Newtonian noise estimate at Terziet- *the Euregio Meuse-Rhine (EMR) candidate site for Einstein Telescope*

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References for detailed understanding

A detailed description of the methodologies can be found in the below mentioned articles:

Classical and Quantum Gravity

PAPER

Surface and underground seismic characterization at Terziet in Limburg—the Euregio Meuse–Rhine candidate site for Einstein Telescope

Soumen Koley[8,1,2], Maria Bader[2], Jo van den Brand[2,3], Xander Campman[4], Henk Jan Bulten[2,5], Frank Linde[2,6] and Bjorn Vink[7]

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Classical and Quantum Gravity

PAPER

Newtonian-noise characterization at Terziet in Limburg—the Euregio Meuse–Rhine candidate site for Einstein Telescope

Maria Bader[1,5], Soumen Koley[8,1,2], Jo van den Brand[1,3,5], Xander Campman[4], Henk Jan Bulten[1,5], Frank Linde[1,6] and Bjorn Vink[7]

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DOI 10.1088/1361-6382/ac1be4

Bader et al, 2022, CQG, 39 025009

Other relevant work:

- Phd Thesis S. Koley, VU Amsterdam
- Phd Thesis M. Bader, VU Amsterdam

Steps for NN estimation

A data-driven approach to NN-estimation

Surface seismic array:

- Direction of propagation (**dynamic**)
- Phase velocity (**static**)
- Rayleigh-wave modes (**dynamic**

- 1 D S-wave subsurface model (**static**)
- Borehole studies

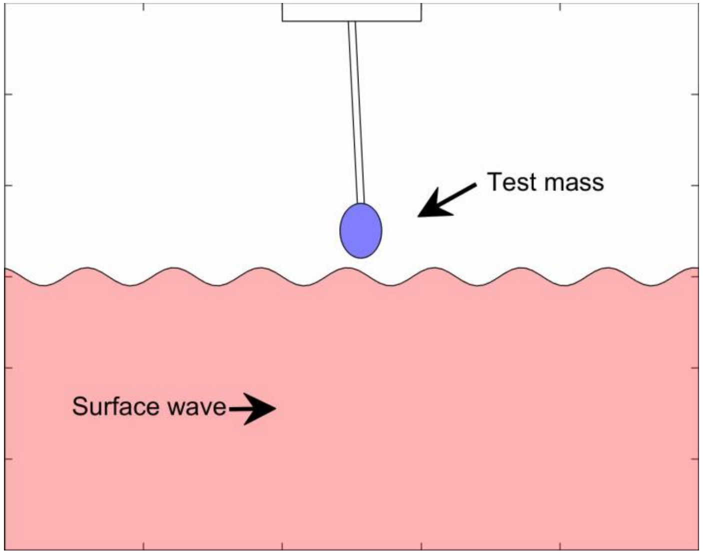
Underground seismic noise

- H-V ratio, Rayleigh ellipticity
- Attenuation
- Body-wave background (**dynamic**)

- Surface sources (**dynamic**)
- Background body waves (**dynamic**)

Elastodynamic solver

- NN Estimate



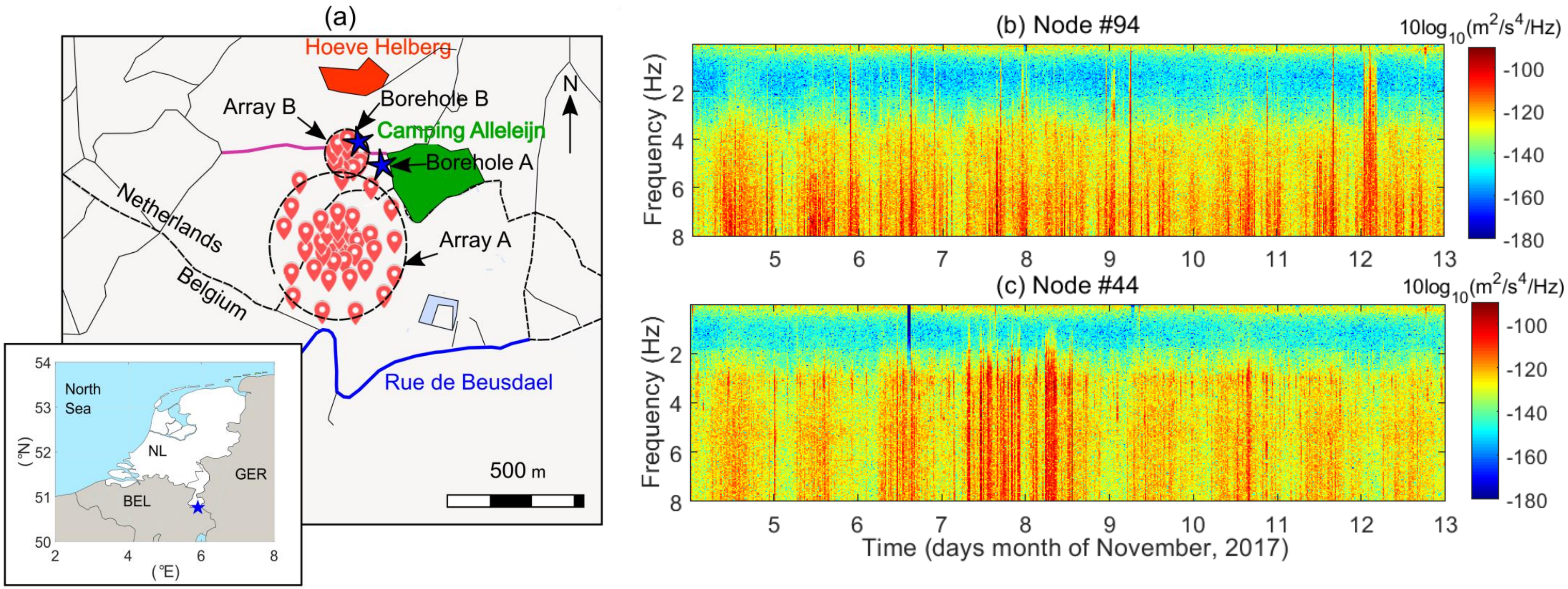
A toy model illustration how propagating seismic surface waves induces oscillations in the suspended test mass due to gravitational coupling; Effects are exaggerated, f = 20 Hz, v = 25 m/s

Surface seismic array

Spatial sampling of seismic waves used to determine: wave types, velocity, direction of propagation

Array features

- Array A and B have maximum apertures of 512 m and 112 m and are sensitive to surface waves in the band **2.4 -14.0 Hz** and **3.4 – 14.0 Hz**, respectively
- Surface seismic noise in the anthropogenic band (> 2 Hz) **shows typical diurnal variation of an order of magnitude in power**

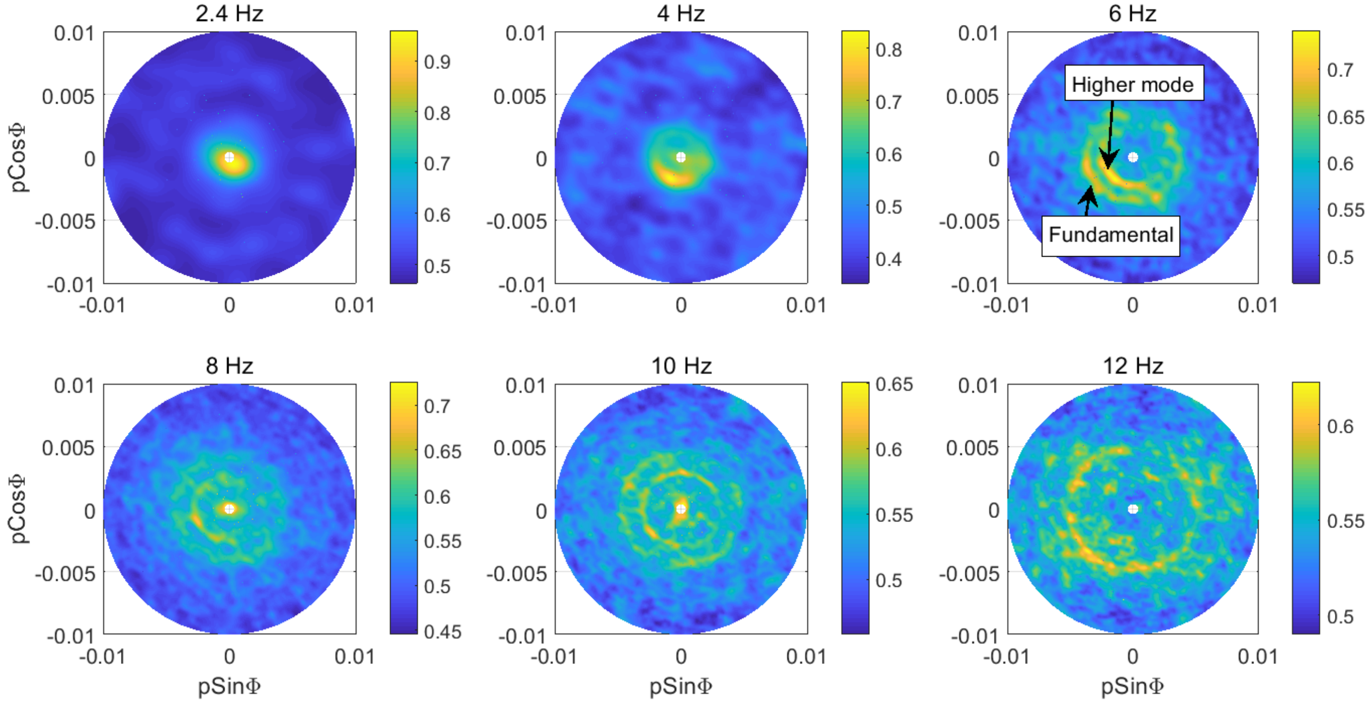


Surface wavefield decomposition

A data driven approach decomposes the surface wavefield into plane waves impinging the array from different direction

Spatial-filtering

- Generation of higher order modes can be attributed to: geology at the site, source mechanism
- Anisotropic illumination at low frequencies. Source distribution tend to be isotropic at high frequencies

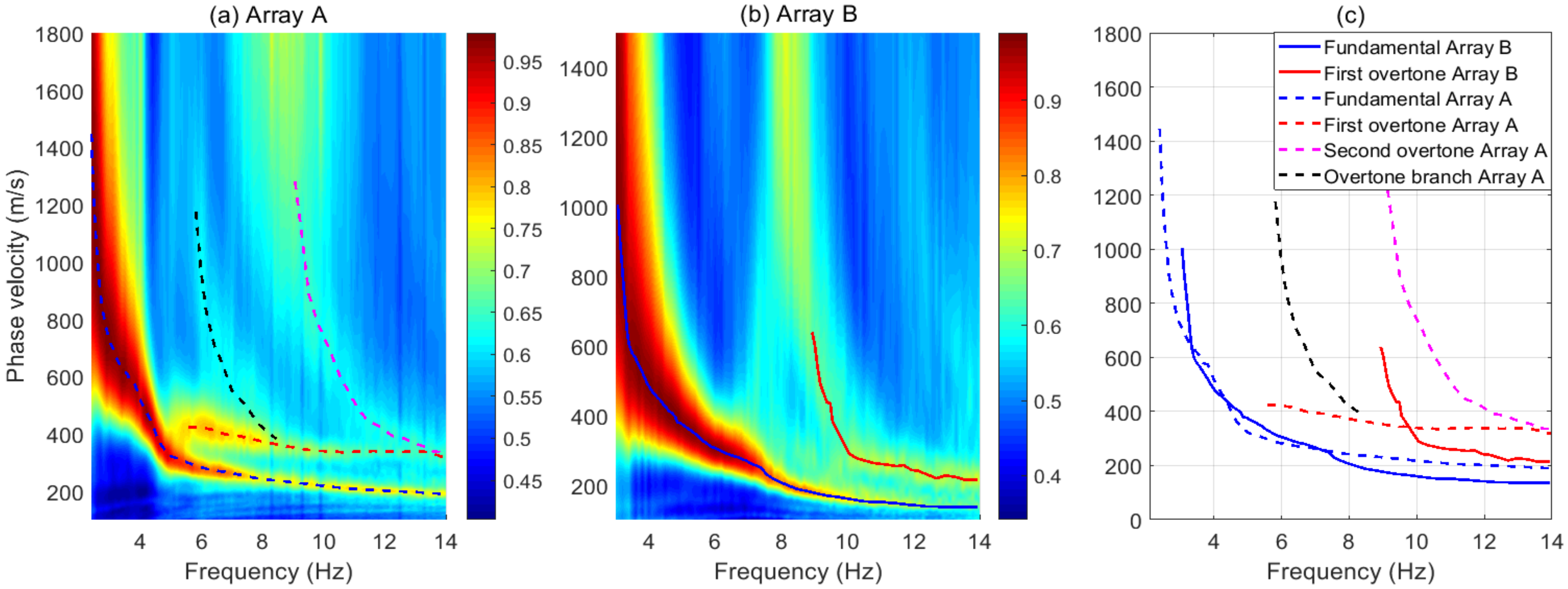


Rayleigh-wave dispersion

Beside the fundamental mode, both arrays show the existence of higher-order modes

Wavefield composition

- Higher-order modes are important for understanding composition of the surface and underground wavefields
- Higher-order modes are more sensitive to deeper subsurface layer velocities compared to the fundamental
- The dispersion curves obtained for Array A and B, point to lateral inhomogeneity in the shallow subsurface geology

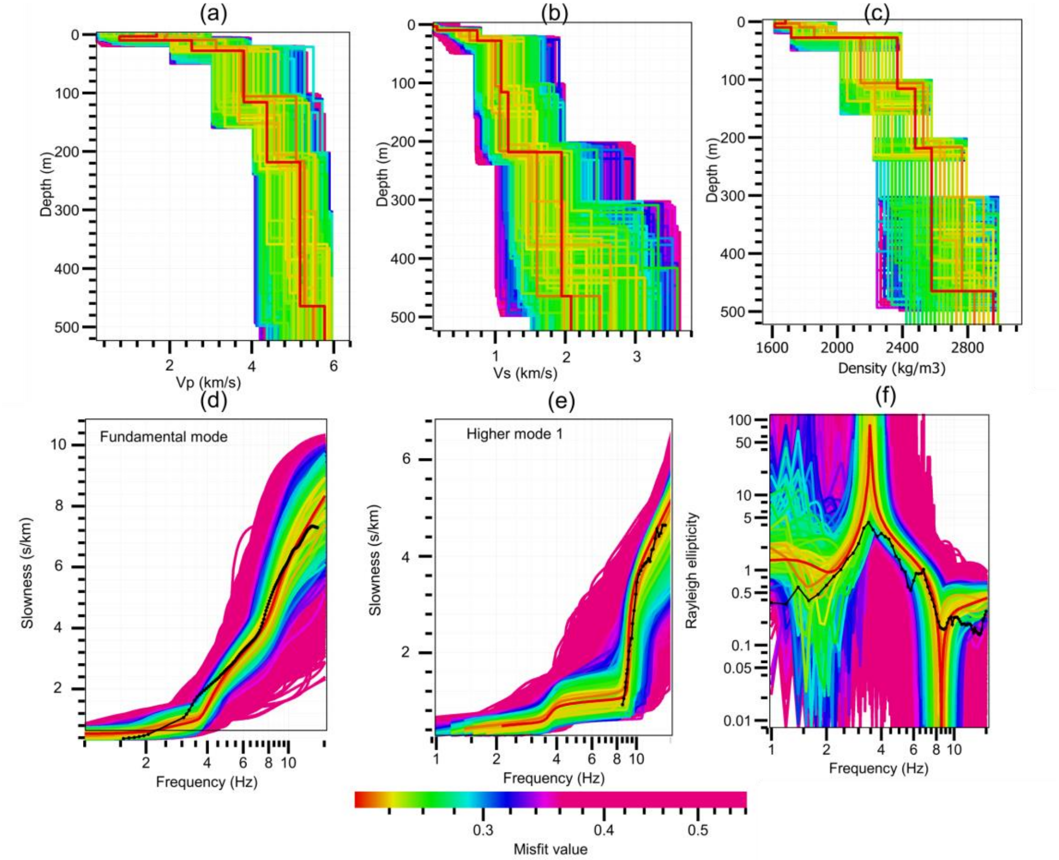


1D S-wave subsurface velocity model

A first transition from soft-soil to hard-rock is observed at depths between 35-40 m and P-wave velocities in excess of 4 km/s are observed

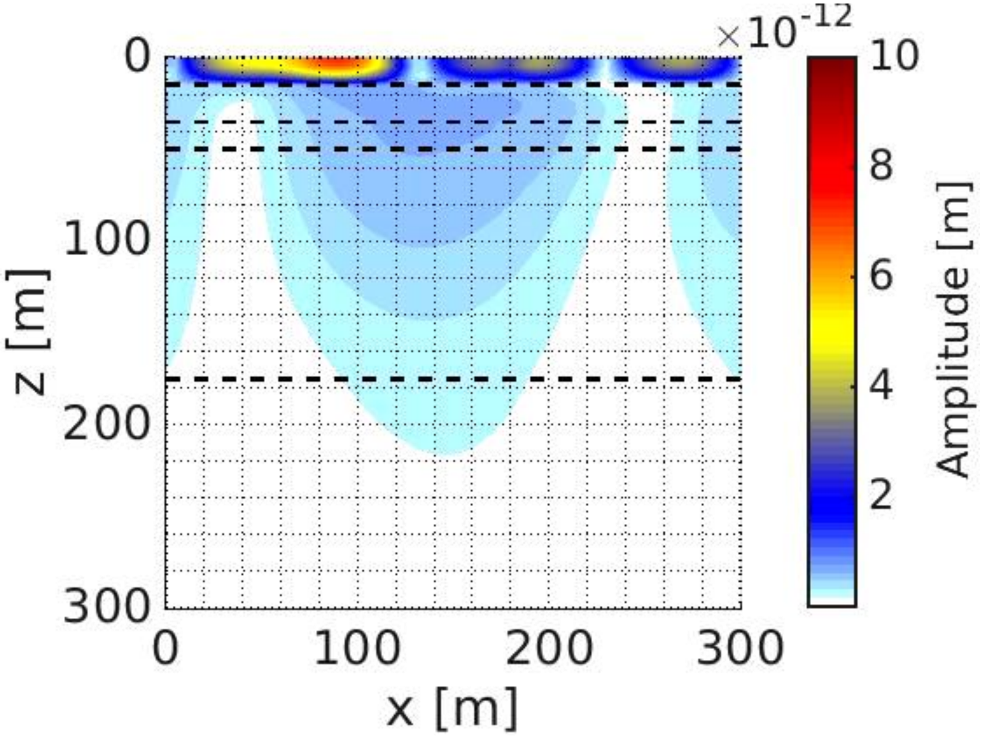
Subsurface modeling

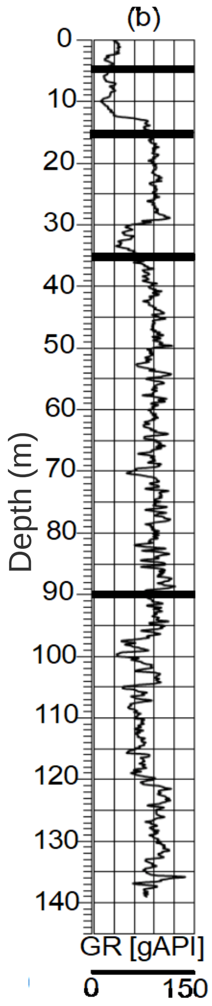
- Fundamental and first overtone phase velocities are used for subsurface model estimation
- Besides, the Rayleigh-wave ellipticity is also used to constrain the subsurface model estimation
  - This helps in estimating a deeper subsurface model since the ellipticity information is available down to 1 Hz



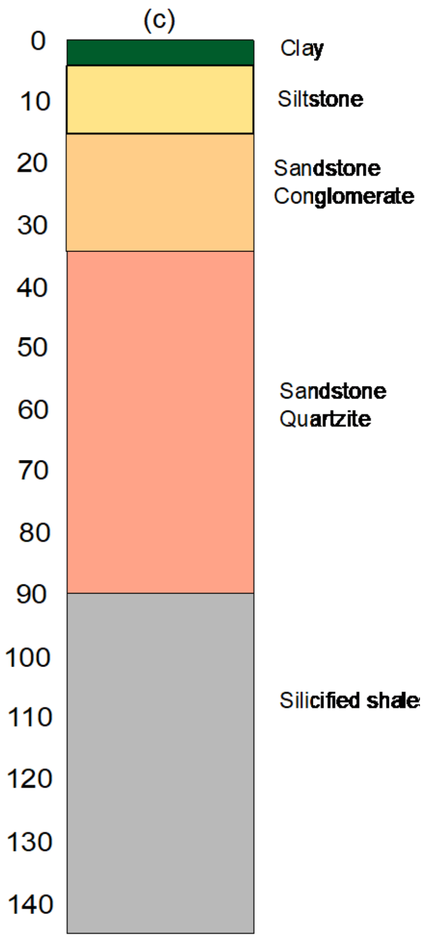
Studies of quality at potential Euregio Meusse-Rhine (EMR) site

The geology of the EMR Limburg border area: hard rock with on top a layer of soft absorbing and damping soil





Gamma ray



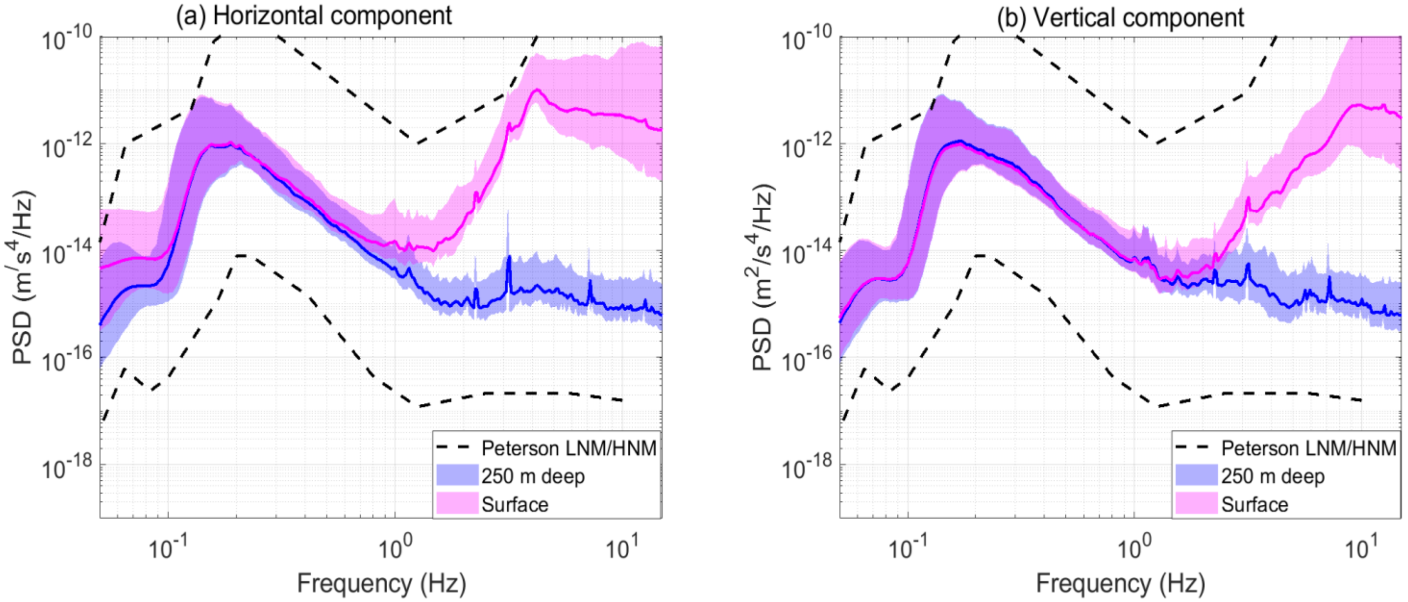
Lithology model

Underground seismic noise

Underground seismic noise reduces upto a factor 10^4 in power

Noise attributes

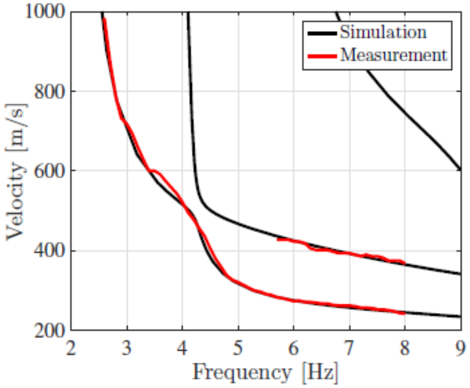
- We characterize the underground and the surface seismic environment for a period between Nov. 2019 to Oct. 2020
- STS-5A seismometer stationed at a depth of 250 m and a Trillium-240 seismometer on the surface
- Surface seismic noise peaks at 4 Hz and 9 Hz in the horizontal and vertical component, respectively
- The attenuation ($\mathrm{PSD}_{\mathrm{surface}}/\mathrm{PSD}_{\mathrm{underground}}$) at high frequencies can be attributed to body waves

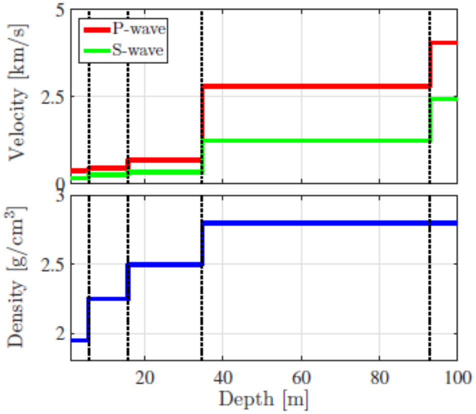


Towards modeling Newtonian noise from surface sources

Calculating Newtonian noise involves integrating the 3D wavefield over a volume surrounding all test-masses

Using an Elastodynamic solver to simulate the ground motion (EDT):

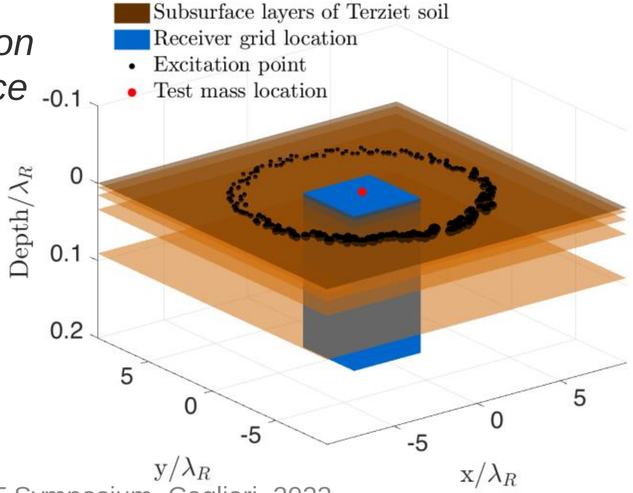


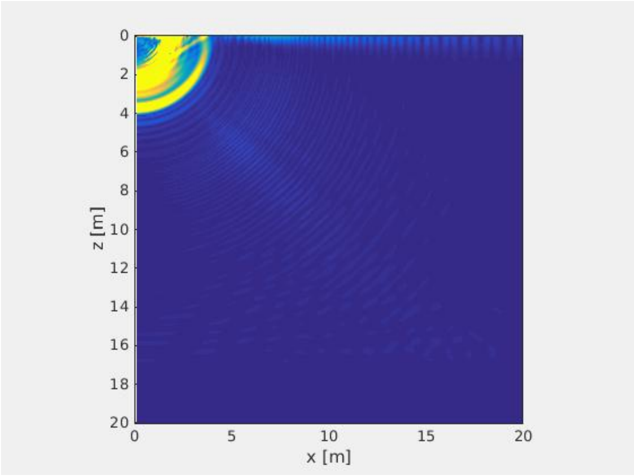


Input subsurface model

+

Vertical Source distribution on surface

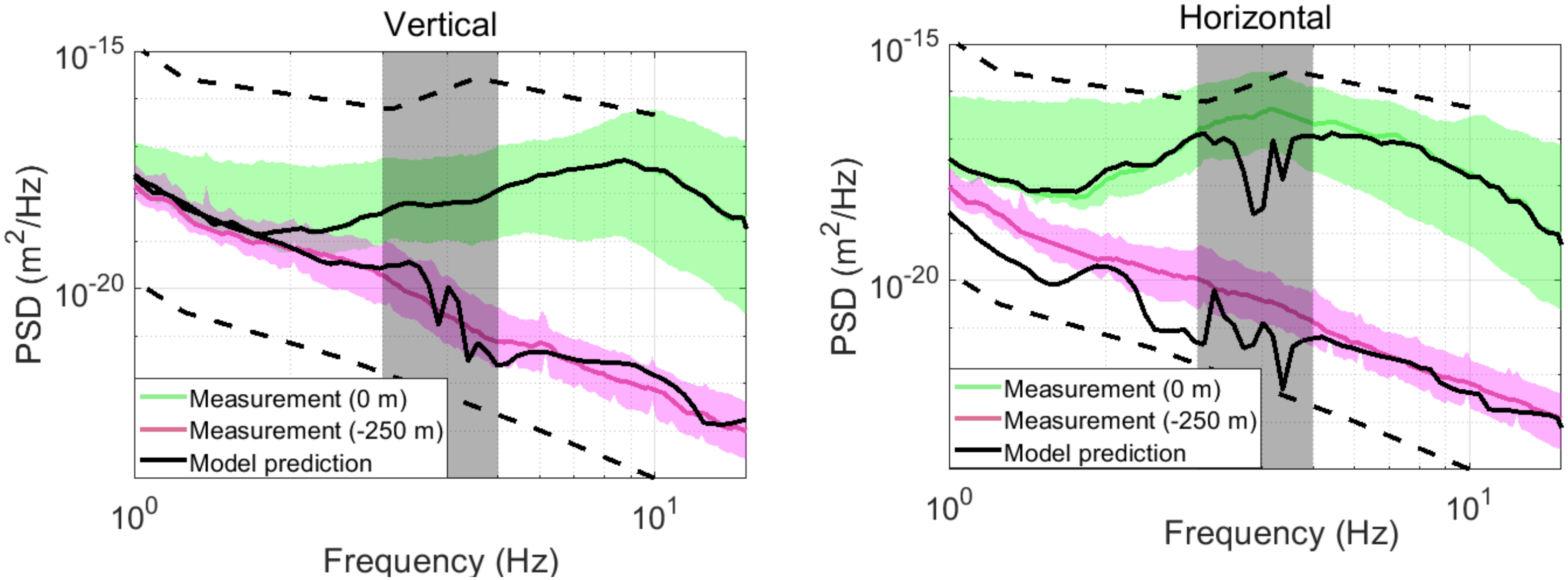




Output ground motion

Modeling Newtonian noise – simulated displacement

- While the relative strength of each source is set to reproduce the measured beamforming profile
- The absolute source strength in the model is set by scaling the vertical PSD of the synthetic data to that of the surface sensor at the borehole
- Seismic modeling then allows to predict the horizontal PSD on the surface as well as the underground PSDs for horizontal and vertical direction at 250 m depth
- We attribute the 3-5 Hz anomaly to uncertainties in the geology model and the strict use of only vertical sources
- We limited ourselves to vertical sources, since our surveys were done with vertical component geophones and hence our lack of understanding of the horizontal ground motion propagation



Simulated vs observed horizontal and vertical ground motion on the surface and at depth. A fair agreement with the measurements, except between 3and 5 Hz (shaded grey).

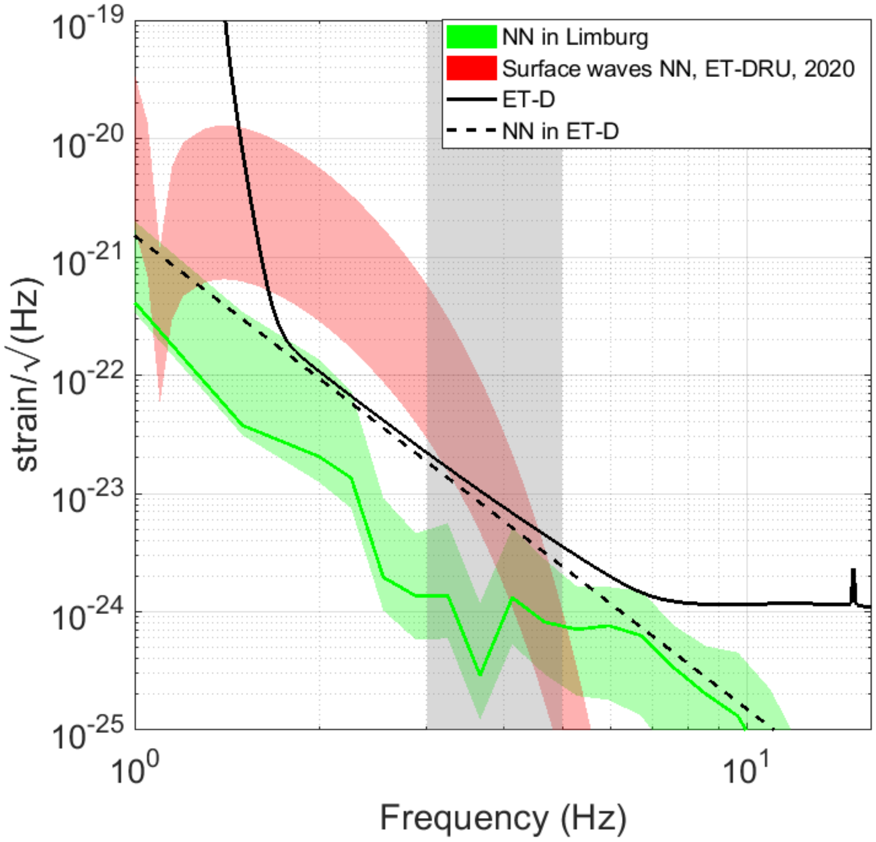
Newtonian noise from surface sources

From the viewpoint of surface-source Newtonian noise, the EMR-site offers suitable conditions to host Einstein Telescope

Model attributes.

- $$\delta\vec{a}(f) = \sum_{m=1}^{M} G\Big(\int_V \rho_m(\vec{u}.\nabla)\vec{k}\,dV_m \; + \; (\rho_{m-1}-\rho_m)\int_S(\overrightarrow{u}.\overrightarrow{n_m})\vec{k}\,dS_m\Big)$$
- Where ρ_m is the density of the m^{th} layer; volume and surface integral of the m^{th} layer are dV_m, dS_m; unit vector normal to interface of m^{th} layer is $\overrightarrow{n_m}$; $\vec{k}$ is the wave-vector

- At frequencies < 3 Hz, the 90th percentile of the site-based Newtonian noise is predicted to be approximately equal to the Einstein Telescope design sensitivity curve.
- In the band from 3 – 5 Hz, , Newtonian noise estimate can be treated as a lower limit:
  - seismic amplitudes are uncertain due to the limitations in the subsurface model and seismic source mechanism
- At frequencies above about 5 Hz, surface waves in the top layers are the main contributor to the total Newtonian-noise level



Ambient body-wave background

Body-wave background contributes to about half of the underground seismic noise

Total seismic noise underground

$$PSD(f)_{\text{depth}} = PSD(f)_{\text{surface}}\alpha(f) + \beta(f), \qquad \text{where } \beta(f)\ is \text{ the body} - \text{wave background}$$

- The attenuation $\alpha(f)$ is independent of day-night time
- The body wave background is more pronounced at night

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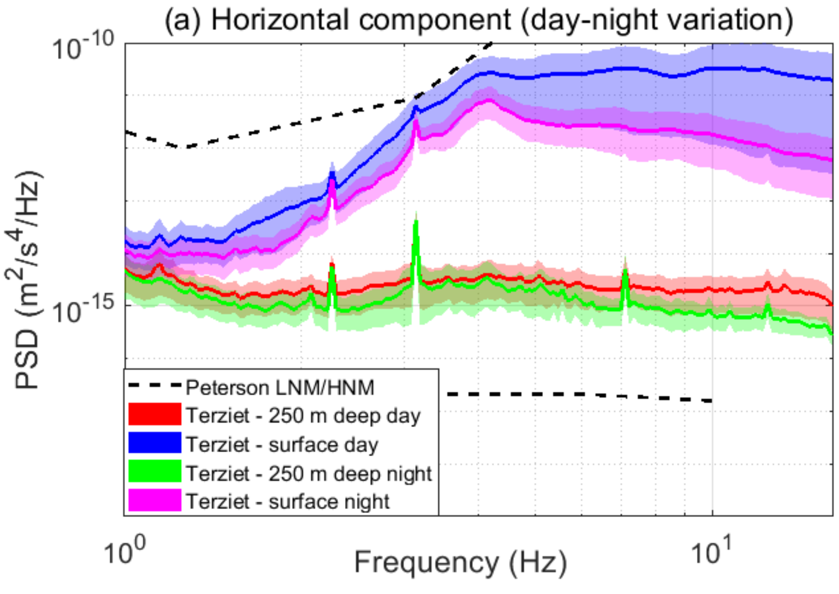
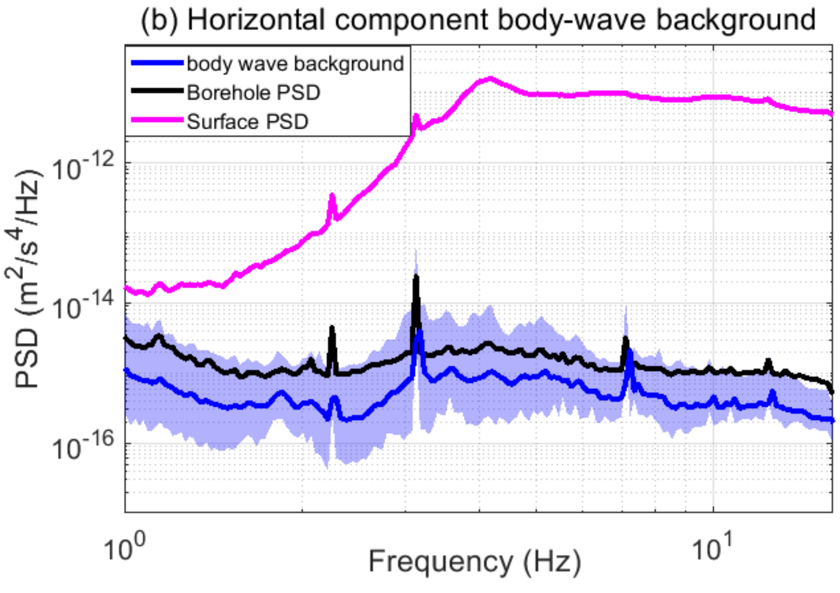


(a) Horizontal component (day-night variation)



(b) Horizontal component body-wave background

Newtonian noise from body-wave background

Newtonian noise from body-wave background is estimated using a set of plane wave sources positioned randomly in the medium

Model attributes.

- In order to model the displacement field $\vec{u}$ resulting from body waves, we assume plane waves →

$$\vec{u}(\vec{x}) = \left(\vec{A}.\vec{\xi}\right)\hat{\xi}e^{-i\left(\frac{\hat{\xi}\vec{x}}{v_P}-\omega t\right)} + \left(\vec{A} - \left(\vec{A}.\hat{\xi}\right)\hat{\xi}\right)e^{-i\left(\frac{\widehat{\xi\vec{x}}}{v_S}-\omega t\right)}$$

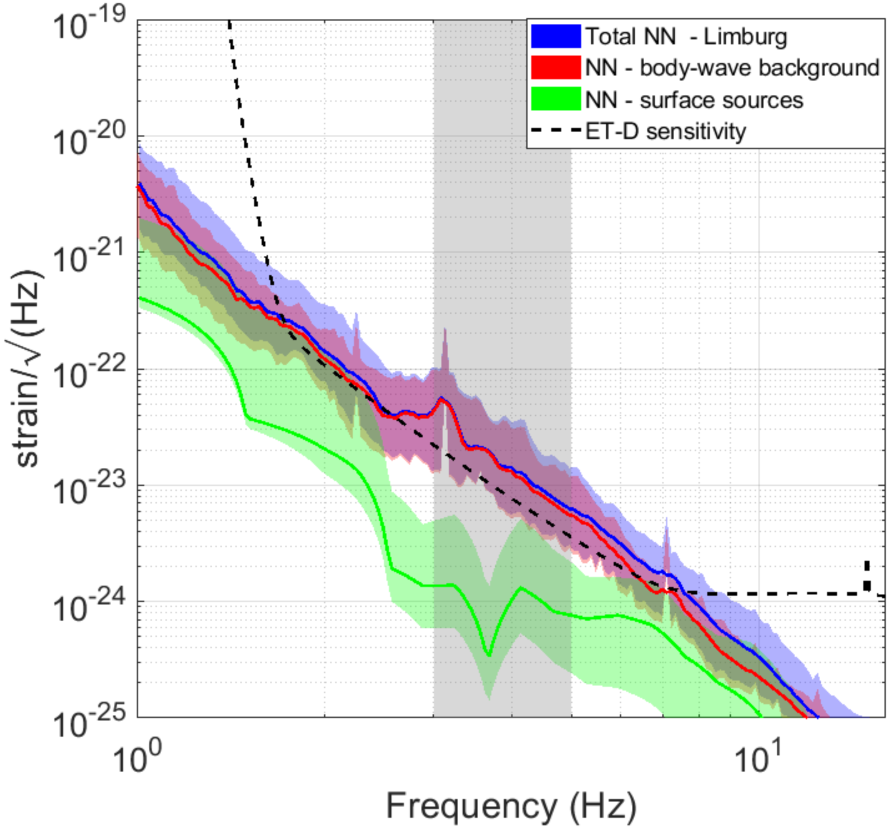
- with $\vec{A}$ the amplitude and direction of the displacement; $\hat{\xi}$ the unit vector pointing in the direction of the wave, $\vec{x}$ the soil coordinates, and $v_P(v_S)$ the P-wave (S-wave) speed.
- Both the displacement amplitude $\vec{A}$ and the wave direction $\hat{\xi}$ are assumed to be distributed isotropically (1/3 P, 2/3 S)
- we assume random phase offsets for each component (sideways, parallel, perpendicular)
- The assumption of plane waves implies that we do not consider rescattering and dispersion of the waves
- The waves are not modified when crossing a soil layer boundary and the amplitude is constant everywhere in space (infinite coherence length)
- The body-wave background is modeled with 4,000 isotropically-distributed plane waves at each frequency, of which the total power matches the deduced body-wave power spectral density
- In the Newtonian noise calculations, the soil displacements due to these waves have been integrated up to a radius of 10 km

Newtonian noise predicted for EMR-site

The mean Newtonian-noise estimate is up to a factor of 2 higher than the ET-D design sensitivity for frequencies up to about 8 Hz, and the body-wave background dominates

Parameters for background body-wave NN

- Both the displacement amplitude and the wave direction are assumed to be distributed isotropically
    - 1/3rd P-waves and 2/3rd S-waves.
- Fixed P-wave speed - 4.50 km/s, and 2.82 km/s for S-waves
- Random phase offsets for each component.
- The assumption of plane waves implies:
    - we do not consider re-scattering and instrinsic-dispersion of the waves
    - the waves are not modified when crossing a soil layer boundary and the amplitude is constant everywhere in space
- Therefore we expect that the modeled results for the body waves may add inaccuracies



Conclusions

Seismic

- The fundamental Rayleigh-wave mode dominates the vertical component of surface-seismic noise up to frequencies of 5 Hz. While the first Rayleigh-wave overtone and the fundamental mode were found to contribute equally in the band 5−8 Hz
- Contribution from body waves to seismic noise is dominant for frequencies greater than 8 Hz. Although in horizontal component, above 4 Hz, mixing of body waves and higher modes of surface wave occurs
- Transition to hard rock occurs at a depth between 15 – 20 m beneath at the borehole site and again at a depth between 35 – 40 m
- At 250 m the seismic noise reduces by about a factor 10^4 in power. At 250 m depth, the horizontal component attenuates faster (4 Hz onwards) than the vertical component (9 Hz onwards)
- Background body waves contribute to about half of the underground noise for frequencies greater than 4 Hz

Newtonian noise:

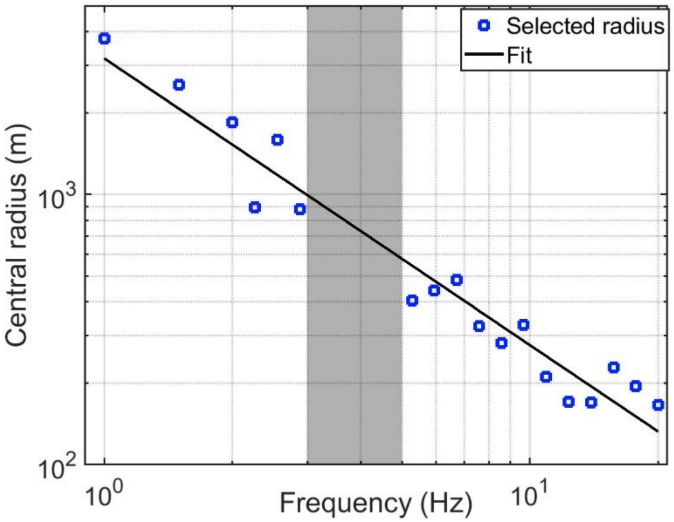
- Newtonian noise estimated due to surface sources is lower than ET-D sensitivity except in the band 3-5 Hz where the estimations can be treated as lower limit
- The mean Newtonian-noise estimate is up to a factor of 2 higher than the ET-D design sensitivity for frequencies up to about 8 Hz, and the body-wave background dominates
- The soft-soil surface layer traps and damps most of the surface activity and little noise penetrates to the depth of the mirrors
- The relatively low wave speeds at the surface lead to many small patches of coherent movement and the total noise from the surface averages out to a large degree

Questions?

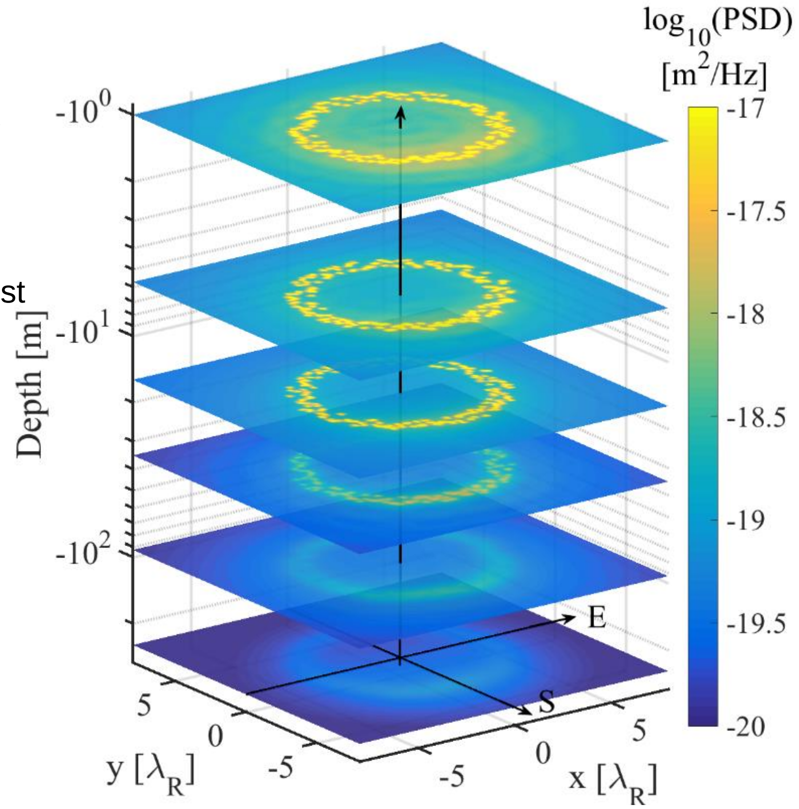
Supplementary material

Modeling Newtonian noise – source ring distance

- Vertical sources are used
- Vertical PSD is normalized at the surface
- Source distances that correctly predict the H-V ratio measured with the T240 surface sensor near the top of the borehole
- This means that for low frequencies the sources may be several km away, whereas at high frequencies the sources are local and may be a few hundreds of meters from the test mass.



Blue dots show the radii of the source-rings for different frequencies. The grey region denotes the frequency band where the observed H/V could not be reproduced, and an interpolated source-ring radius was used.

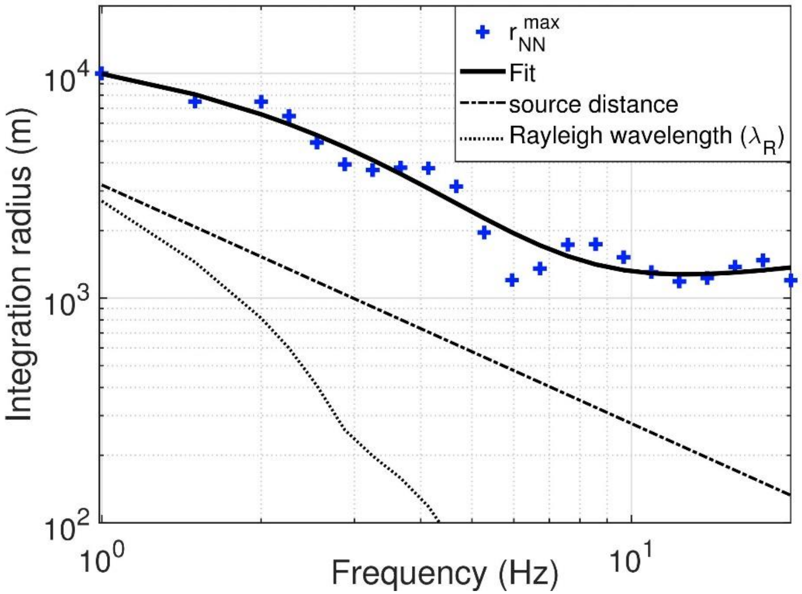


Model of displacement noise that reproduces the measured PSD at 2.6 Hz on the surface at the borehole using 180 sources located at a radius of 1 km and ring thickness of 240 m. Note the strong amplitude reduction at depths greater than 35 m, where the transition to hard-rock layers begins

Modeling Newtonian noise – integration radius

- The maximum integration radius r_{max}^{NN} is the distance after which Newtonian noise does not significantly change when the integration volume is increased any further
- Typically for surface detectors, $r_{max}^{NN} \approx \lambda_R/2$, where λ_R is Rayleigh wavelength
- This generalization is not evident for test masses in layered geologies with realistic wave fields and for underground caverns.
- Therefore, we derived r_{max}^{NN} for a test mass at 250 m depth, with a spherical cavern of radius 10 m in the Limburg geology
- The r_{max}^{NN} in each frequency bin is determined from the contribution of a single source by subsequently increasing the integration radius, starting with 250 m and reaching up to a distance where fluctuations stay within 10 % of the asymptotic value

- Note, that r_{max}^{NN} surpasses the central radius of the source ring (indicated by the dashed curve in the figure), which means that sources are included in the integration volume
- To avoid a bias due to the excess displacement in the vicinity of the source, all seismic displacements within $\lambda_R/2$ are excluded
- If a discrete integration point is located in this area, then its displacement is determined by a linear interpolation based on the displacement field outside the excluded source area



Frequency dependence of the maximum integration radius r max NN for a test mass located at 250 m depth in the Limburg geology. The r_{max}^{NN} exceeds the central radius of the source ring (dashed curve), which means that surface sources are included within the integration volume. The Rayleigh wavelength is indicated by the dotted curve.

Outlook

- Future geology models should treat the subsurface as a three-dimensional medium that includes measured local material damping factors, such that the simulated and the observed ground motion can be matched for all frequencies

- In addition, the differences between measured and simulated underground PSDs below 5 Hz suggest that source mechanisms other than vertical excitation may have to be included

- It is recommended that future studies characterize the body-wave background by employing a string of downhole tri-axial sensors, and model the Newtonian noise arising from it in detail, by including distant and underground sources that can reproduce the acquired seismic data at all depths

- Current calculation of NN due to the background body-waves may be overestimated. Hence, the displacements of the subsurface elements may be more accurately obtained by solving the elastic wave-equation for a random distribution of body-wave sources

- Modeling the cavity shape in the subsurface is necessary; now we just fix the minimum integration radius to 10 m; however, reflections, scattering from the walls of the cavern will impact the current estimate