Seismic and Newtonian noise estimate at Terziet-

the Euregio Meuse-Rhine candidate site for Einstein Telescope

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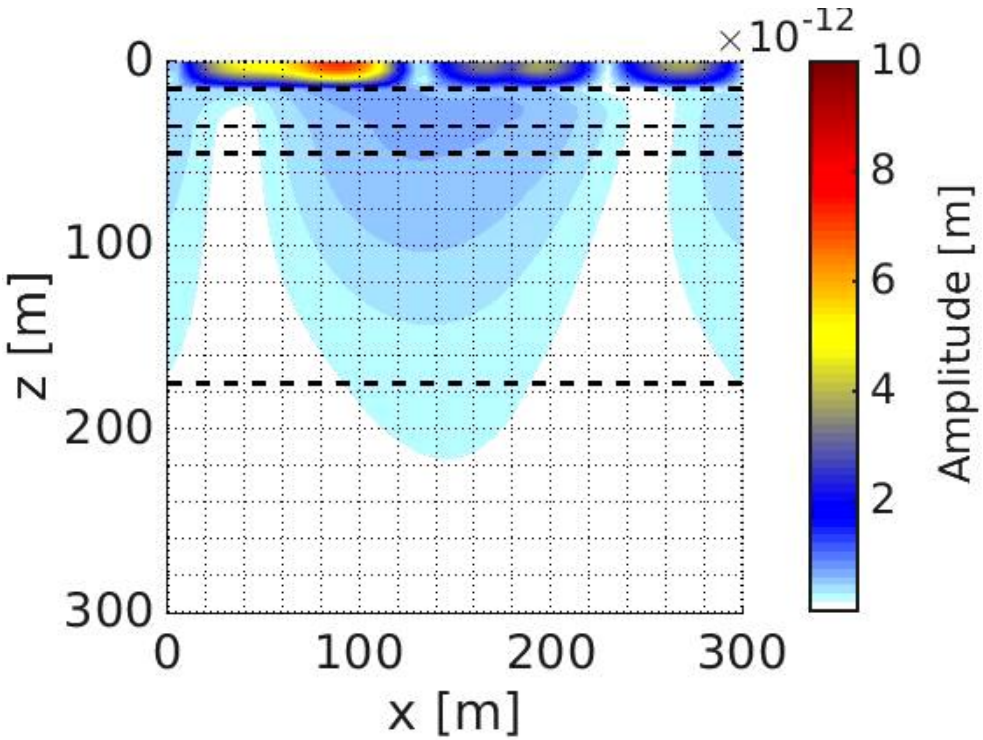
- Surface sources
- Background body waves

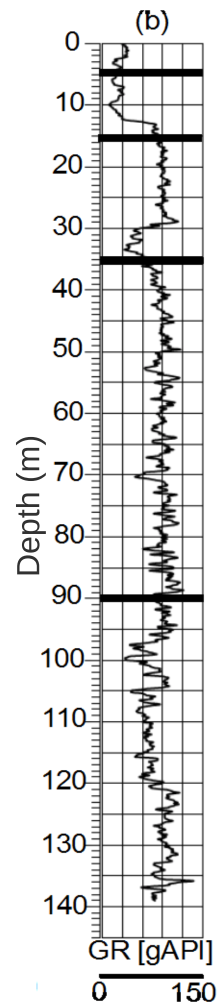
All work reported here are based on:

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

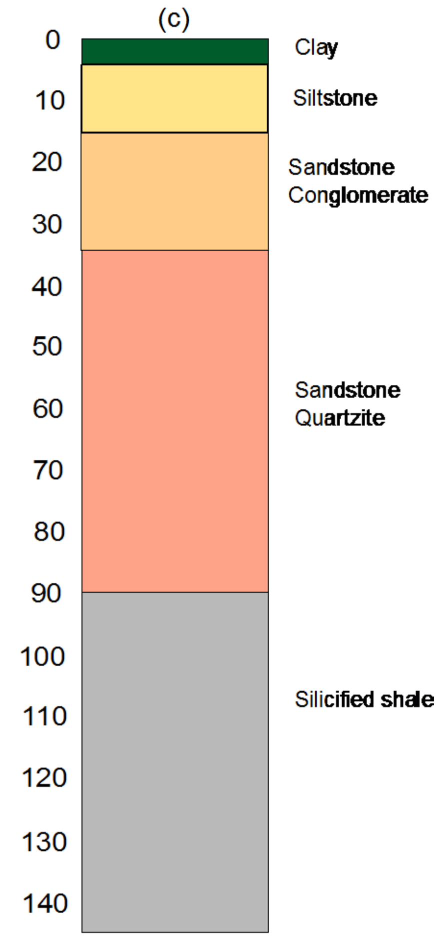
Studies of quality at potential Euregio Meusse-Rhine (EMR) site

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





Gamma ray



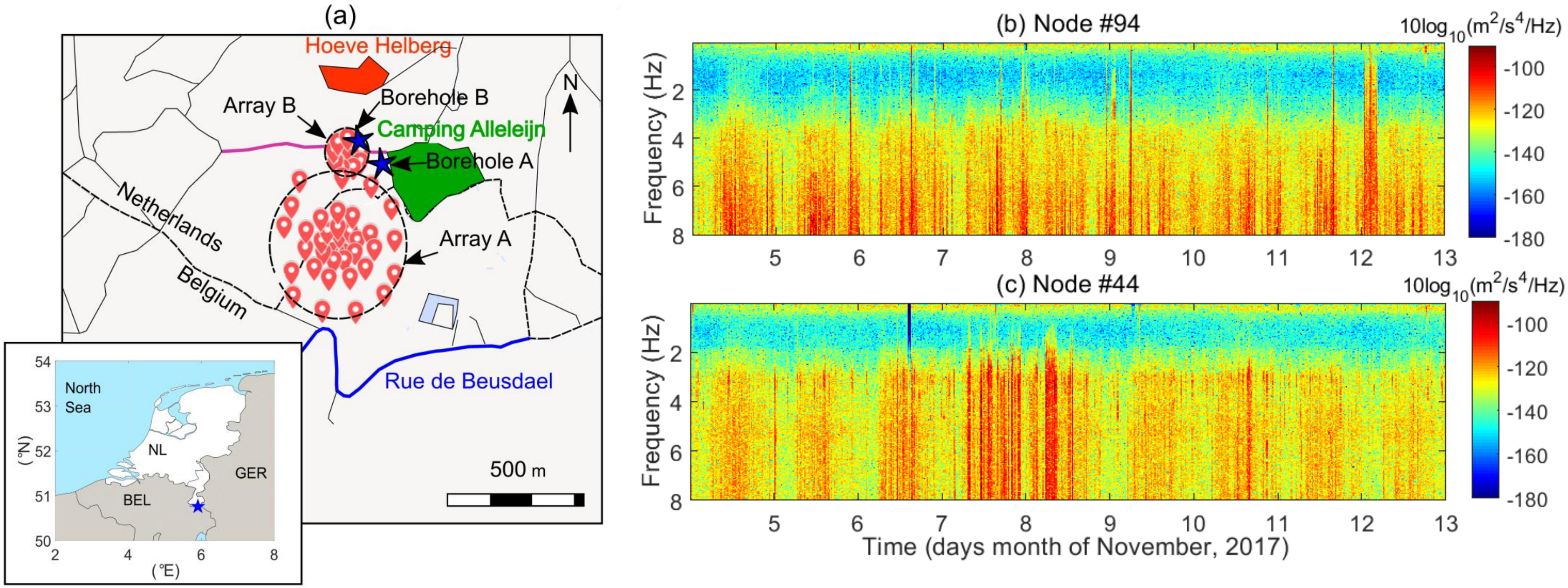
Lithology model

Surface seismic array– Nov. 4 – 28, 2017

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

Array features

- Two circular arrays, each comprising 49 and 25 vertical component geophones were deployed in the vicinity of a 250 m deep borehole at Terziet
- 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

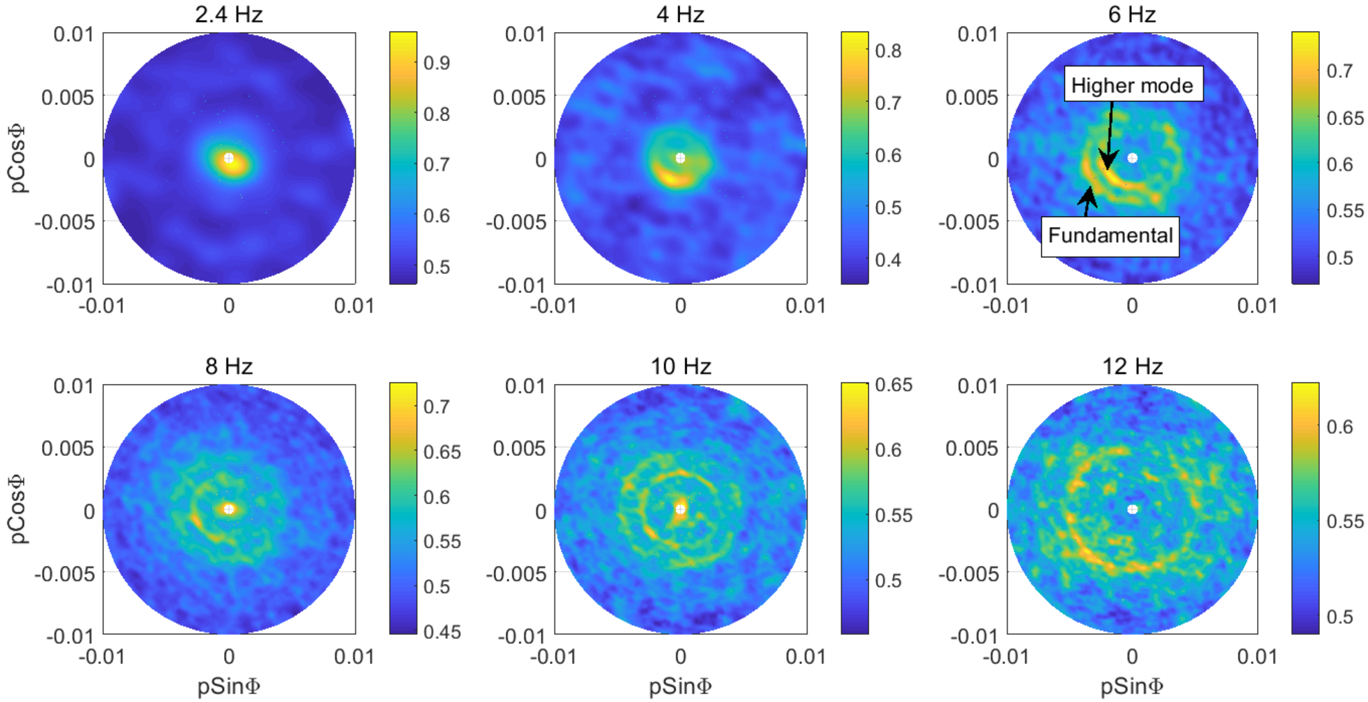


Beamforming output

Beamforming results show the dominant seismic wave propagation in the form of Rayleigh waves and higher-order modes

Spatial-filtering

- Beamforming decomposes the seismic wavefield into a set of plane waves which are characterized by their slowness ($p\ = 1/velocity$) and direction (ϕ)
- Array A is sensitive in the band 2.4 – 14.0 Hz, due to spatial aliasing at frequencies > 14 Hz (Nyquist)
- 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

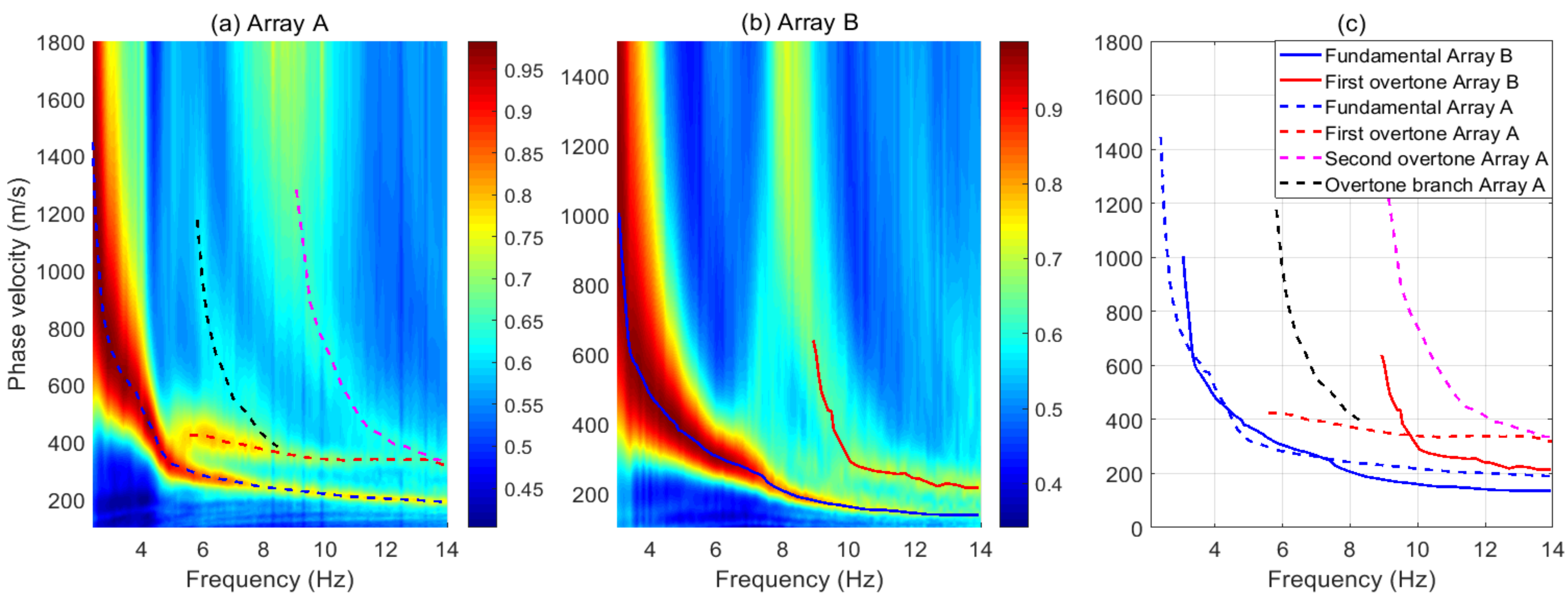


Rayleigh-wave dispersion

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

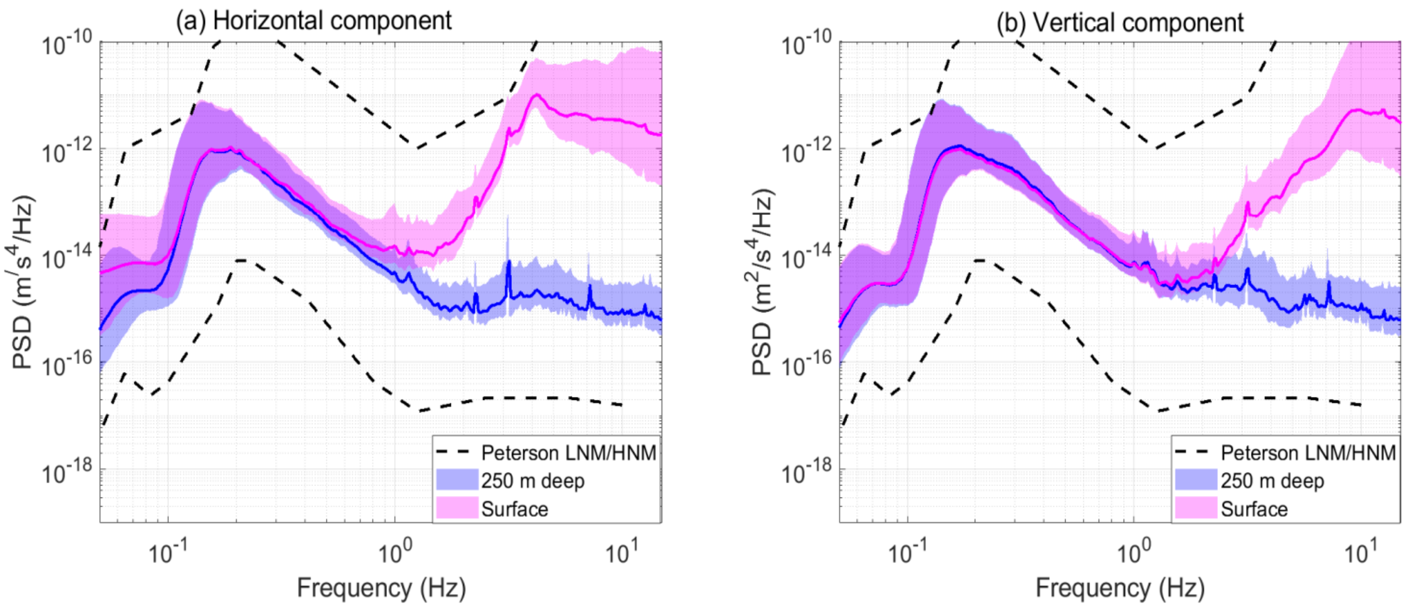


Underground seismic noise

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

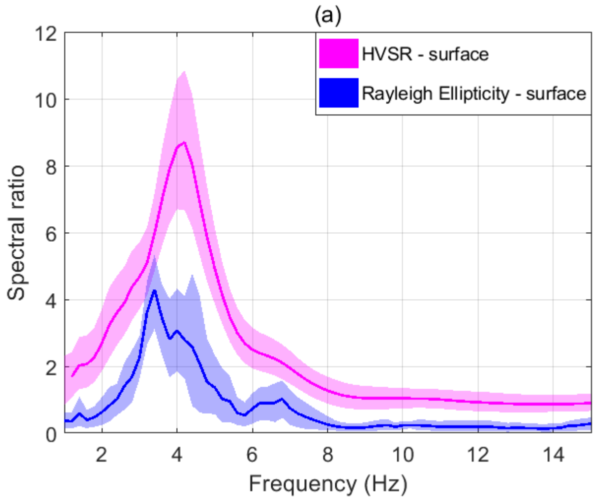


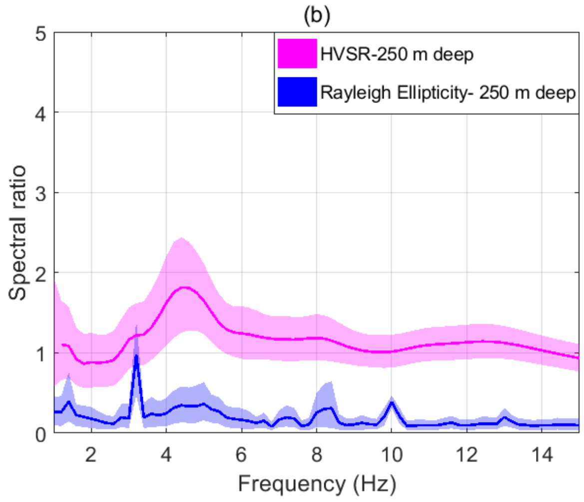
HVSR and Rayleigh ellipticity

A horizontal-vertical spectral ratio (HVSR) peak of about 8 is observed at 4 Hz implying a sharp contrast in velocity at shallow depths

HVSR vs Rayleigh-ellipticity

- HVSR and Rayleigh wave ellipticity are additional constraints for wavefield modeling
- HVSR gives us an estimate of ratio of (Rayleigh + Love+SH) and (vertical-Rayleigh+P+SV)
    - Radial component of Rayleigh waves dominate on the horizontal seismic - 1-3 Hz and 5-7.5 Hz (first overtone of Rayleigh)
- The second peak in the Rayleigh-wave ellipticity at about 7.2 Hz could be due to the ellipticity peak of the first overtone of the Rayleigh wave



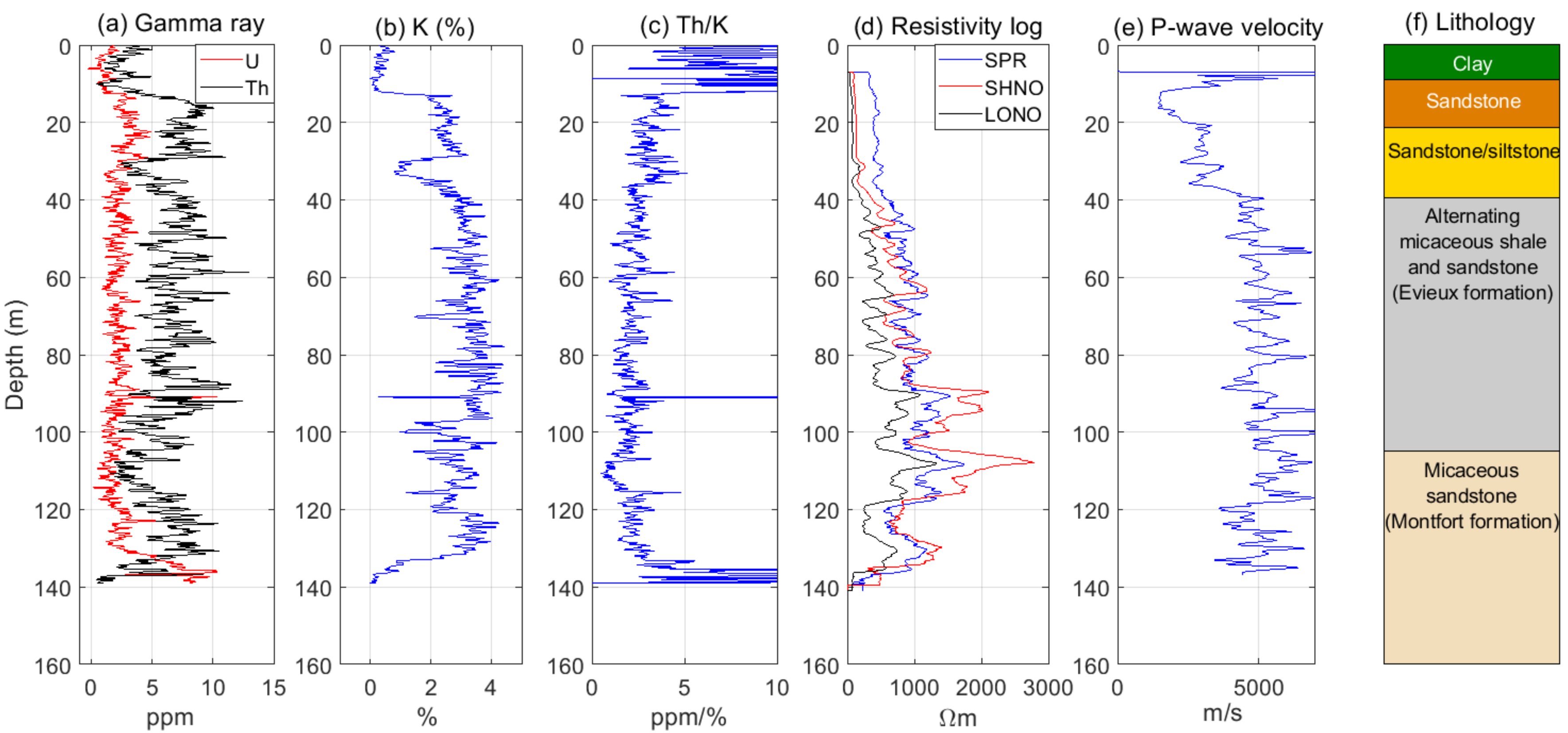


Apriori subsurface information

Resistivity, gamma ray, and sonic logging was performed to get apriori subsurface information which is necessary for setting the constraints for subsurface model estimation

Soft-soil over hard-rock geology

- P-wave velocities higher than 4 km/s are observed for depths > 40 m

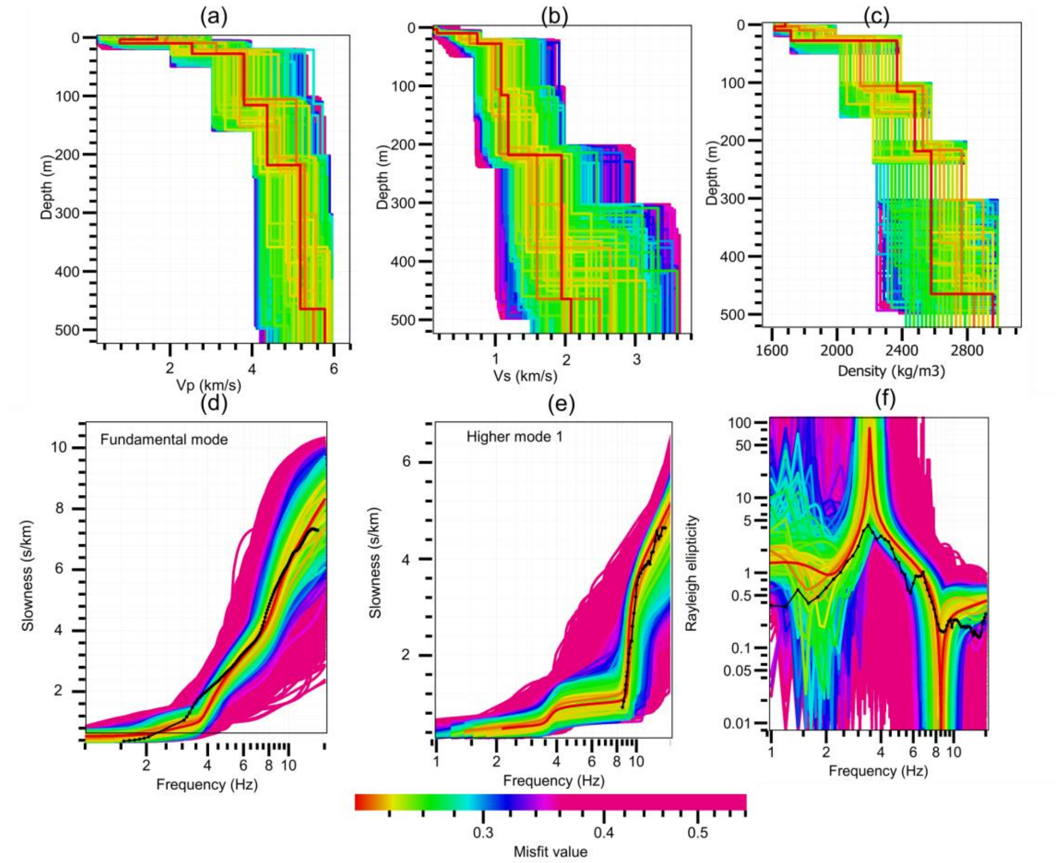


S-wave velocity model

A first transition from soft-soil to hard-rock is observed at depths between 15-20 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



Surface and body-wave contribution – Eigenfunctions

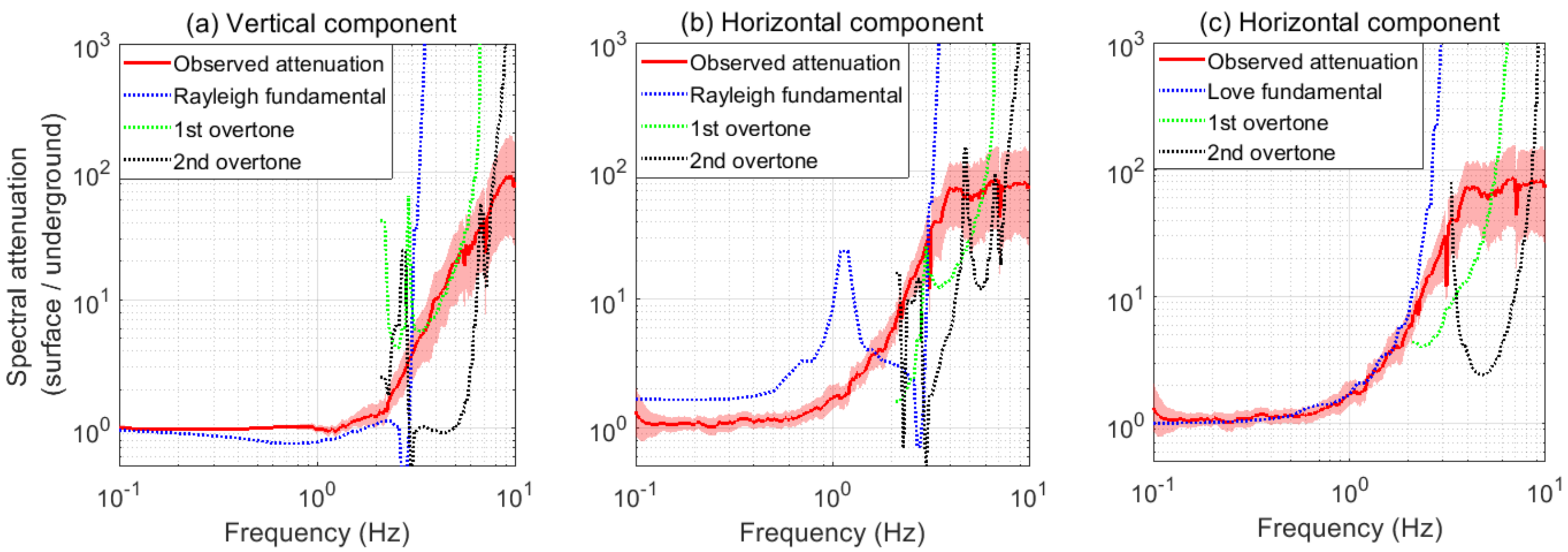
Fundamental and higher-order modes of Rayleigh and Love waves are required to understand the observed horizontal and vertical spectral attenuation

Vertical component:

- Rayleigh fundamental: < 2 Hz; first overtone: 2.5 – 5 Hz; 5- 8 Hz: mixing of body wave and second overtone of Rayleigh waves; >8 Hz: dominated by P-waves (local sources + background)

Horizontal component:

- Love Fundamental: < 3 Hz; Mixing of surface waves and SH waves: 3 - 8 Hz; > 8 Hz - SH waves dominate

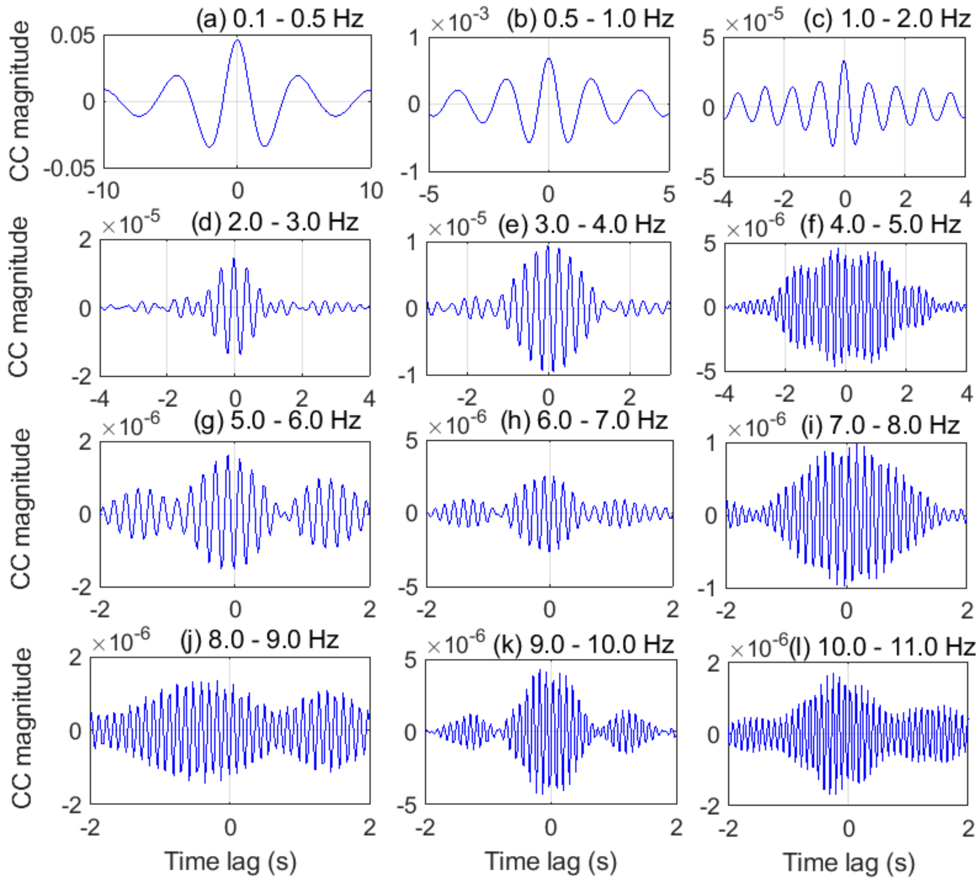


Surface and underground cross-correlations

Evidence of a body-wave background with random angles of incidence is found by cross-correlations peaking at non-zero time-lag for frequencies above 4 Hz

Vertical component:

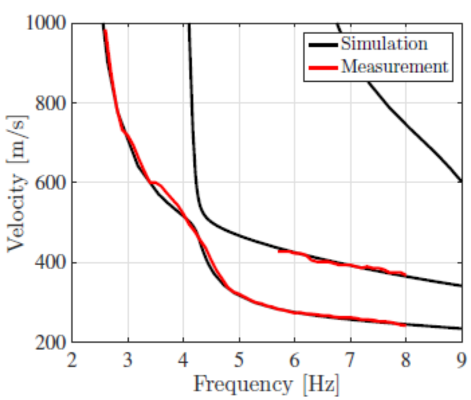
- Rayleigh fundamental: < 2 Hz; first overtone: 2.5 – 5 Hz; 5- 8 Hz: mixing of body wave and second overtone of Rayleigh waves; >8 Hz: dominated by P-waves (local + background)

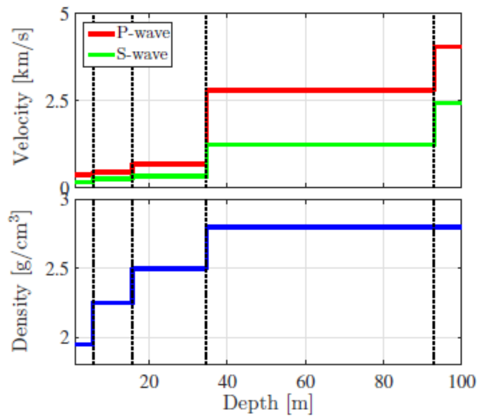


Towards modeling Newtonian noise from surface sources

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

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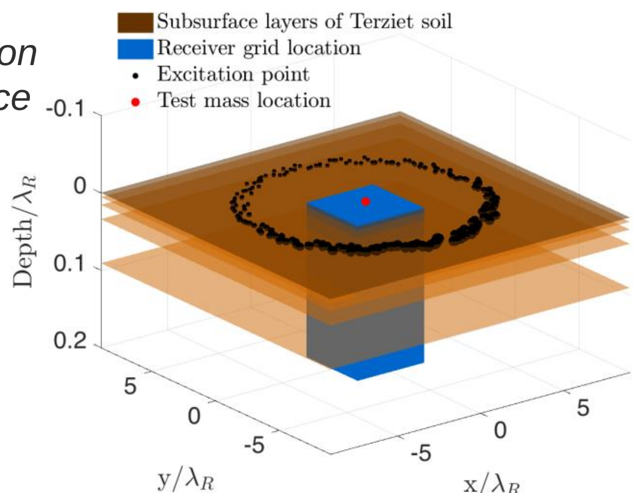
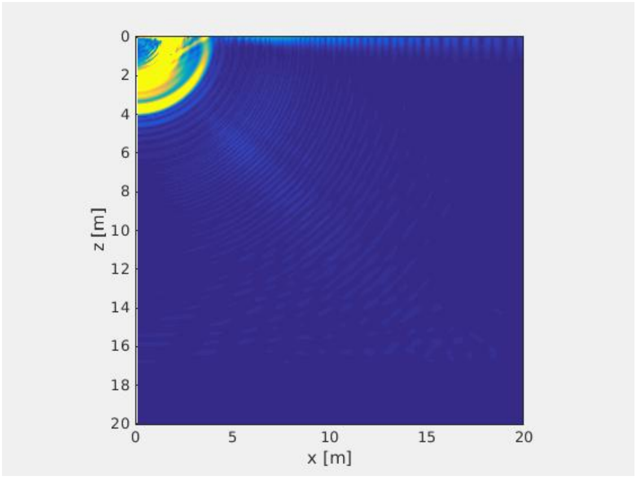
Vertical Source distribution on surface

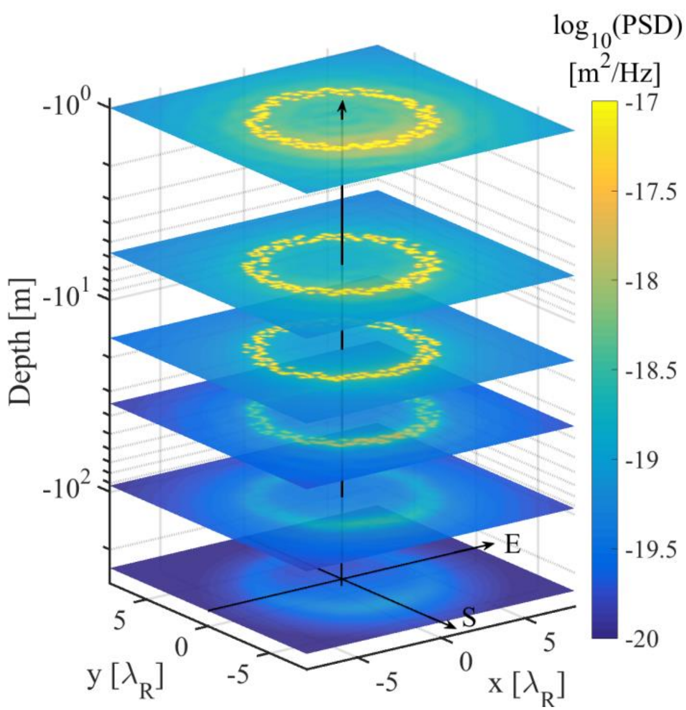


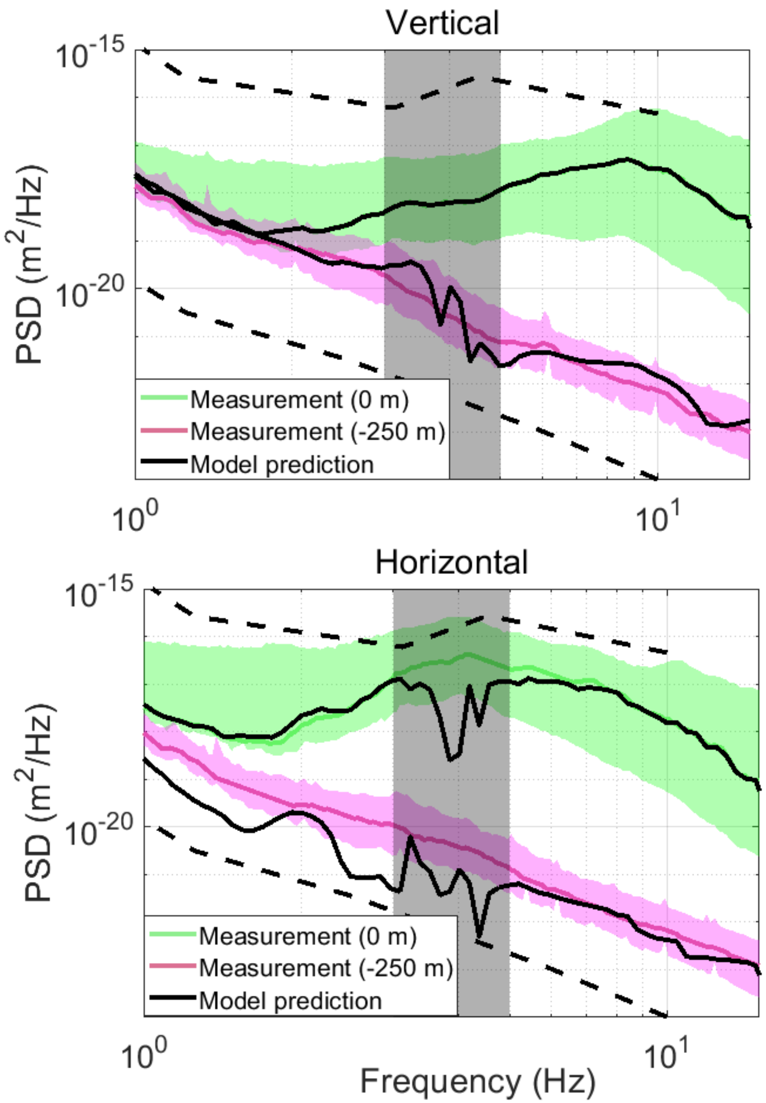


Output ground motion

Modeling Newtonian noise

- Vertical sources are used
- Vertical PSD is normalized at the surface
- The horizontal PSD in the band 3-5 Hz is not reproduced in the simulations
- Offset at low frequencies in the underground horizontal PSD





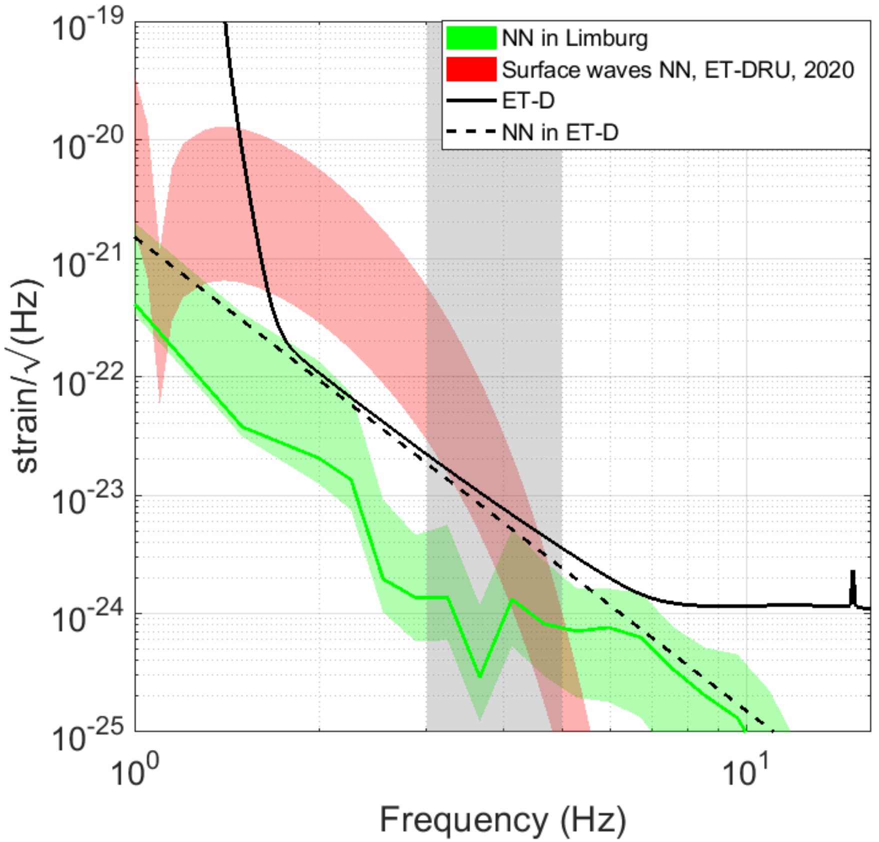
Simulated vs observed horizontal and vertical ground motion on the surface and at depth

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.

- 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**.**
  - Here, Rayleigh wavelengths are large and the seismic waves in the bottom-most layer give the dominant contribution to Newtonian-noise estimates.
- 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

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

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

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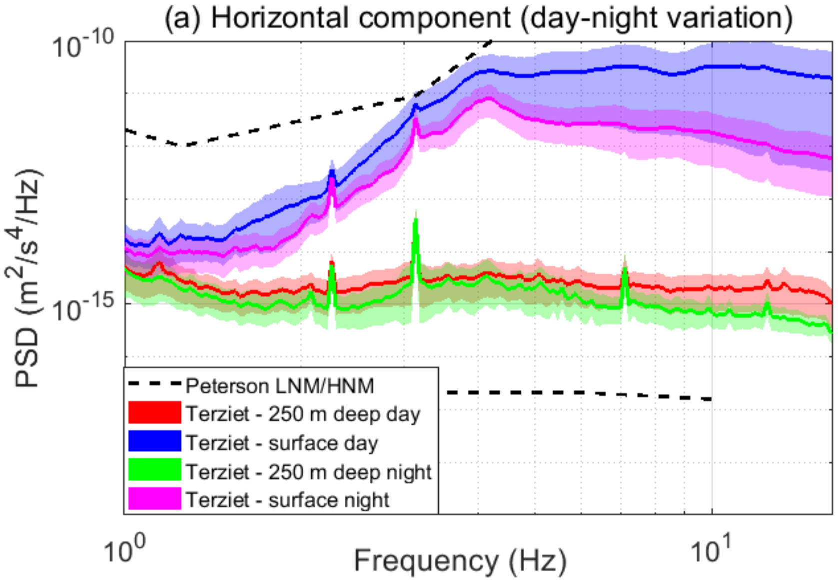
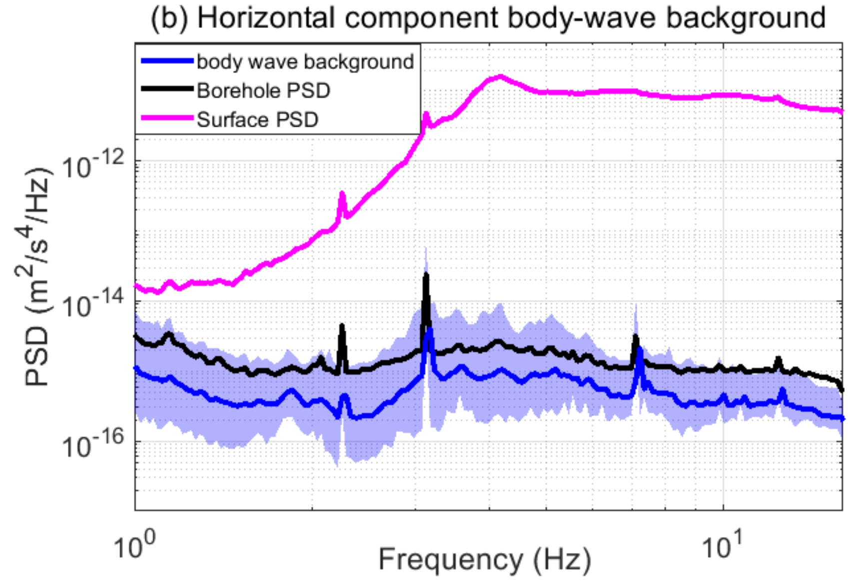


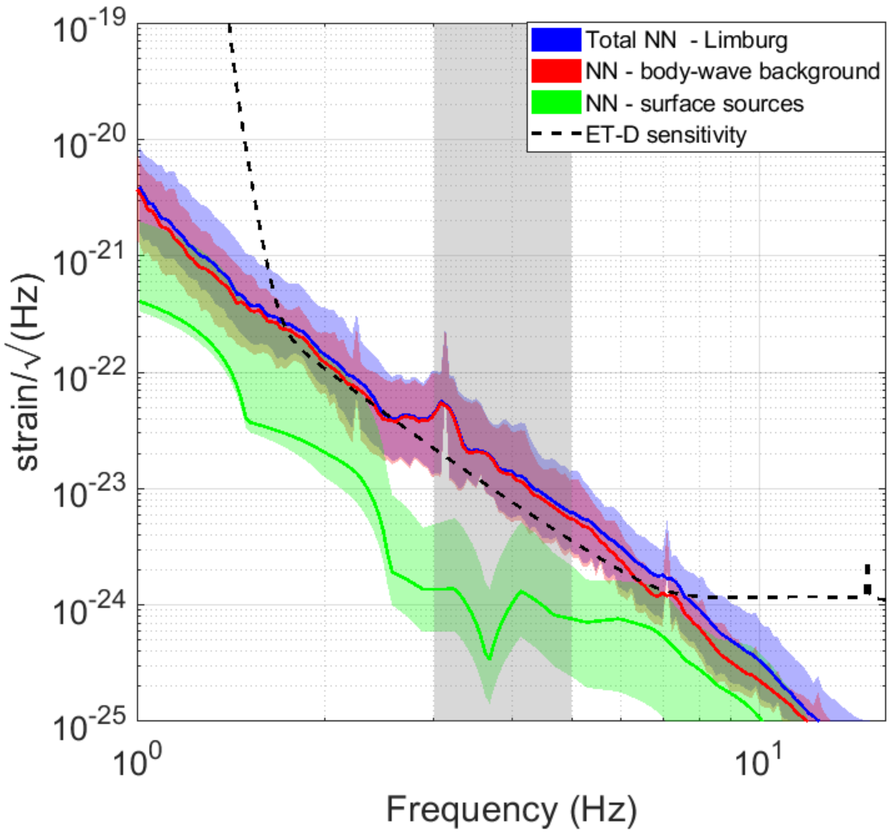


Newtonian noise predicted for EMR-site

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 overestimate the Newtonian noise



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, a weak second Rayleigh-wave overtone was observed for frequencies greater than 10 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
- P-wave velocities at the site range between 1.5 to 2 km/s near the surface and is about 4 – 5 km/s at 250 m deep. Near surface S-wave velocities are as low as 120 m/s
- 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

Outlook

- Larger aperture surface-surveys can be conducted at the site for delineating the surface from the body waves
- Surface array measurements by using three component geophones can be conducted in order to estimate the depth hard rock by using the H-V spectral ratio
- 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 3 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


Questions?