Seismic studies at a candidate site for Einstein Telescope

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Courtesy of the Archives, Calif Inst of Technology

Why build the Einstein Telescope?

Einstein Telescope, a 3rd generation GW detector will improve the current *adv. LIGO* sensitivity by a factor 10 and also improve the detector sensitivity upto low frequencies of 2 Hz.

Advantages of building ET

- An improved detector sensitivity by a factor 10 - *enables a $\mathbf{10^3}$ times larger volume of the universe to be observed.*
- Improved sensitivity upto frequencies of 2 Hz - *observation of BBH or BNS events for longer duration.*
- Strong field tests of General Relativity – *SNR >100*.
- Other astronomical and cosmological implications.

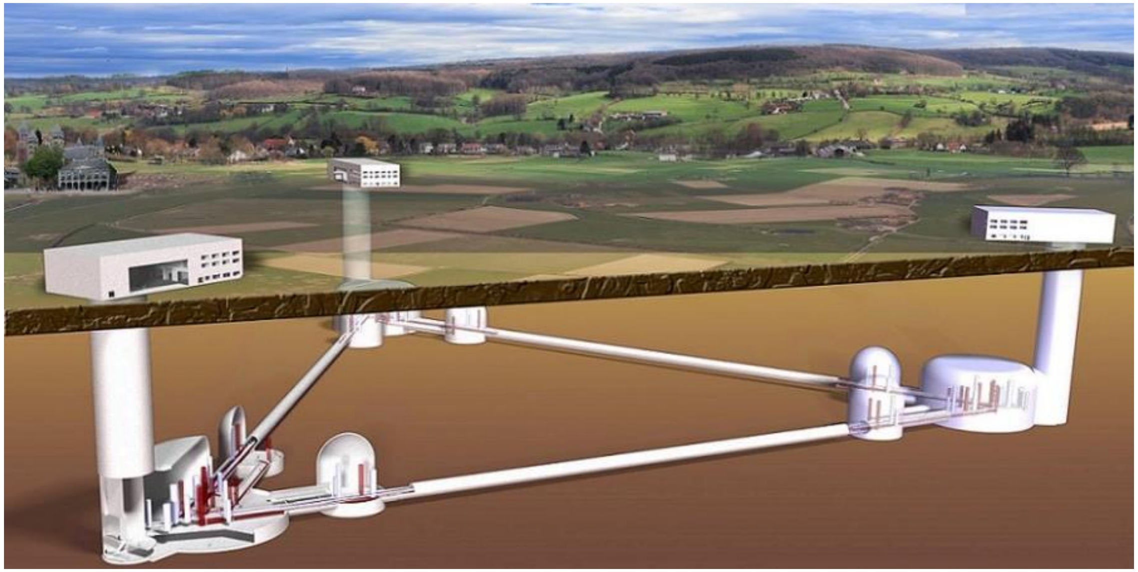

Figure 1. An artists impression of the underground Einstein Telescope GW detector beneath the Limburg landscape.

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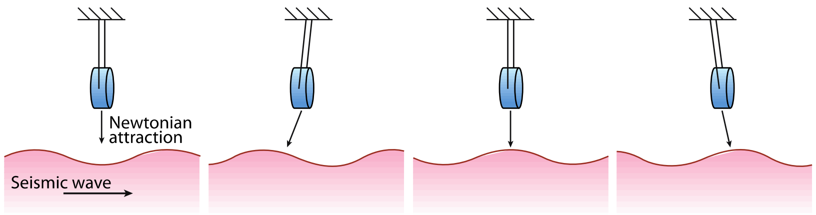
Low frequency noise at gravitational wave detectors

Newtonian noise is the main factor limiting the sensitivity of gravitational wave detectors like Advanced Virgo and Einstein Telescope

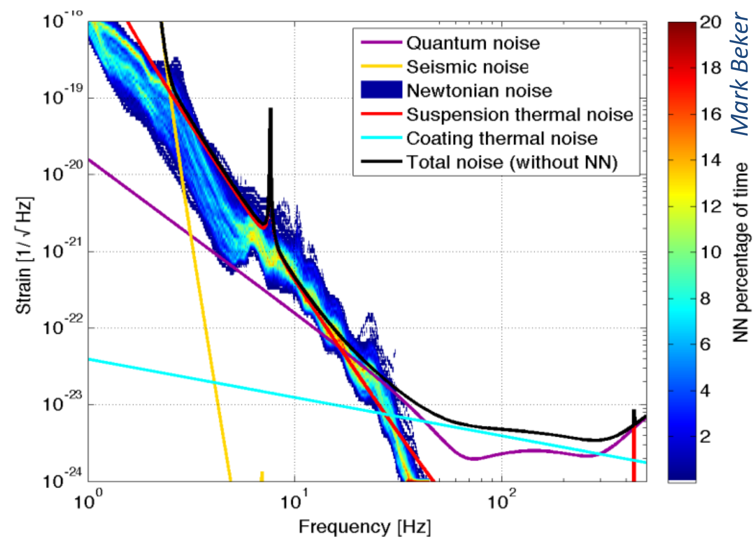
Newtonian interaction between seismic wave field and interferometer test mass



The challenge

- Newtonian noise is dominant at frequencies below 20 Hz
- Direct coupling prohibits isolation of suspended elements from Newtonian noise

Adv Virgo during high seismic activity



- Understanding seismic wave fields surrounding your detector → **Requires large arrays of seismic sensors**
- Develop **models to estimate Newtonian noise** based on seismic field parameters
- Develop **subtraction techniques** tailored to the seismic field surrounding the detector

Limiting noise sources for ET

Low frequency sensitivity of ET ***may*** be limited due to gravity gradient noise also known as Newtonian noise.

Why should ET be built underground?

- Seismic ground motion couple to the suspended elements of the detector through gravitational forces of attraction and cannot be shielded from mechanically.
- Hence only a reduced seismic ground motion can suppress Newtonian noise.
- Ground motion reduces by an order of magnitude as we go deeper (≈ 300 m) in the subsurface. **Hence the need to build ET underground.**

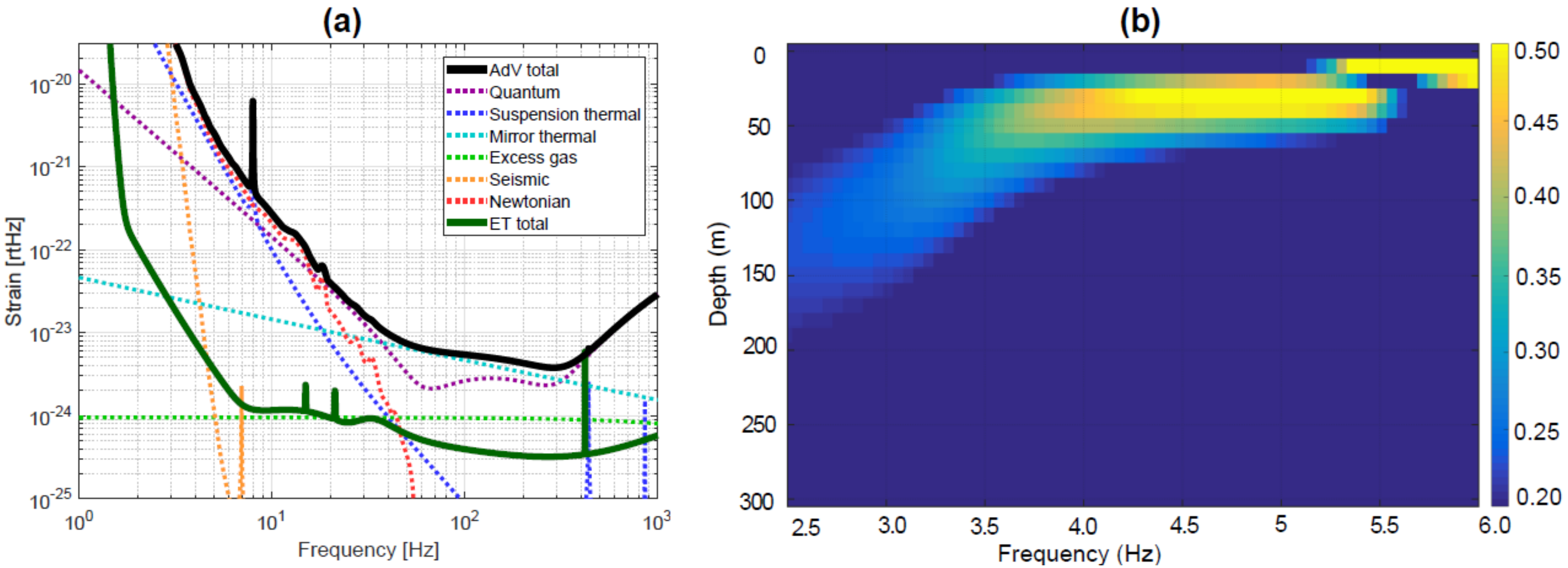


Figure 2(a) AdV noise curves and the ET design sensitivity showing how NN would limit ET sensitivity if built on the earth's surface. (b) Surface wave Eigen function varying with depth and frequency for a Limburg like geology shows the reduced contribution of surface wave seimsic noise at depth.

Inputs to model Newtonian noise

Simulating the subsurface seismic displacement is a necessity for computing the associated Newtonian noise.

Seismic wavefield modeling inputs

- Source mechanism – *Type of body and shear forces acting on the medium (earth surface, underground)*
- Subsurface parameters – V_P V_S ρ *Quality factor (medium attenuation)*
- An *elastic-wave* equation solver – *Finite Element*

Newtonian noise modeling inputs

- Subsurface displacement.
- Distribution of noise sources.
- Discretizing the simulation domain efficiently – *Integration radius*

Newtonian noise subtraction

- *Dense array* of seismic sensors to measure the seismic noise level.
- Synthesis of ambient seismic wavefield that match our observed ground motions.
- Compute NN and design subtraction schemes.

Strategies for modeling the subsurface

Subsurface modeling of the subsurface can be carried out using both ***active*** and ***passive*** seismic methods.

Active seismic principle

- Excite the subsurface with a signal of *desired strength and phase* using a vibroseis or an explosive.
- Measure the subsurface response using a array of geophones.
- Use the reflection and refraction response of the subsurface for imaging it.

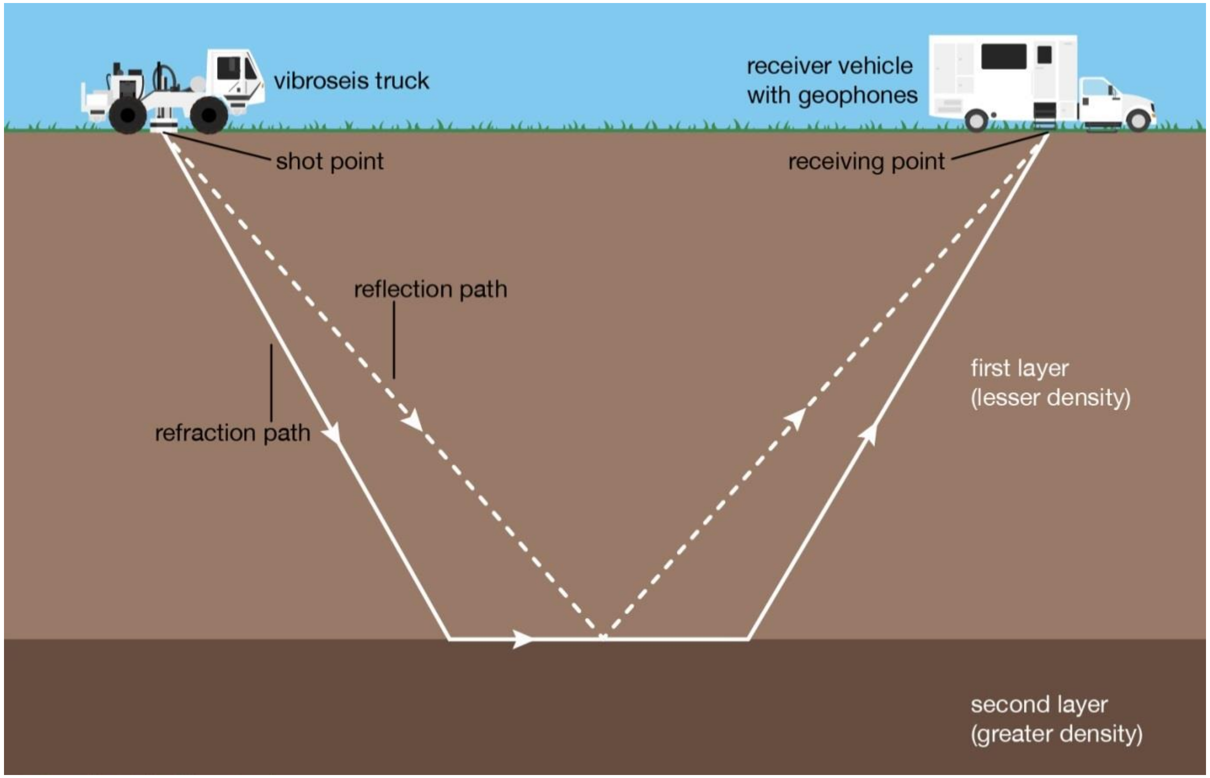


Figure: A toy model showing the fundamentals of an active seismic survey

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Strategies for modeling the subsurface

Subsurface modeling of the subsurface can be carried out using both ***active*** and ***passive*** seismic methods.

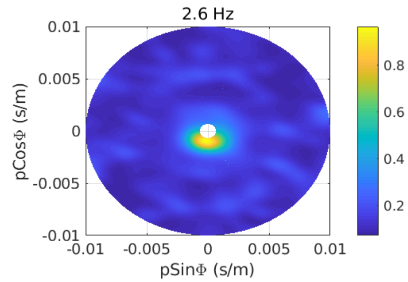
Passive seismic principle

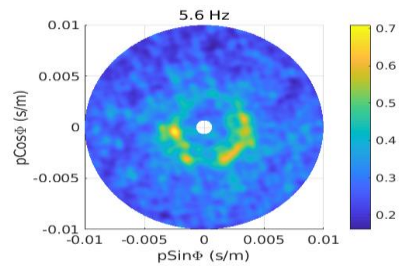
- Extract the response of the subsurface using the *seismic noise* recorded at multiple geophones.
- Unlike active seismic, measurements of seismic noise needs to be *recorded for long periods* in the range of months to years.
- The dominant contribution of *surface waves* in the recorded seismogram is used to extract the subsurface information.

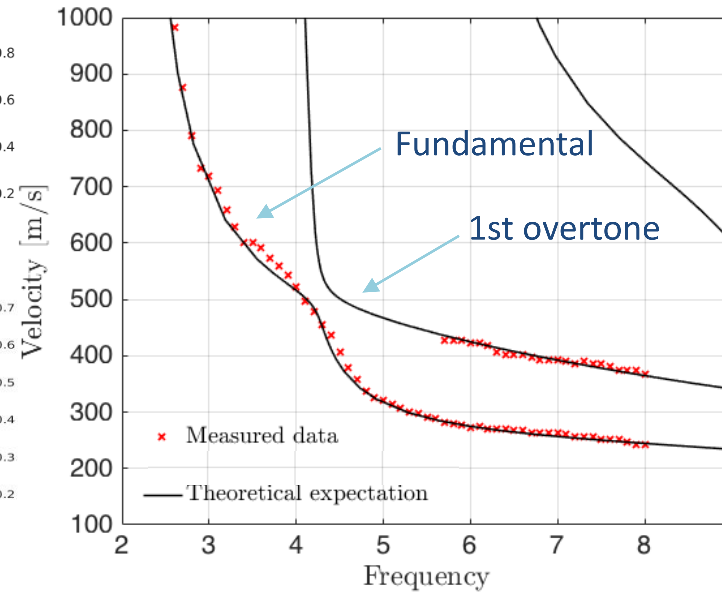
Figure: Typical sources of ambient and anthropogenic seismic noise used for passive seismic imaging.

Results of passive seismic study at Terziet, Limburg

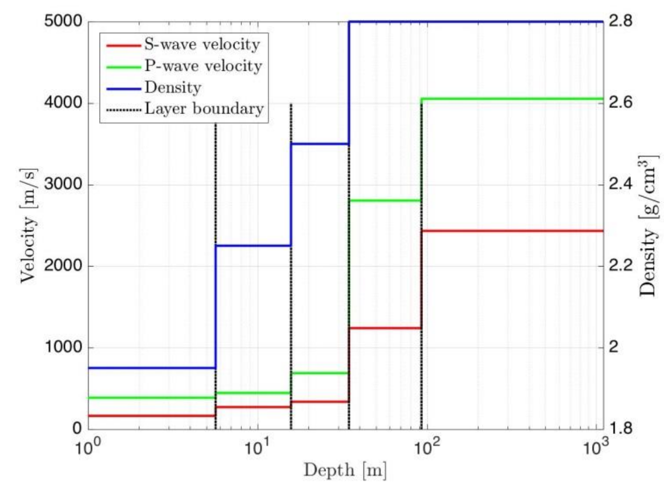
The passive seismic study at Terziet allowed to determine the **main noise sources**, **Rayleigh wave dispersion curves** of fundamental mode and first overtone and a **5-layer subsurface model**







- 3-28 November 2017, with 75 seismic sensors
- Arrays sensitive in the range between ~1 – 8 Hz
- Beamforming analysis:
  - ***Main noise below 4.6 Hz is nearby road in south west direction, above 4.6 Hz sources seem to be more uniformly in all directions.***
  - ***Measured fundamental and higher order mode Rayleigh waves***
- Inversion analysis: Based on 5 layer model from first borehole study



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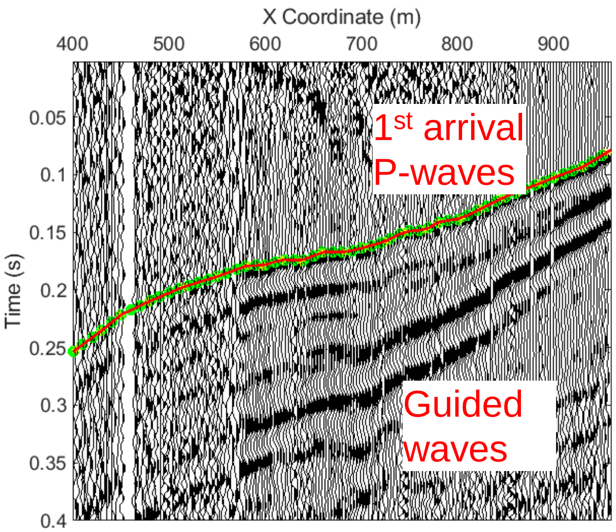
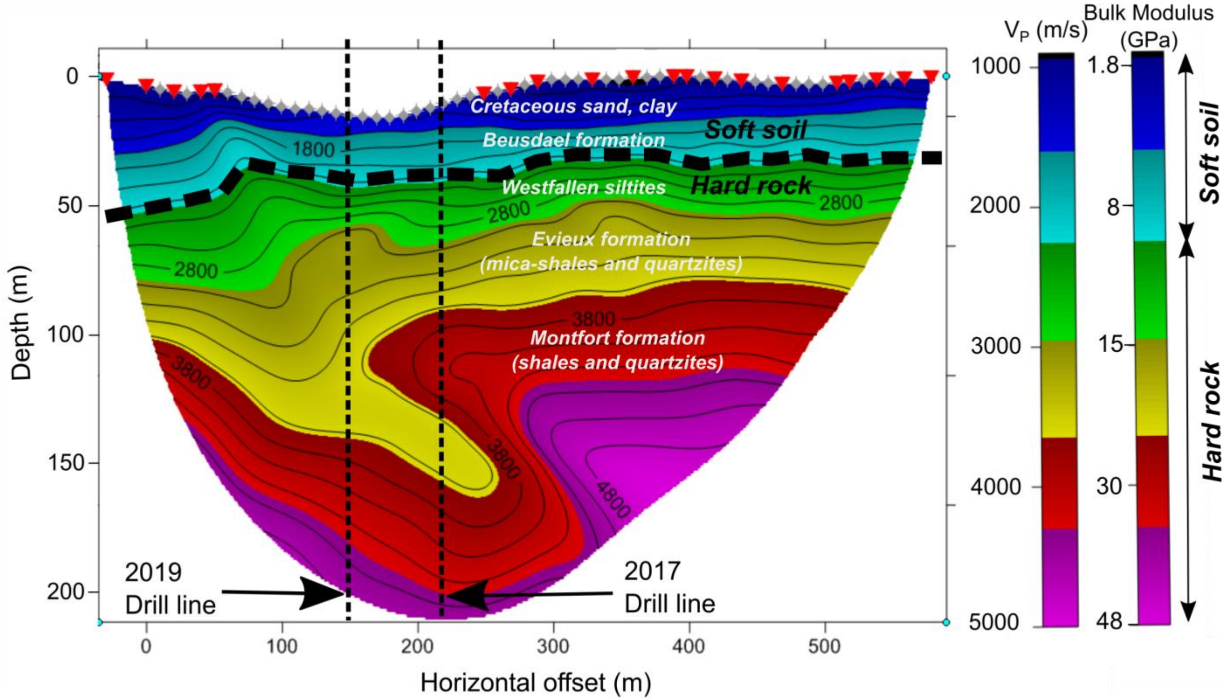
Results from active study

Results confirm the large vertical velocity gradient that has been obtained from the passive study conducted earlier.





Analysis

- Measure and model arrival times of P-waves
- Minimize misfit between measured and modeled arrival times by iteratively changing the subsurface model

Outputs

- Velocities ranging from ~1000 m/s to 5000 m/s across a depth of 200 m
- Very hard rock material at great depth is hard to image as most waves are multiply reflected at the shallow softsoil-hardrock interface.

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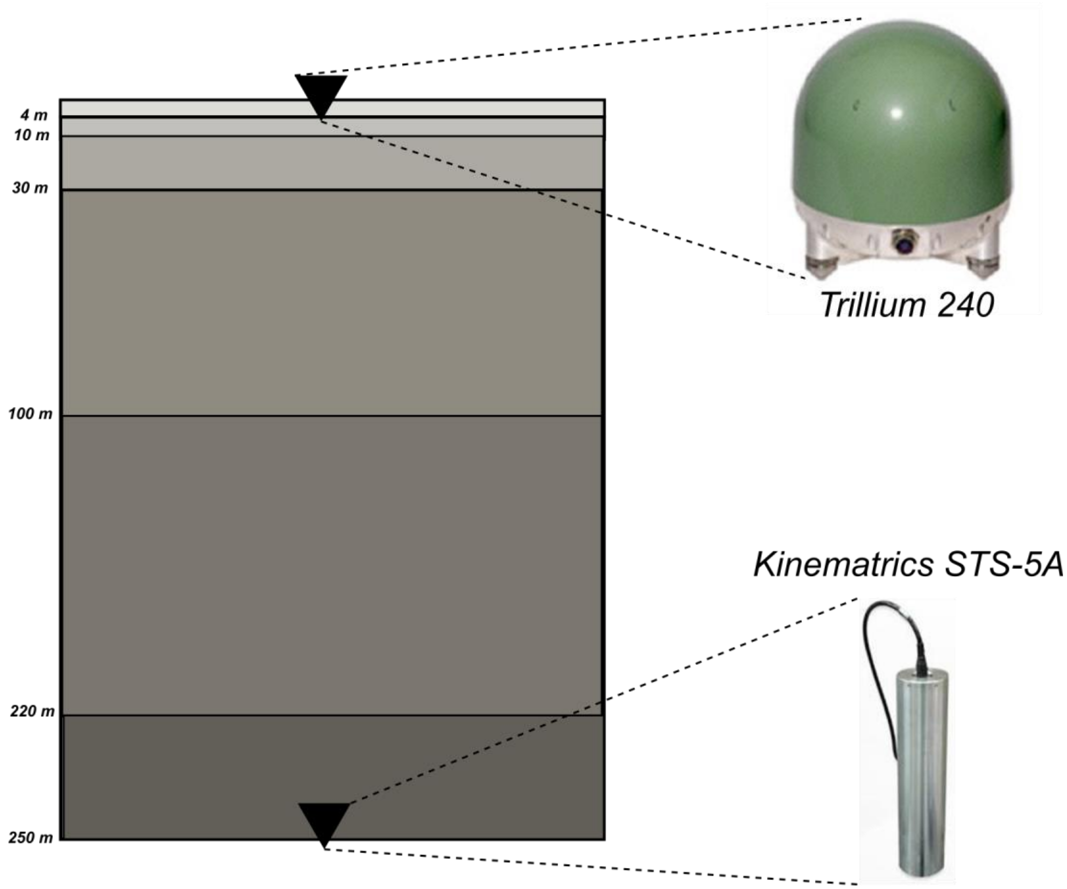
A 260 m deep borehole at Terziet

A Trillium 240A seismometer installed on surface and a STS-5A seismometer installed at 250 m deep.



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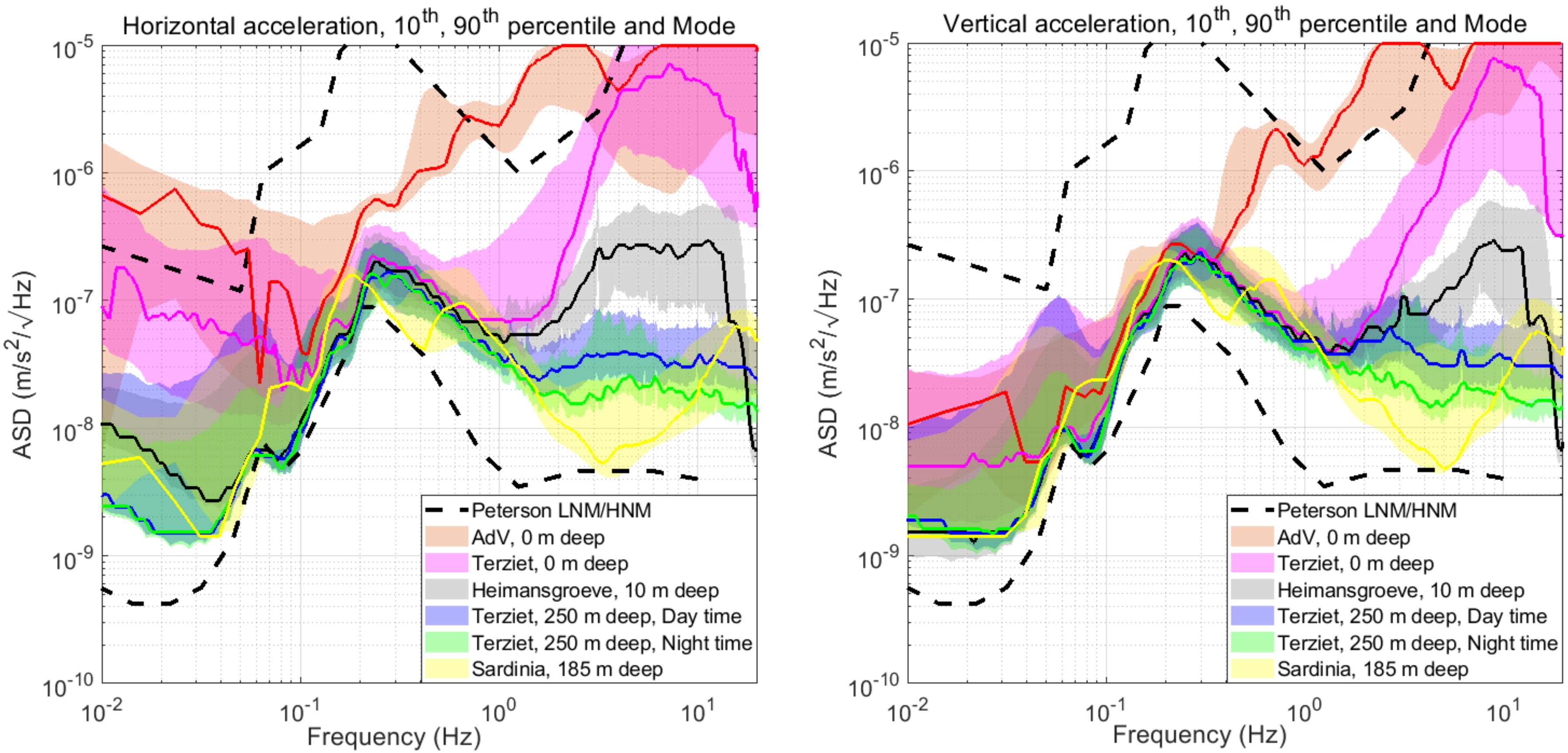
Seismic ground motion at surface and 250 m underground

A comparison of the Amplitude Spectral Density (ASD) of the seismic acceleration is shown in the figure below for the vertical and the horizontal components respectively.

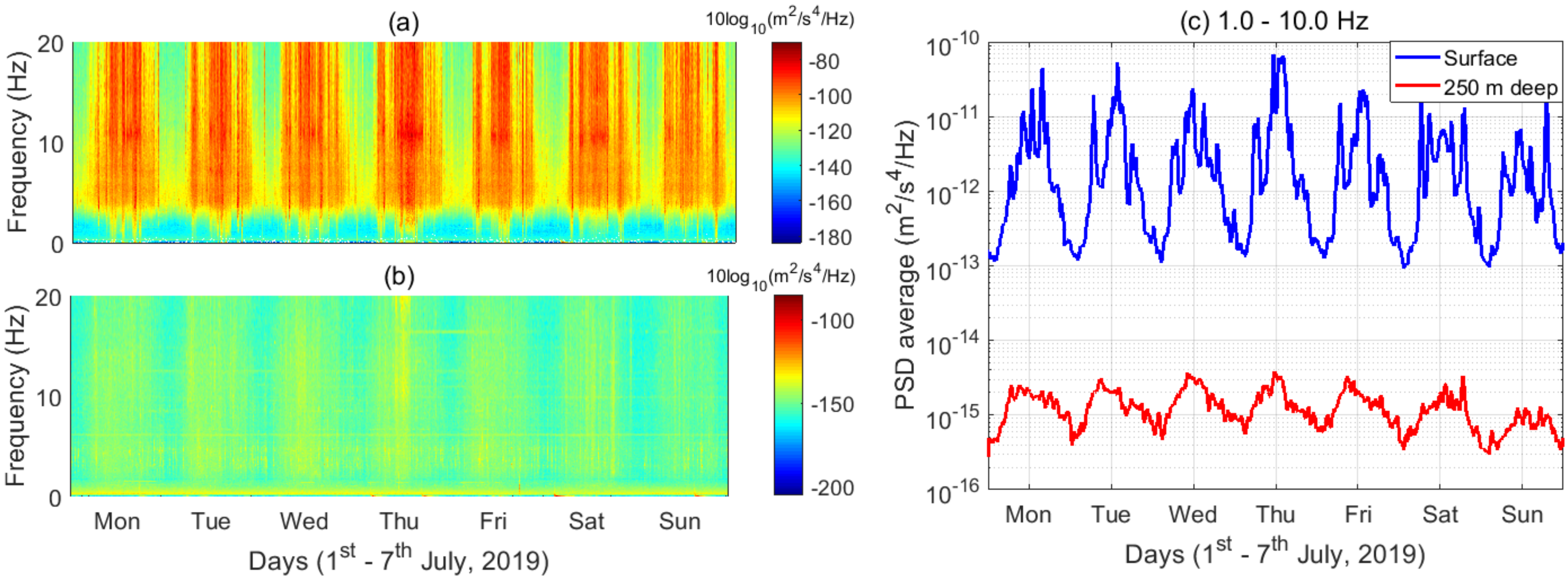


Outputs

- A factor 50-300 reduction in ground acceleration is observed at depths of 250 m in the frequency band 2-20 Hz.

Day-Night variations in seismic ground motion spectra

A reduction in power of the order 10^3 is observed during the day as compared to a factor 50 during night.



Why?

- Surface waves which dominate the day time measurements attenuate much faster at higher frequencies.
- Presence of a body-background during day/night that is only observable when we go deep in the sibusurface.
- Body-wave background is masked on the surface due to anthropogenic noise.

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Inputs to model Newtonian noise

What do we have now and what else do we need for modeling Newtonian noise?

Seismic wavefield modeling inputs

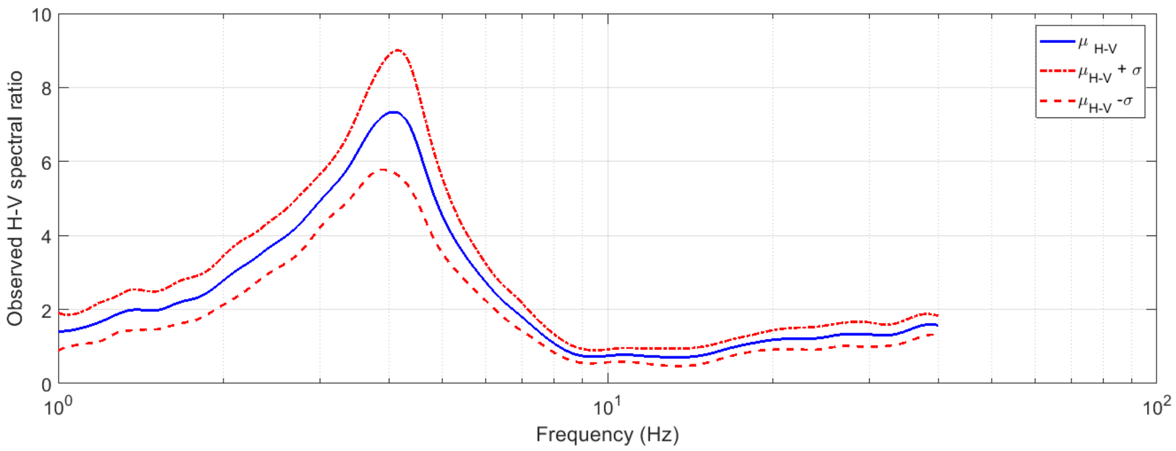
- Subsurface parameters – V_P V_S ρ ✓
- An *elastic-wave* equation solver – *Finite Element* ✓

Newtonian noise modeling inputs

- Subsurface displacement. ✓
- Distribution of noise sources. ✓
- Discretizing the simulation domain efficiently – *Integration radius* ✓

What more ?

- Source mechanism – *Type of body and shear forces acting on the medium (earth surface, underground*
  - *Can be accomplished by scaling observations of H/V ratio of ground motion on surface.*
  - *Body wave background.*



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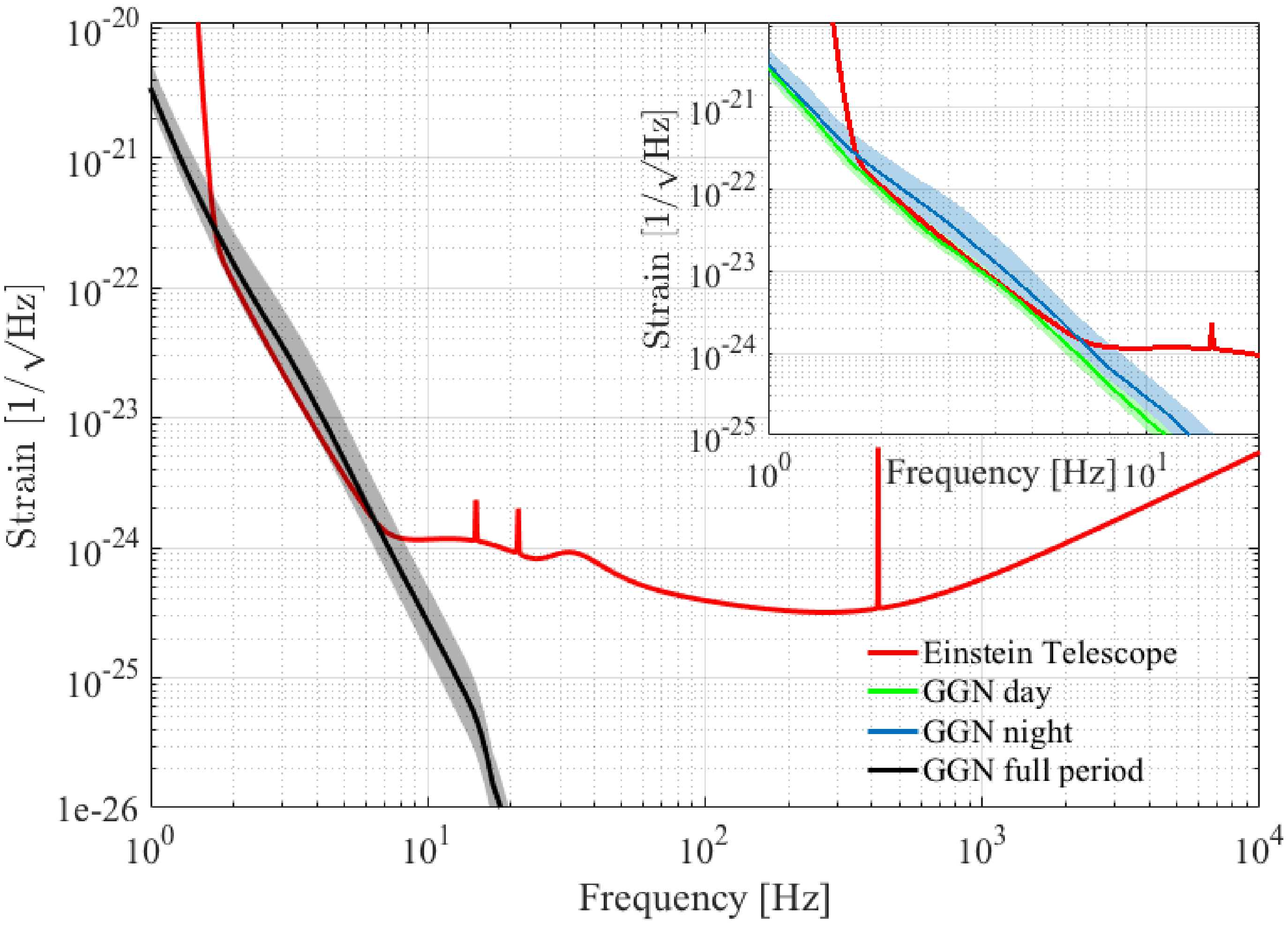
Newtonian noise estimate

Newtonian noise estimates limits the ET design curve in the frequency band 2-7 Hz.



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Questions?