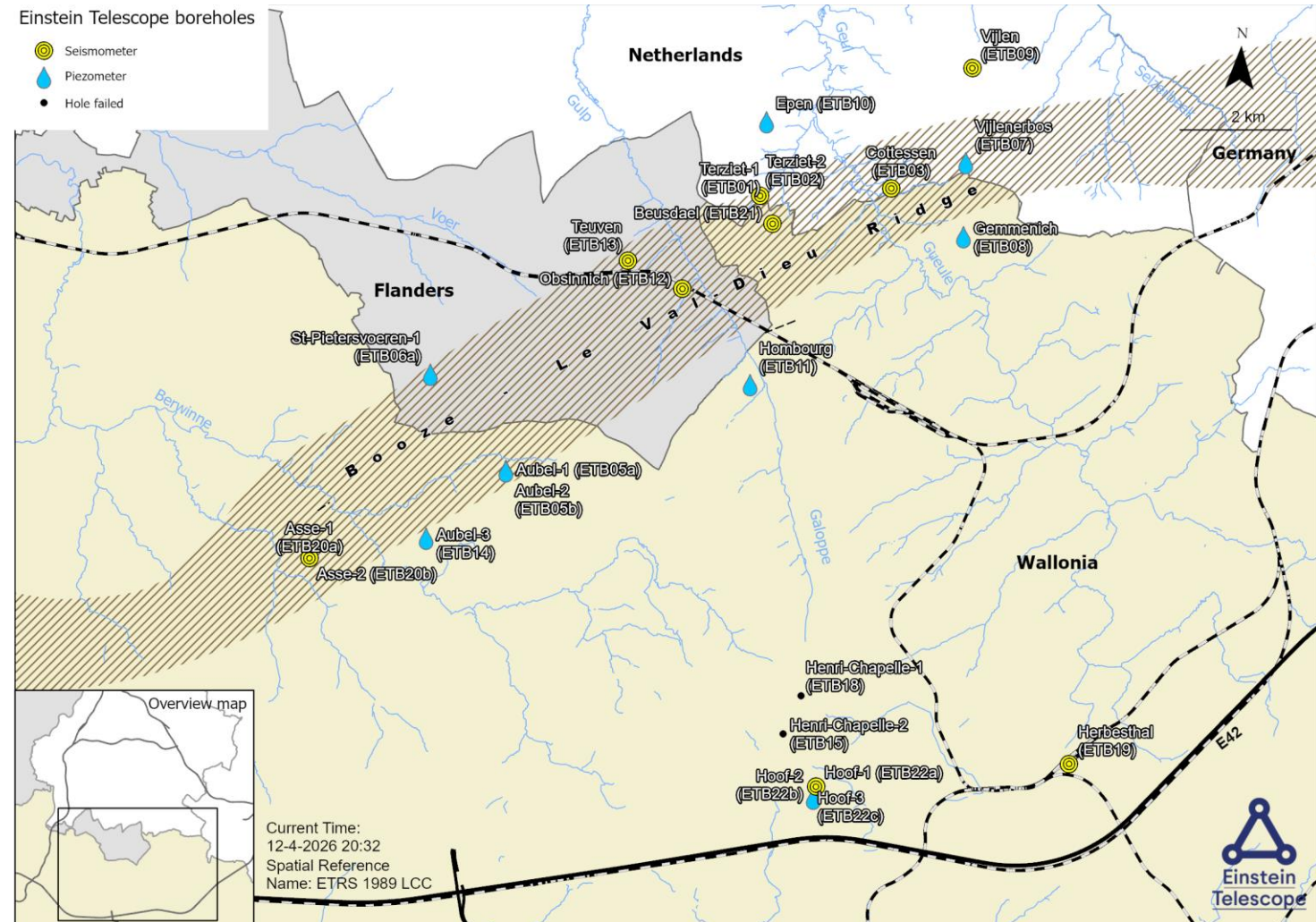
Surface to depth data

- Seismic ambient noise at Depth:

- Terziet (250 m)
- Banholt (196 m)
- Cottessen (250 m)
- Teuven (260 m)
- Obsinnich (280 m)
- Herbesthal (350 m)
- Vijlen (ongoing) (330 m)
- Beusdael (ongoing) (350 m)
- Hoof (pending) (450 m ?)
- Asse (pending) (370 m ?)

Close to Sources

See talk by M. Kiehn & H. Michel and S. Kadmiel & W. Walk as well as S. Koley



Newtonian noise modelling

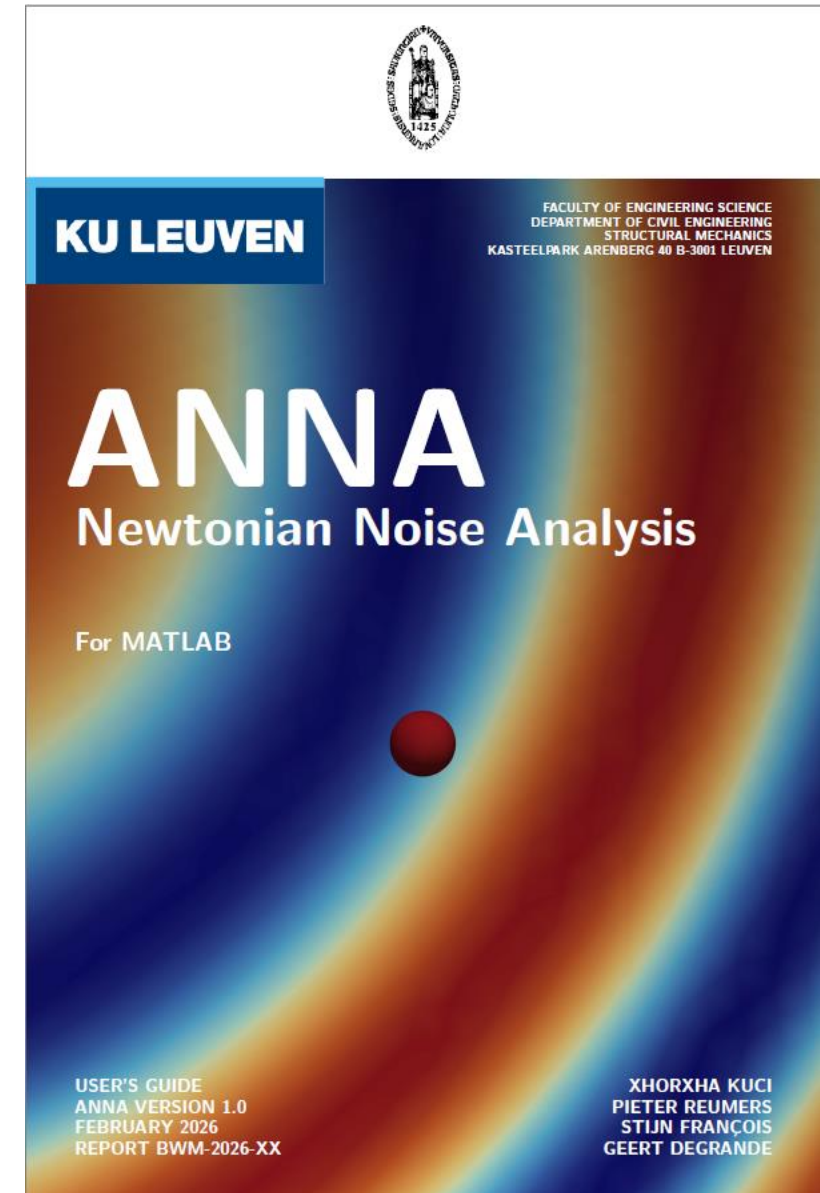
- **ANNA** Newtonian Noise Analysis to compute NN from a seismic wavefield
- Finite element formulation based on functionalities of the Stabil toolbox, using Gaussian quadrature, in heterogeneous media.
- 3D FE meshes composed of linear and quadratic tetrahedral (4-node and 10-node) and brick (8-node and 20-node) elements are supported.

See talk by Giorgia Kuci & Valentin Tempel

P. Reumers, X. Kuci, S. François, and G. Degrande. ANNA: a toolbox for Newtonian Noise Analysis. <https://arxiv.org/abs/2603.15157>

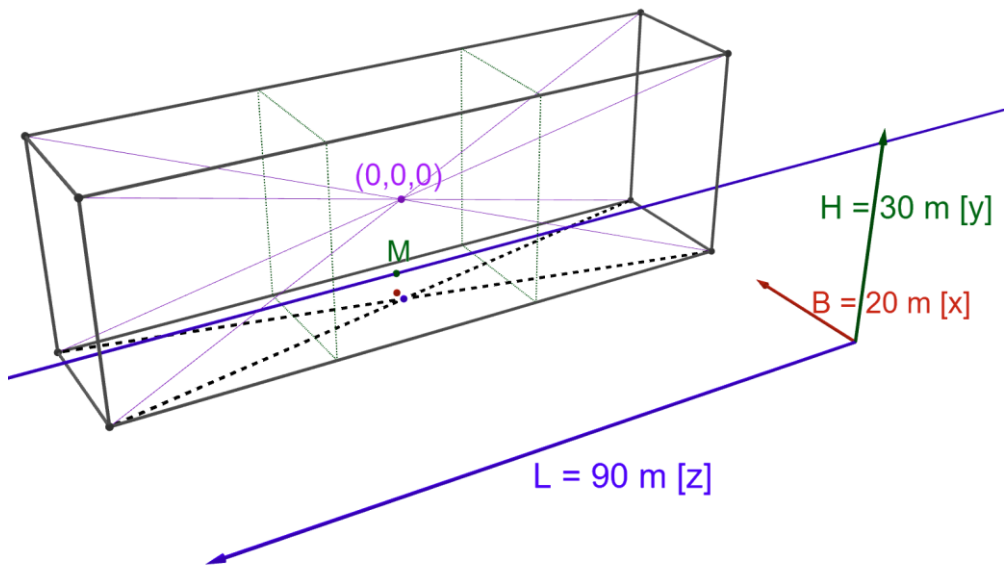
P. Reumers, S. François, and G. Degrande. Validation of a numerical model of seismic Newtonian Noise for the Einstein Telescope. In 9th European Congress on Computational Methods in Applied Sciences and Engineering, ECCOMAS 2024, pages 1-11, Lisbon, Portugal, June 2024.

S. François, M. Schevenels, D. Dooms, M. Jansen, J. Wambacq, G. Lombaert, G. Degrande, and G. De Roeck. Stabil: an educational Matlab toolbox for static and dynamic structural analysis. Computer Applications in Engineering Education, 29(5):1-18, 2021.



Courtesy of G. Degrande (KUL) and team

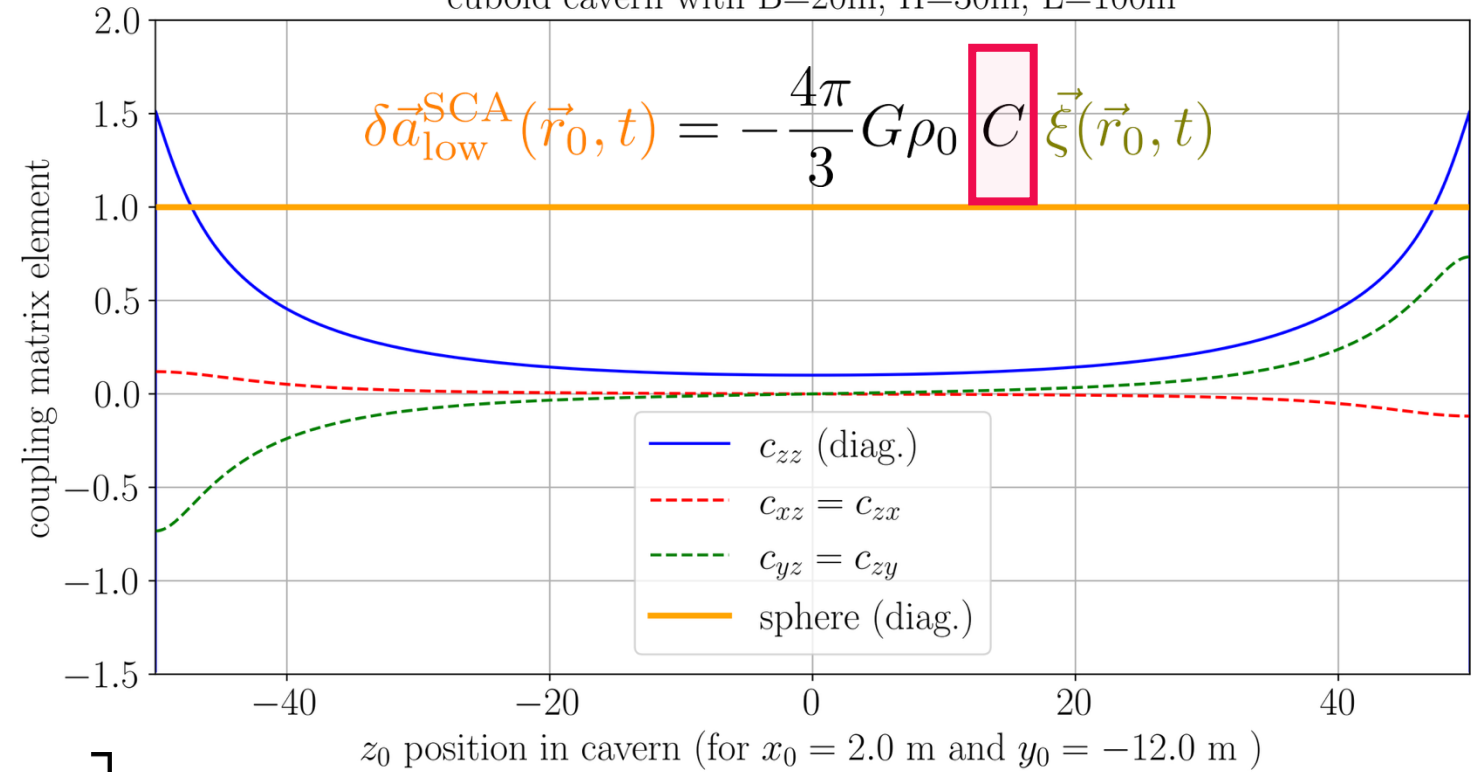
NN analytical solutions for cuboid cavern to validate numerical approaches



B: breadth
H: height
L: length

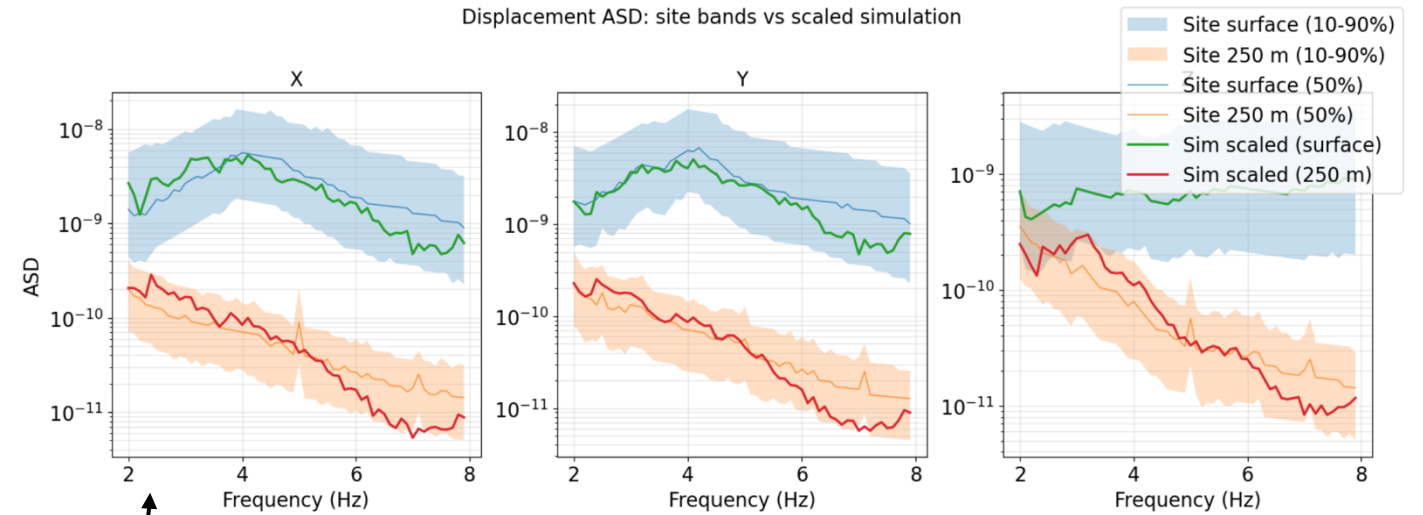
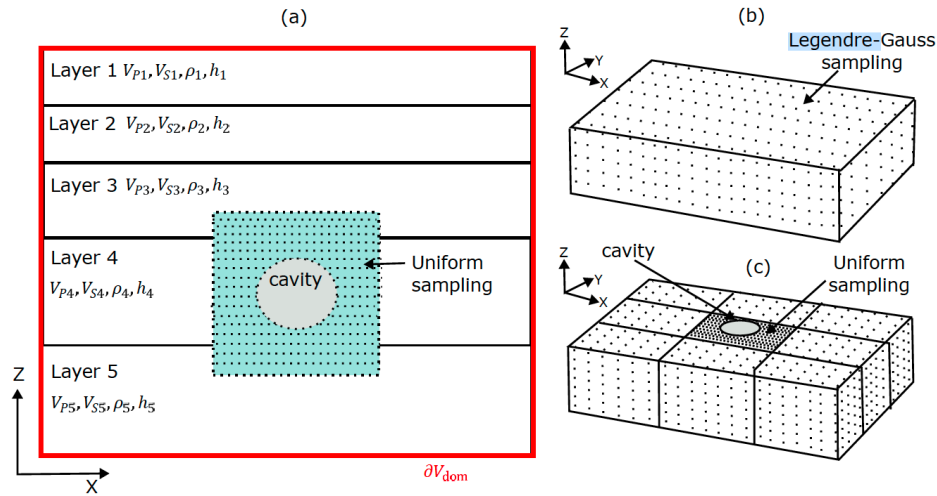
$$\underline{\underline{C}}^{\text{SCA}} = \begin{bmatrix} c_{xx} & c_{xy} & c_{xz} \\ c_{xy} & c_{yy} & c_{yz} \\ c_{xz} & c_{yz} & c_{zz} \end{bmatrix}$$

cuboid cavern with $B=20\text{m}$, $H=30\text{m}$, $L=100\text{m}$

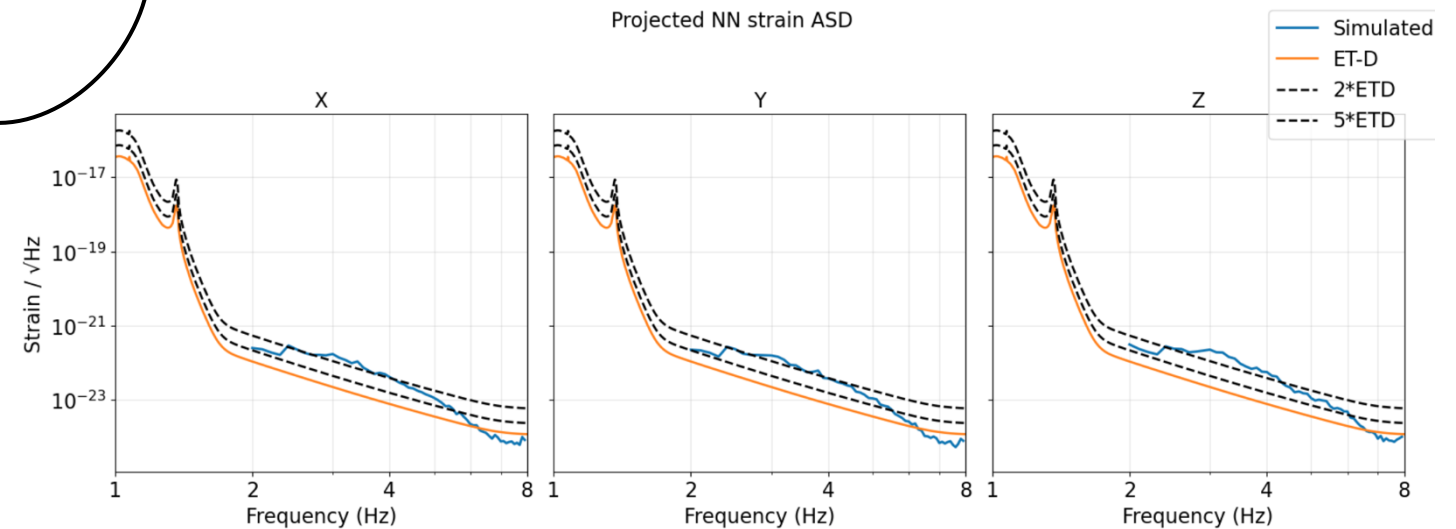


acceleration along laser beam
 \rightarrow three matrix elements relevant!

Open source pySeisNN-1D : 1D layered Earth

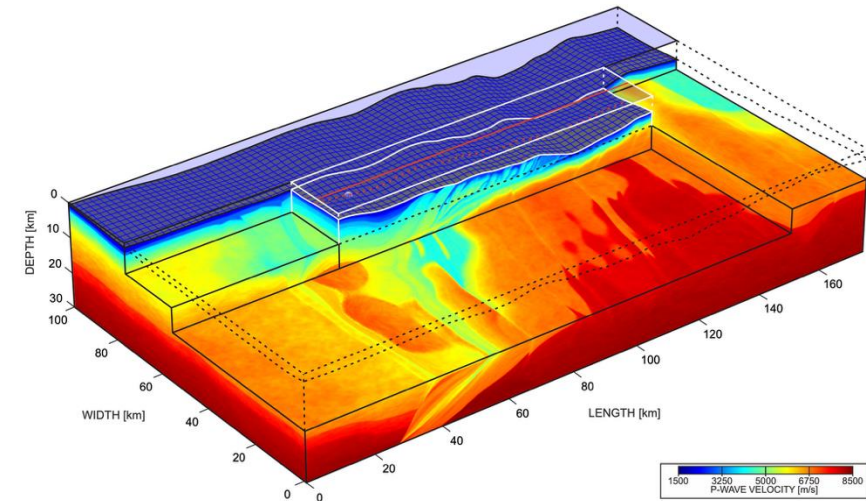
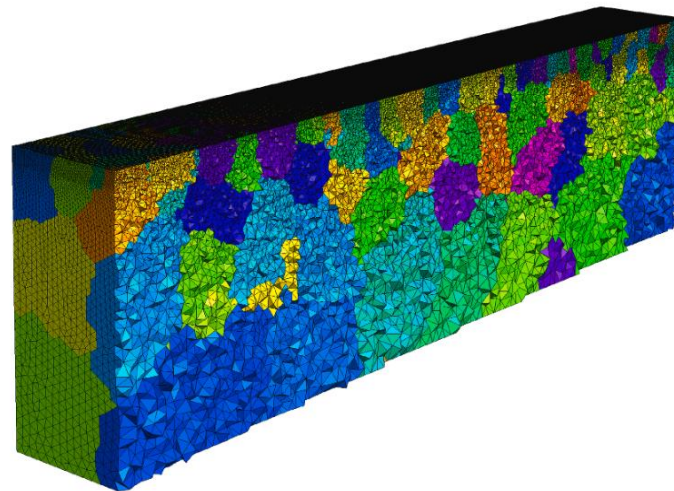
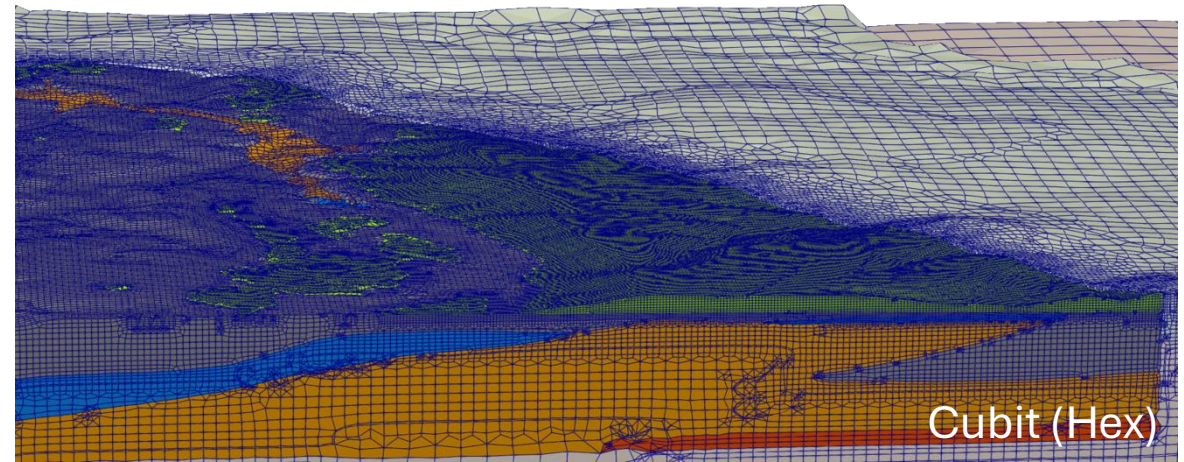


- Makes use of precomputed Green's function (Wang, 1999) database for a 1D media
- Modeling constraints, for given sources distribution and parametrization :
 - match ambient noise spectra at surface and underground
 - match observed surface wave dispersion
 - match correlation (?)



Newtonian noise modelling : 3D modelling

- Including a regional scale geological model into a seismic simulation
 - Topography
 - Include fault zones and folds
 - Caverns and tunnels
 - More **realistic** than a layered geology
 - Spectral finite element
 - « **Ready to use** »: CUBIT + Salvus/SPECFEM3D (**Hex**)
 - **Open Source development:** Gmsh + GmshFEM+ GmshDDM (C. Geuzaine group)
- Tet** with first run on HPC LUMI) will include NN as post-processing.
XVI ET Symposium 2026 id #163



Courtesy of ULiège team (S. Koley, H. Michel, C. Geuzaine, B. Martin)

Martin B. et al., 2026. J. Comp. Physics.

Newtonian noise mitigation

- Baseline is **Wiener filters** f_m (e.g. Coughlin et al., 2014) with the output of a number of reference traces x_m correlated with the NN to predict the noise of a target channel $y(k)$ and then subtracted from the target channel, leaving the non-correlated **residual**. We compare the performance of neural networks to WF.

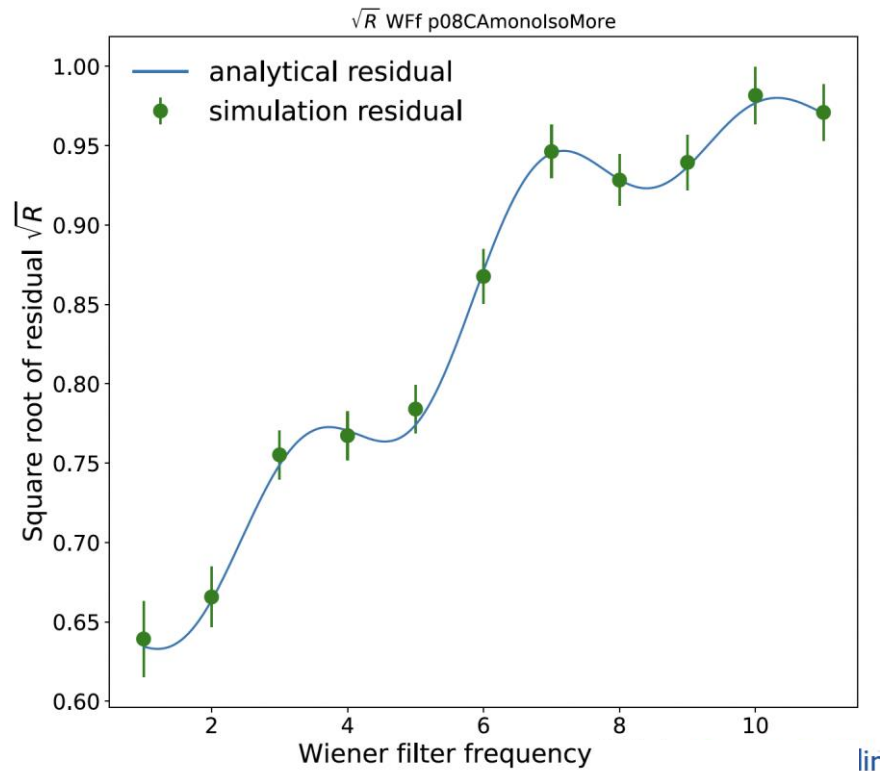
$$r(k) = y(k) - \sum_{m=1}^M (f_m * x_m)(k)$$

GW strain signal contaminated by Newtonian noise

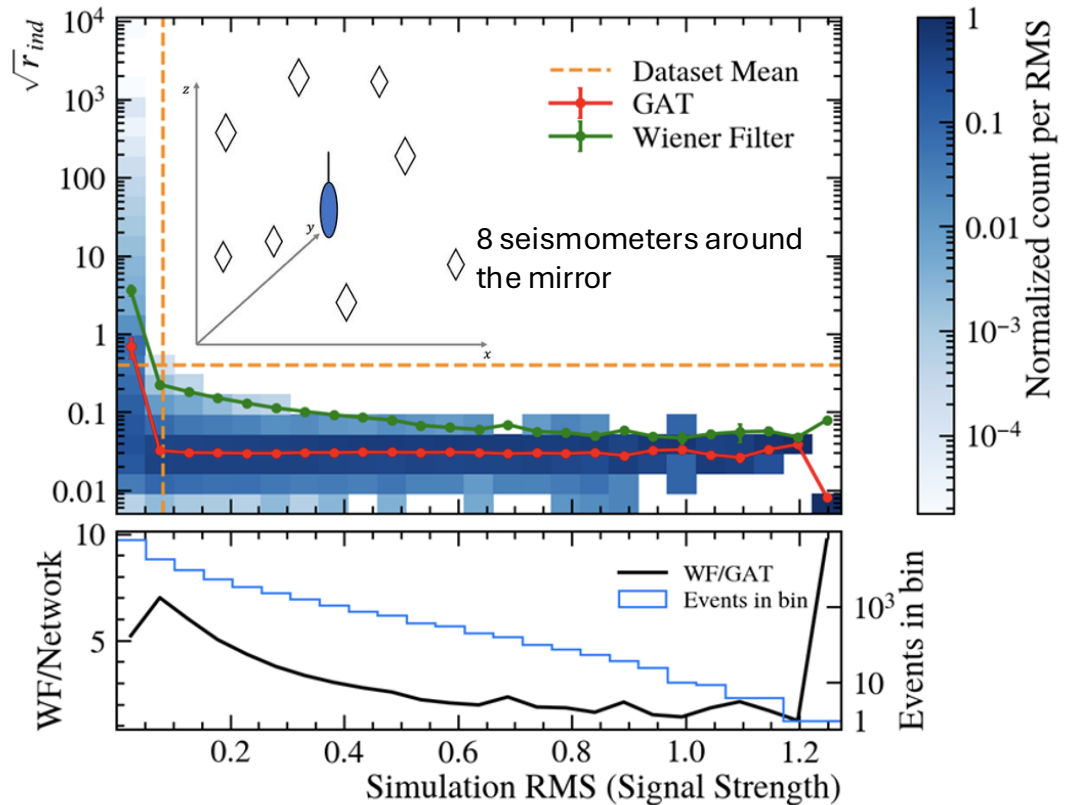
reference data from seismometers or other sensors (correlated to NN)

Testing Graph Neural Network with attention

- Validate Wiener cancellation with numerical solutions (left) and compare to **graph neural networks** (NN down by a factor 20, right)

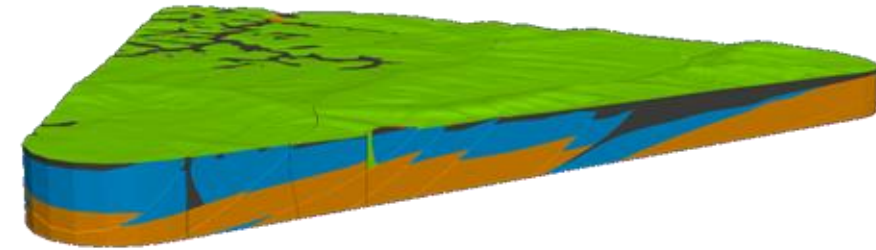


Courtesy of J. Erdmann (RWTH) and team

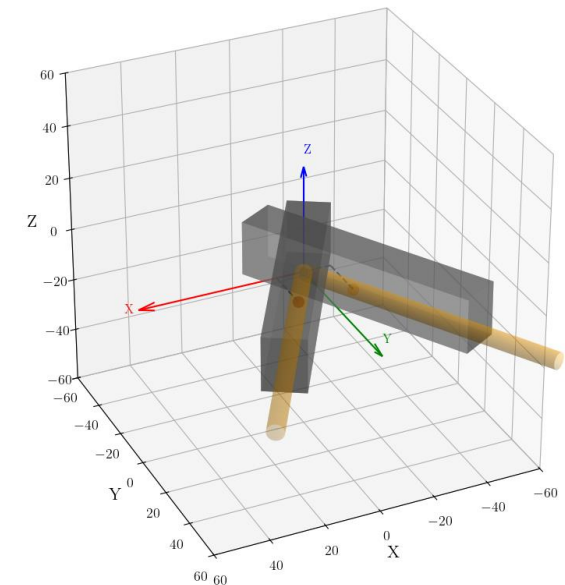


Next steps (lots of)

- **Seismic wavefield modeling**
 - Meshing for geomodel w/o caverns
 - Seismic wavefield understanding and noise sources characterization
- **Newtonian noise modelling**
 - Handling arbitrary density distribution and wavefields
 - Model based uncertainty quantification (XVI ET Symposium 2026 id #???)
 - Application of ANNA+3D model to EMR data
 - NN modeling w. calibrated wavefield (multiple data locations) (HPC)
 - NN modeling with caverns
- **Newtonian noise mitigation**
 - Train network based on realistic simulation (seismic wavefield and NN) and check if mitigation holds in realistic conditions
 - Optimize seismometer/sensors positioning
- **Before summer** : array 5 data acquisition (700 sensors, 1 month)
- Let's not forget other NN noise (HVAC) or self-inflicted



3D geomodel of rock type V1.0 (PO EMR)



Courtesy of V. Tempel (RWTH)

Thanks to in particular

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for providing **slides**

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