13 September 2019

First results of seismic studies of the Belgian-Dutch-German site for Einstein Telescope

Soumen Koley[1], Maria Bader[1],
Alessandro Bertolini[1], Jo van den Brand[1,2], Henk Jan Bulten[1,3],
Stefan Hild[1,2], Frank Linde[1,4], Bas Swinkels[1], Bjorn Vink[5]

1. Nikhef, National Institute for Subatomic Physics, Amsterdam, The Netherlands
2. Maastricht University, Maastricht, The Netherlands
3. VU University Amsterdam, Amsterdam, The Netherlands
4. University of Amsterdam, Amsterdam, The Netherlands
5. Antea Group, Maastricht, The Netherlands

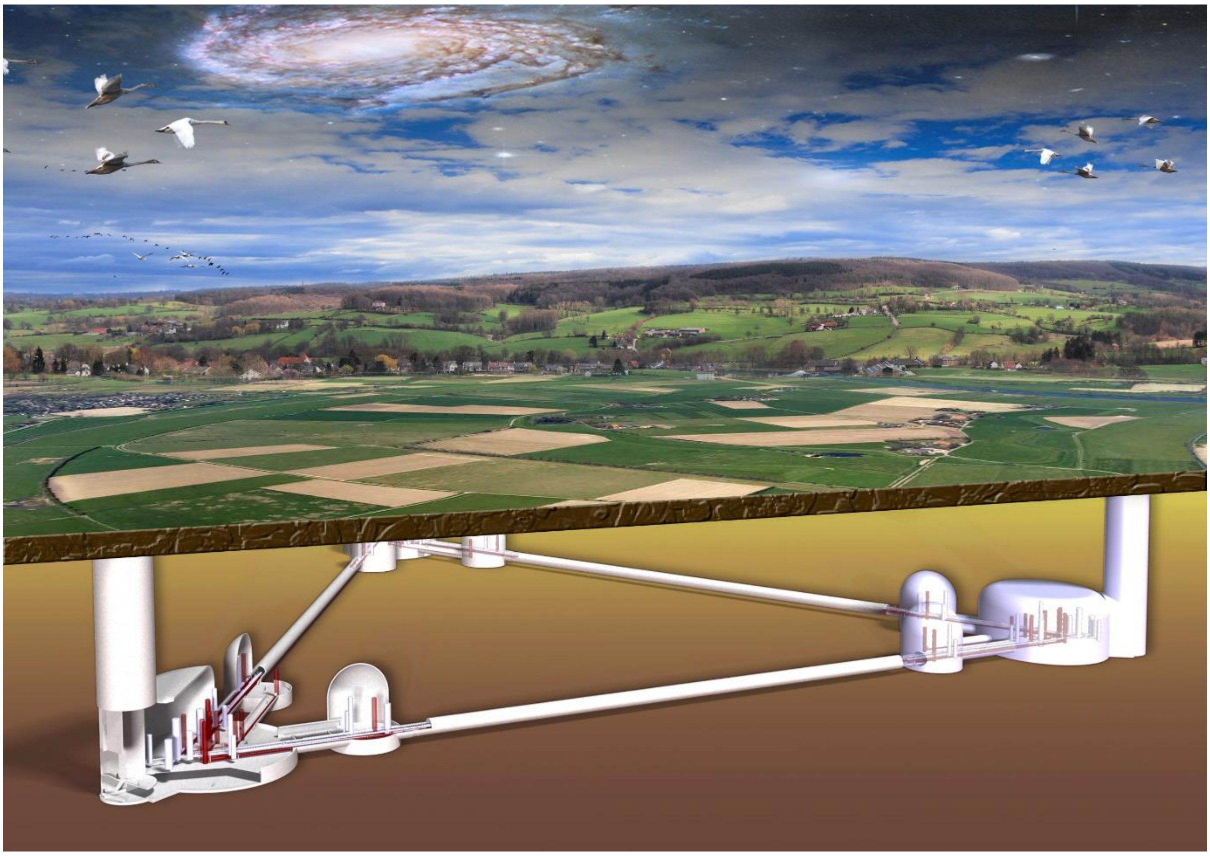

Figure 1: *Artist impression of the Einstein Telescope gravitational wave observatory situated at a depth of 200-300 meters in the Euregio Meuse-Rhine landscape. The triangular topology with 10 kilometers long arms allows for the installation of multiple so-called laser interferometers. Each of which can detect ripples in the fabric of space-time – the unique signature of a gravitational wave – as minute relative movements of the mirrors hanging at the bottom of the red and white towers indicated in the illustration at the corners of the triangle.*

Figure 2: *Drill rig for the 2018-2019 campaign used for the completion of the 260 meters deep borehole near Terziet on the Dutch-Belgian border in South Limburg. Two broadband seismic sensors were installed: one at a depth of 250 meters and one just below the surface. Both sensors are accessible via the KNMI portal: http://rdsa.knmi.nl/dataportal/.*

Executive summary

The European 2011 Conceptual Design Report for Einstein Telescope identified the Euregio Meuse-Rhine and in particular the South Limburg border region as one of the prospective sites for this next generation gravitational wave observatory. Compared to current gravitational wave observatories, Einstein Telescope will have a superior sensitivity all across its 2-10,000 Hz frequency band. In particular at low (2-10 Hz) frequencies anthropogenic (due to human activities) seismic noise risks to limit performance introducing unwanted minute excursions (vibrations) of the mirrors –the key components of Einstein Telescope– in two ways (Figure 3):

- *Indirectly via the mirror suspensions*. These can easily be suppressed by many orders of magnitude through advanced vibration isolation systems integrated in the mirror suspension towers as already proven by the current gravitational wave observatories such as LIGO (USA) and Virgo (Europe);
- *Directly by fluctuations in the gravitational force on the mirrors.* Seismic noise causes mass density fluctuations which induce variations in the gravitational force exerted on the mirrors which as a result start to jitter. This effect is called gravity gradient noise (GGN). The gravitational force cannot be shielded against. To keep GGN acceptable Einstein Telescope must be sited at a seismically quiet location and an active GGN compensation scheme using a network of accelerometers to reconstruct in real time the fluctuating gravitational force on the mirrors is envisaged.

To reduce anthropogenic seismic noise, Einstein Telescope will be realized underground at depths between 200-300 meters. In this respect, the geology in the South Limburg border region is ideal. It is expected to combine hard rock at the depth where Einstein Telescope will be realized facilitating the underground civil engineering with a 'soft' surface layer on top of the hard rock which is expected to strongly attenuate anthropogenic seismic noise.

This study quantifies the geology and seismic noise characteristics in the South Limburg border region based on a number of passive and active seismic campaigns deploying grids of seismic sensors in the region and two deep boreholes drilled in the 2017-2019 period at Terziet near Epen on the Dutch-Belgian border.

Refraction tomography analysis of the data from the seismic campaigns reveals a 30-50 meters thick soft top layer with hard rock underneath (Figure 9). This was subsequently unambiguously confirmed by direct measurements in the first 167 meters deep borehole (Figure 10). **Both approaches show the deepest hard rock layers to have a hardness similar to granite, excellent for underground civil engineering.**

In June 2019 a seismic sensor was installed in a second borehole at a depth of 250 meters. Together with a seismic sensor near the surface, the attenuation of seismic noise going underground was measured to yield about a factor 10,000 in power (100 in amplitude) during the day and a factor 200 during the night (Figure 11). Qualitatively the same results were seen in an active seismic campaign where most injected power was found to be confined to the top 30-50 meters thick soft layer. These findings are in good agreement with earlier simulation results (Figure 5). **Since Einstein Telescope is envisaged for 50 years, the strong attenuation of anthropogenic seismic noise is a key asset of the South Limburg border region since it protects also against possible future new anthropogenic seismic noise sources on the surface. As a by-product of this study it was also shown that local seismic activity –e.g. in the nearby Eifel– will have a negligible effect on the downtime of Einstein Telescope compared to the site-independent downtime due to teleseismic (more than 1000 kilometers away) events.**

Finally, a first one-month snapshot of the seismic noise at depth was measured (with the sensors continuing to take data) to estimate its contribution to the projected sensitivity of Einstein Telescope using two models to estimate the GGN (Figures 13 and 14). **Both models show that a modest (about a factor 2-3) active GGN suppression is needed to reach the envisaged sensitivity for Einstein Telescope, basically due to the higher seismic noise levels during day times as compared to night times. Such an active GGN compensation scheme will be implemented in Virgo in 2020 and tested during the forthcoming observation run of the LIGO-Virgo consortium in 2021.**

The results presented in this note look very promising: they confirm the excellent attenuation of the **soft-soil on top of hard-rock geology** and **low seismic noise at the depth** foreseen to build Einstein Telescope. Nevertheless, these results must be confirmed by measurements at a few other representative locations in South Limburg in the coming 2-3 years. Steps have already been initiated to do so in Belgium (borehole near Voeren on the Dutch-Belgian border) and up to six other boreholes and an optimal siting of Einstein Telescope in the South Limburg border region within the context of the submitted Interreg Euregio Meuse-Rhine ('E-TEST') proposal. By the end of 2022, these studies should culminate into an unambiguous proposal to embed Einstein Telescope in a specific location in the South Limburg border region matching the underground (notably attenuation and presence of good rock for underground civil engineering) and the (seismic) noise requirements as detailed in the Einstein Telescope Technical Design Report to be released early 2020.

1. Introduction

Gravitation is Nature's least understood fundamental force. Gravitational waves –postulated to exist in 1916 by Albert Einstein as minute ripples in the fabric of space-time propagating at the speed of light and first observed a century after in 2015 following the cataclysmic merger of two black holes about 1,4 billion years ago– provide a completely new and exhilarating view upon our Universe. This first observation of gravitational waves led to the 2017 Physics Nobel Prize. Recently, also gravitational waves from neutron star binaries (2017) have been observed.

The future Einstein Telescope observatory (Figure 1) will provide access to at least a thousand times larger volume than what can be reached ultimately with the current observatories. It also will push the detection limit to frequencies as low as 2 Hz. This will increase the recording time of a gravitational wave from the 1 minute record for the 2017 neutron star binary to as much as 24 hours allowing ample time for astronomers to point their telescopes to the region of interest to observe the actual merger. As such Einstein Telescope will allow to probe gravitational waves from directly after the Big Bang until today. This will almost certainly lead to new groundbreaking discoveries and thereby deepen our understanding of the origin and evolution of our Universe. Therefore Einstein Telescope is of great significance for astronomy, cosmology, (particle) physics, and –more generally– theoretical physics with as long-standing enigma: an understanding of the gravitational force in accord with the two pillars of modern physics: relativity and quantum mechanics.

From a technology point of view, the detection of gravitational waves is truly mindboggling: controlling the instrument's heart –the mirrors– to a precision of better than 0.000 000 000 000 000 001 meter. This is equivalent to the rise of the water level in the IJsselmeer due to a single extra small rainwater droplet. At the lowest attainable frequencies i.e. in the 2-10 Hz range, seismic noise plays a dominant role. Firstly, due to seismically induced vibrations (ground motion) that are easily suppressed by many orders of magnitude by the elaborate mirror suspension system (see Figure 3, Left). Secondly, due to fluctuations in the gravitational force –referred to as gravity gradient noise or in short GGN– acting directly on the mirrors due to the movements of masses inherent to not only seismic noise but also for example to atmospheric density fluctuations (see Figure 3, Right). Since the mirrors cannot be shielded against GGN, Einstein Telescope will be realized underground to guarantee reduced seismic noise. Any residual GGN is anticipated to be suppressed by reconstructing in real time the fluctuating gravitational forces using a network of accelerometers positioned in the vicinity of each mirror.

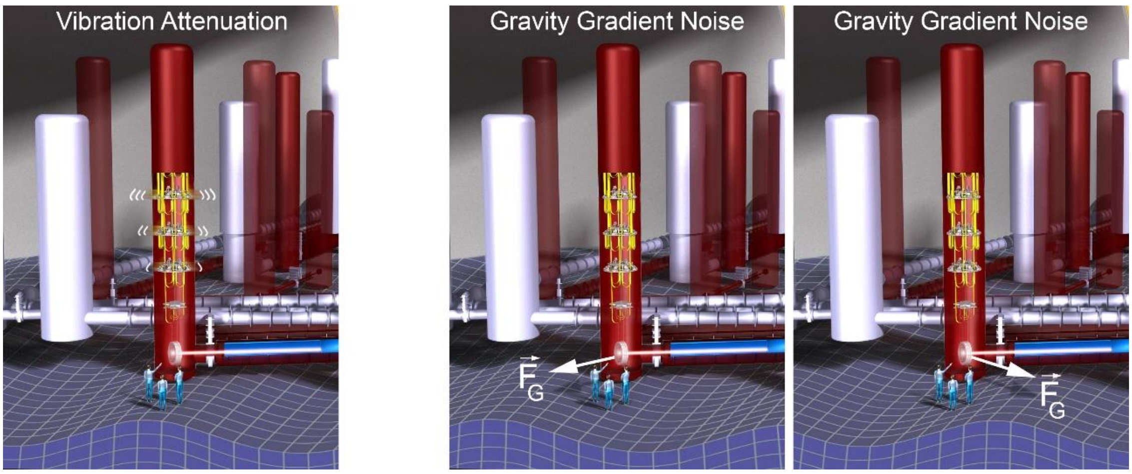

Figure 3: *The undulating blue surface represents the (seismic) vibrations that risk to compromise the performance of Einstein Telescope. To avoid this, each mirror (the shiny disk pointed at by the left person) is suspended from a set of coupled pendula to progressively attenuate (typically by about 2 orders of magnitude per pendulum) the effect of ground vibrations as illustrated in the left figure and as indicated by the '(((', '((' and '(' symbols. Density fluctuations as for example due to seismic noise exert a direct stochastic gravitational force on each mirror as indicated by the white arrows in the two figures on the right, which cannot be shielded against and causes the mirror to jitter around. This noise source is referred to as gravity gradient noise or GGN and turns out to be the dominant noise source for Einstein Telescope at low, 2-10 Hz, frequencies.*

This note addresses the shallow sub-surface geology and the observed seismic noise in the Euregio Meuse-Rhine and in particular in the region Terziet near Epen based on passive and active seismic campaigns. These are then verified by comparing real-time seismic noise measurements of a seismometer installed at 250 meters depth in a 260 meters deep borehole to that of a seismometer mounted just below the surface. The measured seismic noise at depth is used to estimate the resulting GGN for Einstein Telescope without making use of the envisaged additional GGN suppression using real-time active GGN compensation.

2 Euregio Meuse-Rhine: South Limburg

The Belgian-Dutch-German border region, referred to as South Limburg in this note, is a relatively quiet region without heavy industries, windmills, major highways and railroads. While major cities such as Aachen, Liège and Maastricht are still nearby, they are sufficiently far away to avoid disturbances of an observatory such as Einstein Telescope. Apart from farming activities, South Limburg attracts tourists seeking a tranquil outdoor atmosphere and also this interest is aligned with the requirements for Einstein Telescope. This is e.g. well illustrated by the measured power spectrum of the seismic noise (referred to as PSD –power spectral density– in this note) in one of the near-surface stations of KNMI (Heijmansgroeve at ten meters below the surface). Over the course of a year, Figure 4 shows this PSD both in the microseismic band dominated by oceanic activity (0.04-1 Hz, Top) and in the relevant band for Einstein Telescope (1-10 Hz, Bottom). As expected the microseismic band shows higher noise –due to notably the 'nearby' North Sea– in the Winter season as compared to the Summer season whereas the noise in the 1-10 Hz band is fairly constant over the year with possibly a slight excess in the Summer –tourist– season. In both bands the observed noise is significantly less than the measured noise at the EGO –European Gravitational Observatory– site near Pisa where the Virgo laser interferometer started to observe gravitational waves in 2017 (see Figure 12).

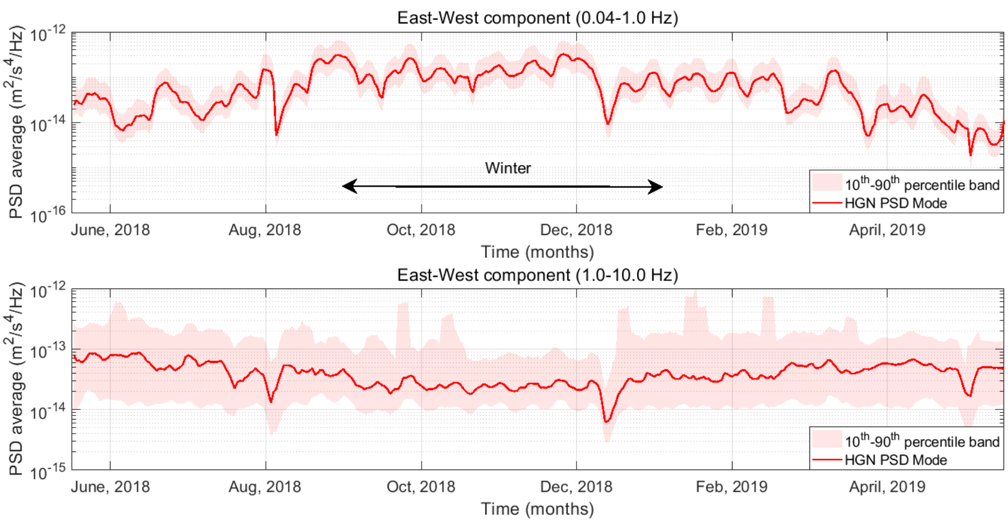

Figure 4: *Averaged power spectrum of the seismic noise (PSD) in the East-West direction (North-South and Up-Down show the same behavior) in the microseismic 0.04-1 Hz band (Top) and in the 1-10 Hz band (Bottom) as extracted from the KNMI sensor in the Heijmansgroeve at 10 meters below the surface just on top of the hard rock. The central lines show the mode (most likely PSD) whereas the shaded bands show the 10^{th}-90^{th} percentiles. In the 0.04-1 Hz band (Top) the higher activity in the Winter is due to the 'nearby' North Sea. In the 1-10 Hz band (Bottom) at best a slightly higher activity in the June-August period can be observed and, if so, is almost certainly due to the tourist season.*

The seismic data from the Heijmansgroeve can also be used to estimate the downtime of an eventual Einstein Telescope realized in the South Limburg region due to seismic activity occurring for example in the nearby Eiffel region. Observatories such as Einstein Telescope are required to be operated in a so-called 'lock mode' (controlled interference pattern of the two laser beams in the cavities in between the main mirrors constituting together the laser interferometer) needed for stable data acquisition. The lock can be lost following a serious earthquake occurring anywhere around the globe. Based on the seismic data from the Heijmansgroeve we estimate a downtime of about 0.8% by counting the number of 'events' causing a lock disruption[1]: typically about 75 events a year of which only 1 from 'nearby' i.e. less than 1000 kilometers away and 10 from 1000-2000 kilometers away. This demonstrates the local seismic activity in notably the Eifel region to have a negligible effect on the downtime of Einstein Telescope if sited in the South Limburg border region.

South Limburg features a unique geology where relatively old hard rock (about 360 million years) is covered by layers of soft soil. This allows the infrastructure to be realized in a cost effective manner in hard rock. Simulations show that the impedance contrast between the soft soil layers on top and the hard rock below effectively shields the sensitive equipment from anthropogenic (human induced) seismic noise generated at the surface as illustrated in Figure 5. Once confirmed (see below) this will be an important characteristic since it not only attenuates the present anthropogenic seismic noise generated at the surface, but it also safeguards Einstein Telescope against possible future unknown anthropogenic noise sources in the region.

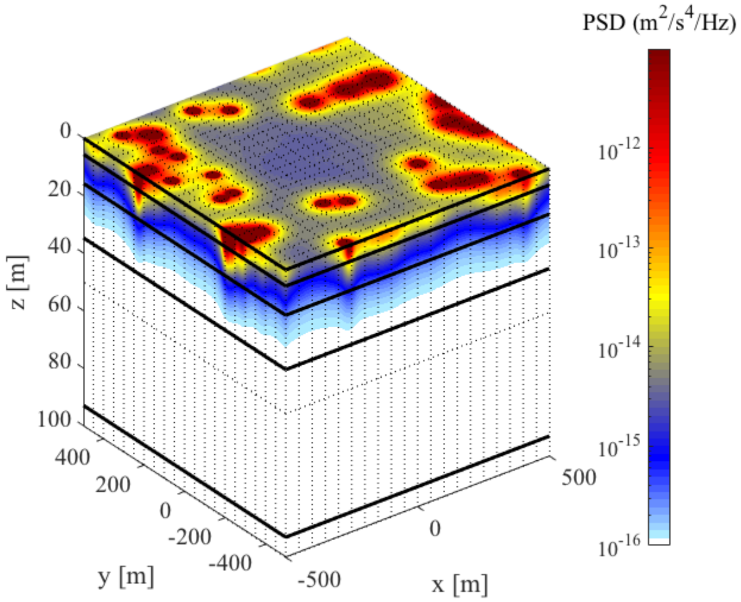

Figure 5: *Simulation of the propagation of the power spectrum at 5 Hz of the seismic noise (PSD) of noise sources (red blobs) located on the surface along a three-dimensional grid. The seismic power is largely confined to the soft soil layers extending down to 40 meters depth in this example. The fraction of the seismic power transmitted into the hard rock material below 40 meters is almost negligible with respect to the seismic power confined to the soft surface layers.*

[1] *A catalog of all earthquakes registered by KNMI and exceeding 0.7 on the Richter scale is used selecting those that would exceed a LIGO (the two gravitational wave observatories in the USA) set limit on the velocity of 5 μm/s for the loss of a lock. From the about 2,000 earthquakes between June 2018 and June 2019, 74 satisfied this criteria. Average time required to recover from a lock loss was estimated to be 1 hour (real numbers are typically 20 minutes for a lock loss due to a minor –scale 4– earthquake and multiple hours for a major –scale 8 or higher– earthquake).*

3 Passive & active seismic campaigns in Terziet

A pre-requisite for the successful realization of a 200-300 meters deep borehole for seismic measurements at depth, is a detailed map of the underground geology. For this several seismic campaigns were undertaken over the period 2017-2018.

- *Passive survey 1*
  This sparse array of 74 (autonomous) seismic sensors deployed as shown in Figure 6 was used to study the anthropogenic seismic noise in the 2.5-8 Hz frequency band. Apart from the overall power spectrum of the seismic noise on the surface, this study was used to identify the distribution of the dominant noise sources (typically roads) as a function of frequency. Moreover, the Rayleigh wave phase velocity dispersion observed from the vertical component surface seismic noise was used to estimate subsurface parameters e.g. P-wave velocity, S-wave velocity and density. Studies confirmed the presence of an abrupt transition from a soft top layer to hard rock at shallow (about 40 meters) depth in the region as evidenced by a drop in the Rayleigh wave phase velocity from 1000 to 250 m/s at a frequency of 4 Hz.

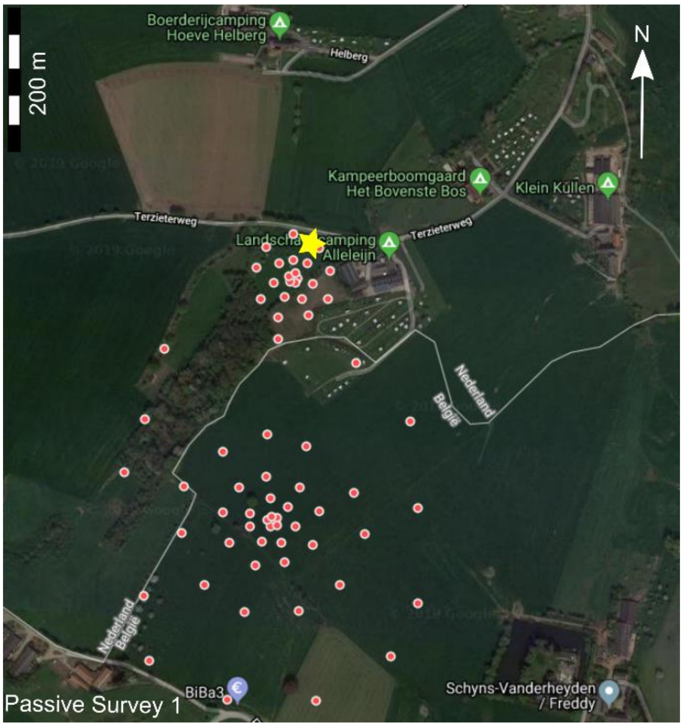

Figure 6: *Layout of the 74 seismic sensors (red dots) for passive survey 1. The yellow star represents the drill site (see Section 4).*

- *Passive survey 2*
  160 seismic sensors were deployed on a dense grid with an almost uniform spatial sampling of 50 m as shown in Figure 7. The objective was to extend the results of *passive study 1*; notably to compute the spatial distribution of the Rayleigh wave phase velocity in the region by analyzing phase travel-times between all possible pairs of seismic sensors. This way the geology could be reconstructed to a maximum depth of about 100 meters due to the limited energy in the passive seismic spectrum, notably at frequencies below 2.5 Hz.

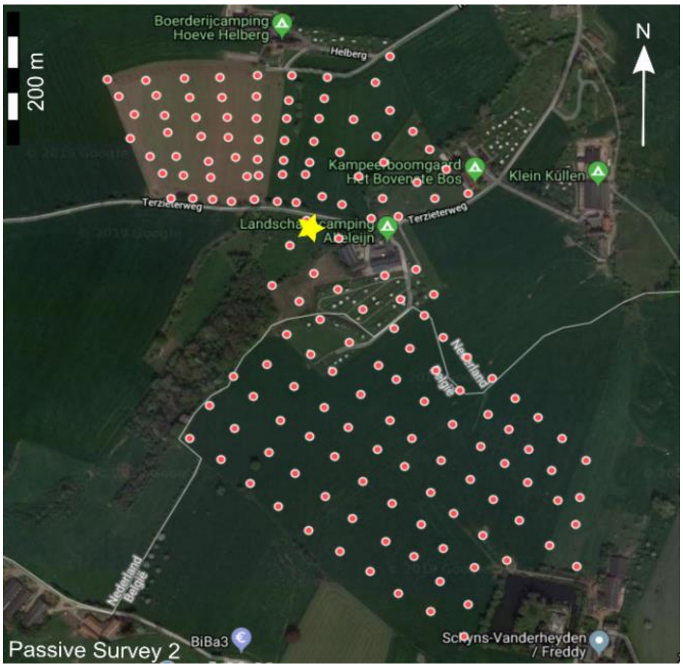

Figure 7: *Layout of the 160 seismic sensors (red dots) for passive survey 2. The yellow star represents the drill site (see Section 4).*

- *Active survey*
  To image the sub-surface at larger depths, an *active seismic survey* was conducted using a mini-vibroseis (see Figure 8) to inject a well-defined (location, time, and amplitude-phase frequency spectrum) excitation (or 'shot') into the ground. The vertical compressional force the vibroseis could exert onto the ground was limited to 1,200 N. Two parallel receiver lines separated by a distance of 40 meters and each with 182 seismic sensors positioned at 3 meters interval were used to record the ground response (see Figure 8). A total of 508 shots were recorded while moving the vibroseis along the two receiver lines with a shot-interval of 6 meters (maximum vibroseis-receiver offset: 1,500 meters).

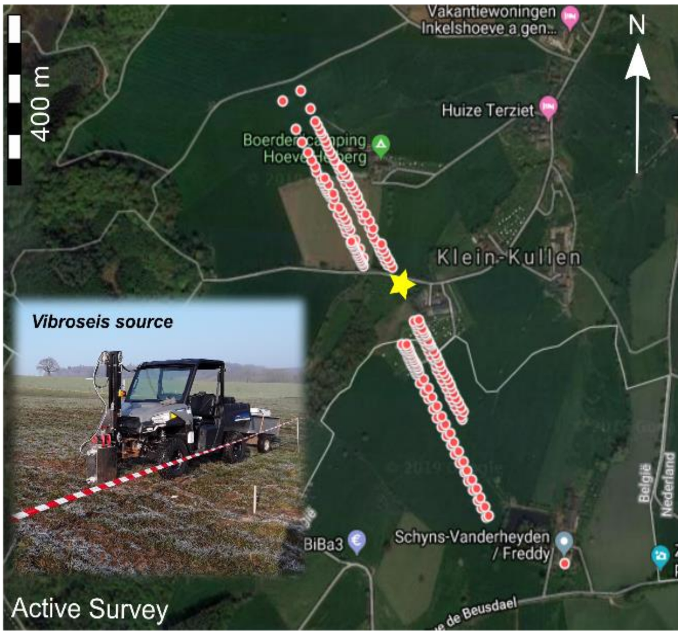

Figure 8: *Layout of the seismic sensor locations (red dots) for the active survey. The yellow star represents the drill site (see Section 4). The insert shows the vibroseis used to excite the ground.*

Data analysis showed the presence of guided waves due to the strong impedance contrast between the soft soil layer on top of the hard rock. Whereas beneficial for Einstein Telescope because this special geology shields against anthropogenic noise, it also complicates imaging the deeper underground geology given the maximum power of the vibroseis. The maximum depth that could be imaged turned out to be about 200 meters. Figure 9 shows the structure of the sub-surface geology (using a P-wave velocity model) as a function of depth as determined from so-called 'Wavepath Eikonal Tomography' using only the direct and the refracted wave travel-times. The Figure also shows as dotted lines the 2017 and 2019 boreholes for which the results are presented in the next Section.

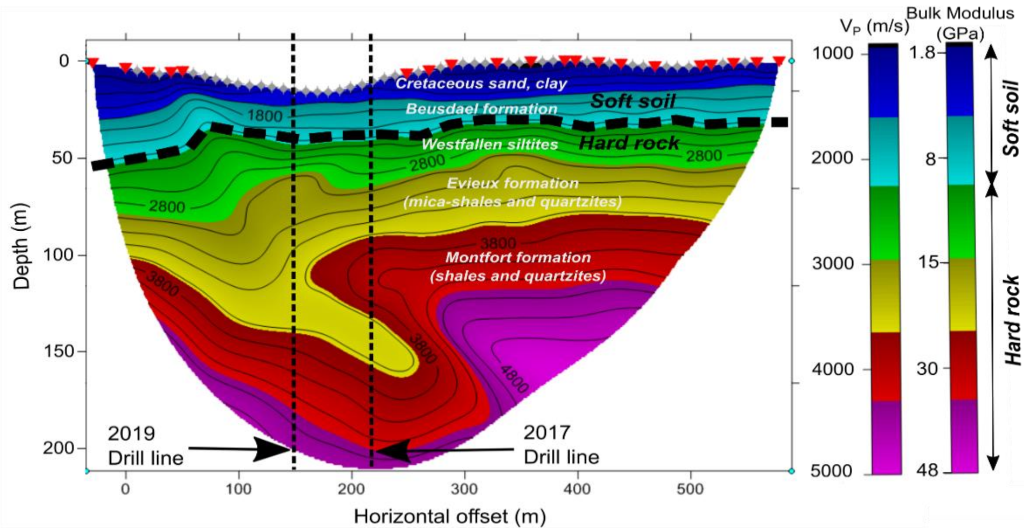

Figure 9: *Seismic array studies allow an accurate description of the sub-surface as illustrated in this Figure. The higher the velocity the harder the rock (right scales). The geology is layered and features soft soil (sands and clays) on top of hard rock as indicated in on the right. In this analysis the boundary between soft soil and hard rock –using the reconstructed velocities– seems more gradual than indicated in the Figure which is inherent to the analysis method. Direct in-situ velocity measurements in the 2017 borehole (Figure 11) show a very discrete step around 40 meters depth. Also the locations of the boreholes that were realized to a depth of 167 m (2017) and 260 m (2019, with a seismometer installed at 250 meters depth) are shown.*

4 Borehole measurements

Confirmation of the expected favorable seismic conditions as shown by the simulations (notably Figure 5) of the South Limburg underground requires in situ measurements of the correlation between an on-surface and a 200-300 meters deep installed seismometer.

A first drilling campaign was started in Terziet on the Dutch-Belgian border (see Figures 6-8) in March 2017. Regretfully the drill broke at 167 meters depth and could not be retrieved which prevented the installation of a seismometer at depth. Nevertheless, a detailed characterization of the sub-surface geology was performed lowering several diagnostic devices to the still accessible depth of 147 meters. These measurements confirm the soft top layer on top of hard rock topology as presented in Section 3 (Figure 9). Details of these bore-hole measurements are shown in Figure 10. Most important is the one but right most panel showing the abrupt velocity change at a depth of 40 meters due to the soft layer–hard rock interface already introduced in Section 3.

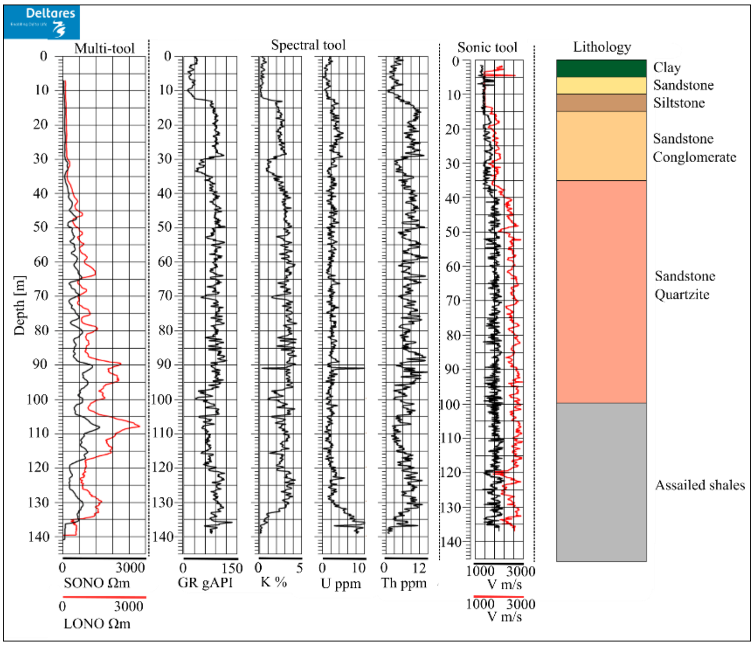

Figure 10: *Standard borehole logging techniques were applied, like resistivity logging (SONO, LONO), which gives information about rock porosity, Gamma ray (GR) logging, which determines the content of potassium (K), uranium (U) and thorium (Th) in the rock, and sonic logging which measures wave speeds in the rock material. High porosity, low wave speeds, and a high gamma ray content up to 35 meters depth indicate a conglomerate of soft material such as clay, sand- and siltstone. The drastic increase of wave speeds below 40 meters depth, the decreasing porosity and changes in the GR spectrum indicate hard rock material such as quartzite, dense sandstone and shales.*

A second drilling campaign (see Figure 2 for the drilling rig) was completed in April 2019 reaching a depth of 260 meters and after (water) sealing of the borehole a seismometer was successfully installed at 250 meters depth together with a seismometer just below the surface. The readout frequency for both seismometers was fixed at 200 Hz and both sensors are now included in the KNMI seismic network which allows to access the data via the KNMI public portal (http://rdsa.knmi.nl/dataportal/).

Figure 11(a) shows the observed attenuation of the seismic noise (vertical acceleration) measured on the surface and at 250 meters depth inside the borehole over a one week period. The large day-night differences –about a factor 200– in the noise spectrum at the surface averaged over the 1-10 Hz region (blue line in Figure 11a) indicates that most of the noise is generated by local traffic and farming activities in the region. At 250 meters depth (red line in Figure 11a), the same day-night ratio is only a factor 3-4 due to the strong attenuation of the noise contribution of surface waves while going underground. The remaining noise at 250 meters depth is mainly due to the body wave background in the region, with some contribution from long

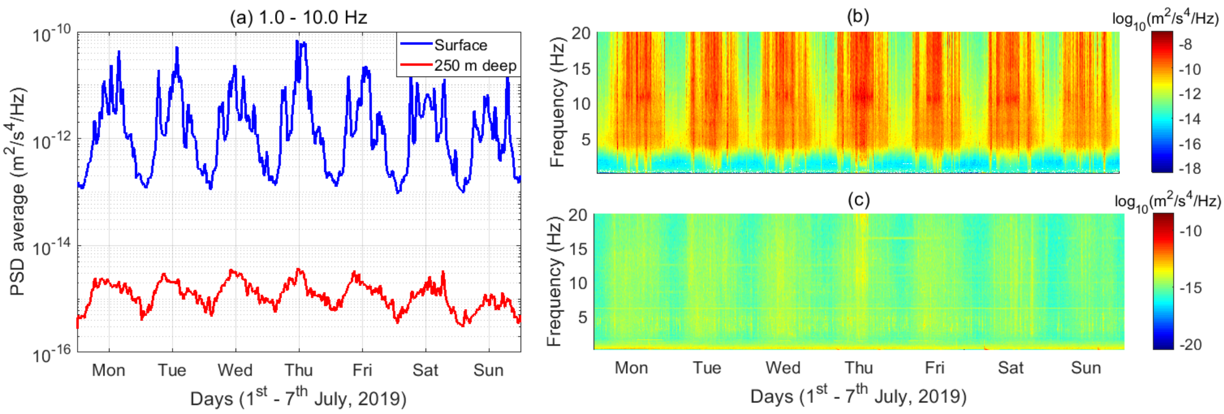

***Figure 11:** .(a) Power spectral density of the vertical seismic noise measured on the surface (blue solid line) and in the borehole (red solid line) averaged for the 1-10 Hz frequency band during a 7-day period. One clearly sees a pattern where activity starts around 7 am and stops around 9 pm. This is typical for anthropogenic seismic noise. The power of the seismic noise is 200 (night) to 10,000 (day) times lower underground as compared to on the surface. The diurnal pattern underground is reduced significantly compared to the same pattern observed on the surface. (b) Vertical seismic noise spectrogram measured on the surface and (c) at 250 meters depth.*

wavelength surface waves in the frequency band 1 to 3 Hz. Figure 11 confirms the anticipated overall strong attenuation of seismic noise going underground by a factor about 10,000 and 200 for day- and night times, respectively. Figures 11b and 11c show the spectral decomposition of the seismic noise in the 1-20 Hz band over the same 7-day period.

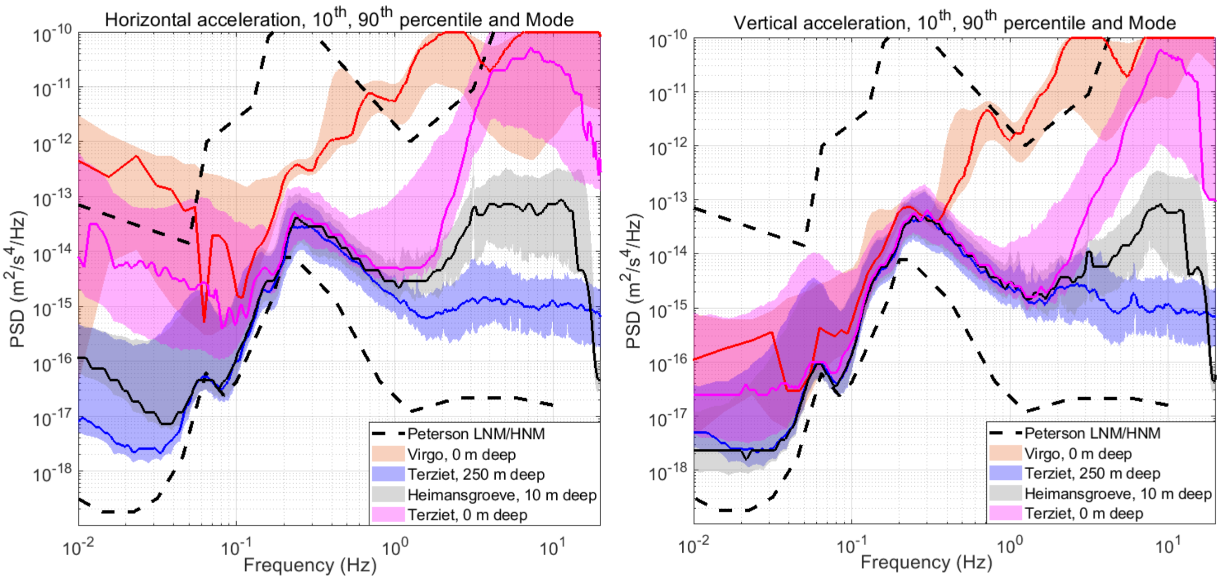

***Figure 12:** Left: The power spectrum of the horizontal seismic noise measured by the borehole seismometer (250 meters depth) between June 21-July 21, 2019 in blue (the mode as the solid line and the 10th-90th percentiles as the band) compared to the same data measured with the surface seismometer in purple. For comparison –albeit for a different time period– the plot also shows the same data for the EGO site (location of the Virgo observatory) in orange, and the data as measured at the Heijmansgroeve –same June 21-July 21 period– in grey. Right: Same as the Left panel, but now for the measured vertical acceleration. In both graphs the dashed black lines show the Peterson's low noise and high noise (LNM/HNM) models.*

In Figure 12 the power spectrum of the observed seismic noise (PSD) measured at 250 meters depth –corresponding to the anticipated depth for Einstein Telescope– is shown. The data cover the first month of operation: June 21–July 21, 2019. The left panel in Figure 12 addresses the horizontal seismic noise in the 0.01–20 Hz frequency region. The mode, the most likely observed value, is shown as the solid blue line. The blue band shows the region covered by the 10th to 90th percentiles i.e. at each frequency 10% of the time the measured PSD falls below the blue band or above the blue band, respectively. In the 0.05-0.1 Hz frequency band, the primary microseismic energy is close to the Peterson's low noise model (LNM) shown as the dashed line indicating the site to be one of the quietest on Earth. Even though Figure 12 is based on measurements in the microseismic quiet Summer season, Figure 4 (top) shows that also in the Winter season this location is relatively quiet. However, there are some outliers observed for less than 5% of the observation time in the microseismic band indicating a higher seismic noise level. A part of this noise is due to several teleseismic (more than 1000 kilometers away) and regional earthquakes that are recorded by the seismometers during the one month recording time. In the region where the projected sensitivity of Einstein Telescope (Section 5) will be limited by seismic noise i.e. the 1-10 Hz region, the measured seismic noise power falls more than a factor 10,000 below what is measured at the EGO site (orange solid line and band for the mode and 10^{th}-90^{th} percentiles region, respectively) where the Virgo observatory is located. For reference and for the same June 21–July 21 period, also the seismic noise power measured at the Heijmansgroeve is shown (grey solid line and band) and measured by the seismometer near the surface (purple solid line and band). The excellent agreement in the microseismic (0.04-1 Hz) band of the three bands measured at Terziet (purple-grey-blue) confirms that these three (different type) sensors are correctly calibrated. The reduced seismic noise measured at larger depths also demonstrates the benefits of building the Einstein Telescope underground. The right panel shows the same distributions, but now for the vertical direction which show the same characteristics i.e. very low noise in 0.05-1 Hz frequency band and low noise in the relevant region, 1-10 Hz, for Einstein Telescope.

5 Impact on the sensitivity of Einstein Telescope

Einstein Telescope will be sensitive in the frequency band from about 2 to 10,000 Hz. The performance of all terrestrial interferometric gravitational wave detectors at frequencies below about 10 Hz is limited by seismic noise. As already mentioned in the introduction (Section 1) seismic noise affects Einstein Telescope adversely in it two ways:

1. *Indirectly via the suspensions of the mirrors* which is efficiently suppressed by many orders of magnitude through advanced vibration isolation systems integrated in the mirror suspension towers (see left part in Figure 3) as demonstrated in Virgo (Europe) and LIGO (USA);
2. *Directly by gravitational attraction* as a result of seismically induced mass density fluctuations as shown in the right part of Figure 3. This effect is called gravity gradient noise (GGN). Since the gravitational force cannot be shielded against but, as mentioned in Section 1, its adverse effects are envisaged to be remedied using a network of accelerometers to reconstruct (and compensate) in real time the fluctuating gravitational force on the mirrors.

In the following only the GGN will be considered, assuming adequate seismic attenuation for the mirror suspensions and assuming that 'trivial' noise sources generated by e.g. local equipment (e.g. pumps, air conditioning) will be properly mitigated. Furthermore, the effects of GGN from atmospheric pressure variations and other displacements of masses on the surface (trees, trucks, etc.) –important for surface detectors– can safely be neglected for an underground observatory.

The projected sensitivity of the Einstein Telescope as published in the 2011 Conceptual Design Report, used a simple analytic expression –known as the Saulson model[2]– to convert a power spectral density of the seismic noise to GGN. The seismic noise as measured in the Black Forest in Germany (a seismically quiet region) was used for this estimate. It still limits –as expected– the sensitivity up to 10 Hz; above 10 Hz quantum noise is the dominant contribution. The projected sensitivity over the full 2-10,000 Hz bandwidth is shown in Figure 13 as the red curve. The red

[2] *The Saulson model is an approximation e.g.: it applies to surface detectors since it only accounts for seismic noise in a half-sphere (below the mirrors) as opposed to a full sphere for an underground detector; it assumes uniform rock density; and it excludes a wavelength dependent (1/4 wavelength) cut-off volume around the mirrors which is for long wavelengths much larger than the actual cavern size. Nevertheless, as a comparison of the expected GGN between different sites –as effectively done in this note– the Saulson model is very useful, despite its limitations.*

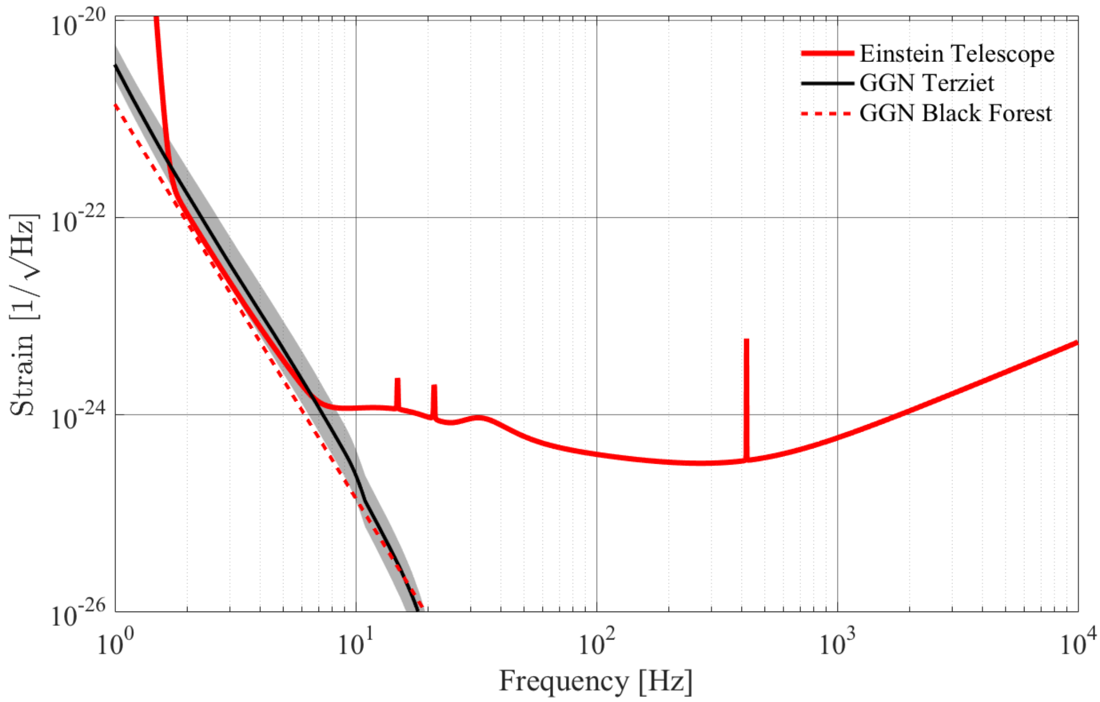

Figure 13: *The projected sensitivity curve for Einstein Telescope as solid red curve over the 1 to 10,000 Hz frequency band. The red dashed line indicates the GGN as determined using the Saulson model and the measured seismic noise at the Black Forest at the time the Einstein Telescope Conceptual Design Report was written (2011). The black solid line (mode) and grey band (10th-90th percentiles) show the expected horizontal GGN (without active GGN compensation) using again the Saulson model and the seismic noise measured at Terziet at 250 meters depth.*

dashed curve gives the GGN calculated using the Saulson model from the measured seismic noise in the Black Forest. In this same Figure, the black solid line (mode) and grey band (10th-90th percentiles) gives the GGN extracted from the power spectral density of the seismic noise measured at Terziet at 250 meters depth using the same Saulson model (using an appropriate rock density). Compared to the projected Einstein Telescope sensitivity a modest –factor two– active GGN compensation scheme will be needed.

More detailed estimates of the GGN require a complete model of the geology and the seismic field in the 'vicinity' of the crucial elements of Einstein Telescope (the mirrors) ranging from 200 meters for the high end (20 Hz) to 2000 meters for the low end (2 Hz) of the relevant frequency band, respectively. For this an advanced simulation tool was set up using a layered geology with characteristics as reported in Sections 3 (Figure 9) and 4 (Figure 10) and the dominant anthropogenic noise source locations mentioned in Section 3 to iteratively reproduce the power spectra of the seismic noise measured by the near surface and the borehole seismic sensors to yield the complete seismic field. Subsequently, this field is used to estimate the resulting GGN for Einstein Telescope. The analysis addresses the GGN in the horizontal plane since that is the plane crucial for the observation of gravitational waves. Figure 14 shows the result, again together with the projected sensitivity curve for Einstein Telescope across the 1 to 10,000 Hz region as the solid red line from the European Einstein Telescope Conceptual Design Report published in 2011. The black solid line shows the best (most likely i.e. the mode) prediction for the GGN whereas the grey band shows the combined estimated uncertainty herein due to modelling inputs and the 10th-90th percentiles.

From these results it can be concluded that the simple Saulson model and the advanced simulation tool predict very similar GGN levels. Based on the advanced simulation tool a modest –factor three– active GGN compensation scheme will be needed to achieve the projected Einstein Telescope sensitivity.

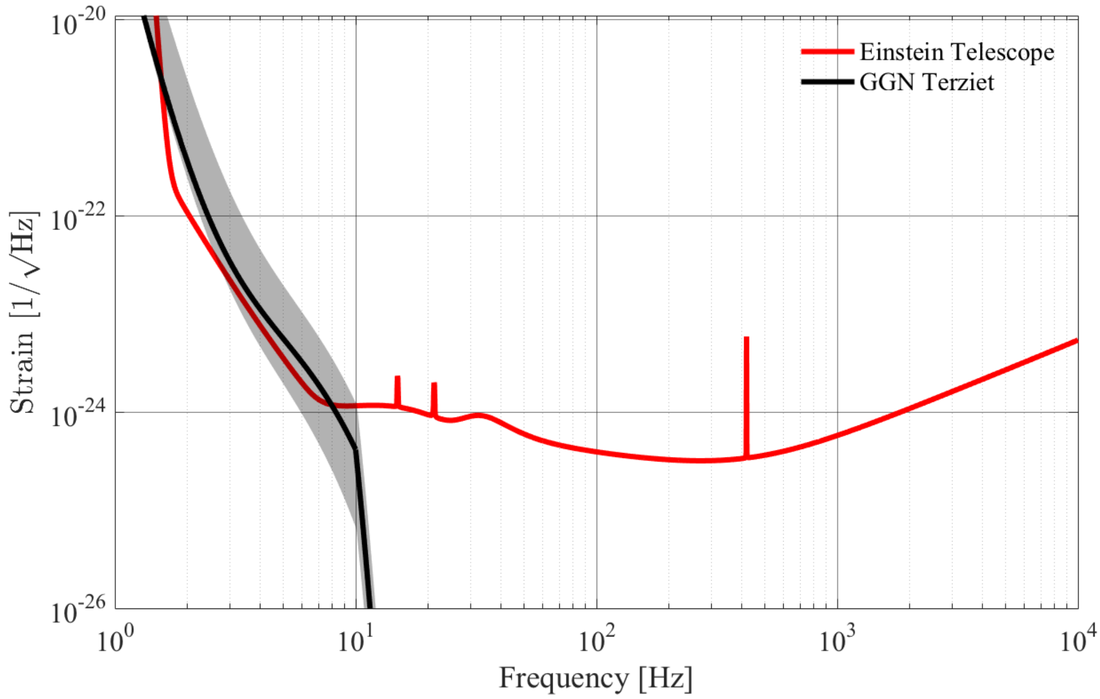

Figure 14: *The projected sensitivity curve for Einstein Telescope as solid red curve over the 1 to 10,000 Hz frequency band. The black solid line (mode) and grey band (10th-90th percentiles as well as some model uncertainties) show the expected horizontal GGN (without active GGN compensation) at 250 meters depth from a seismic model with full solution of the wave equation using the measured seismic noise measured at Terziet on surface and at 250 meters depth.*

Outlook

This note covers the first month of data taking with a seismic sensor installed at 250 meters depth in a borehole at Terziet near the Dutch-Belgian border. It will be important to collect data for at least a full year to measure seasonal variations. It will be very desirable to measure at other locations in the region. Options include a drill site near Voeren in Belgium and the chance to realize six additional boreholes in the region within the context of an Interreg Euregio Meuse-Rhine proposal submitted by the University of Liège (funding decision in October 2019). With long time (at least a full year) measurements at multiple locations it will become possible to identify the optimal site for Einstein Telescope in the region: one of the two goals of the mentioned Interreg Euregio Meuse-Rhine proposal. A complementary study was recently initiated to address the civil engineering aspects –layout, rock (in)stability, water in-flow, costs, etc.– of an Einstein Telescope in the South Limburg border region with a first analysis expected in September 2019.

In parallel active GGN compensation will be vigorously pursued. Nikhef recently ordered 140 accelerometers to be installed at the Virgo site in 2020 for active GGN compensation during the next observation run ('O4') of the LIGO-Virgo consortium scheduled to start in 2021. Once demonstrated to perform as anticipated –up to a factor ten GGN reduction– and assuming the measurements at Terziet to be representative for the South Limburg region, Einstein Telescope can be realized in the South Limburg border region with the projected sensitivity in the frequency band where GGN limits the sensitivity.