Impact of seismic noise on Einstein Telescope

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Introduction

Ground vibrations (seismic noise) affect the astrophysical horizon (the maximum distance of observable gravitational wave sources) of Einstein Telescope in two ways:

- indirectly via the mirror suspension mechanics. This contribution can be efficiently handled by the state-of-the-art vibration isolation systems that link the mirrors of the detector to the external environment, as already proven in the existing LIGO and Virgo observatories.
- Directly by fluctuations in the gravitational force acting on the mirrors. Seismic noise causes mass density fluctuations which induce changes in the gravitational force felt by the mirrors which as a result start to jitter. This effect is known as Newtonian noise (NN). The gravitational force cannot be shielded against. For this reason, to keep NN level acceptable, Einstein Telescope must be sited at a seismically quiet location and an active NN compensation scheme using a network of accelerometers to reconstruct in real time the fluctuating gravitational force on the mirrors is envisaged. In this respect, recent studies have shown that NN compensation of at least a factor of 3 are achievable thanks to Machine Learning techniques.

Major scientific breakthroughs from the Einstein Telescope are expected thanks to its unprecedented sensitivity in the low frequency band starting from 2 Hz. In order to not endanger the reach of the telescope, it is of paramount importance to minimize the vibration input from the environment especially in the 2-10 Hz frequency region, where anthropogenic (generated by human activities) seismic noise may be overwhelming. For this reason, the Einstein Telescope must be realized underground at depths between 200-300 meters. The geology of the EMR region has been shown to be an ideal location for Einstein Telescope since it combines hard rock at depth, which will facilitate underground civil engineering, with a soft soil surface layer on top of the hard rock, which strongly attenuates anthropogenic seismic noise. Large vibration attenuation factors from surface to depth have been measured at the borehole site in Terziet (see figure 1), where the seismic noise level at 250-m depth was found to be compatible with the Einstein Telescope realization [1].

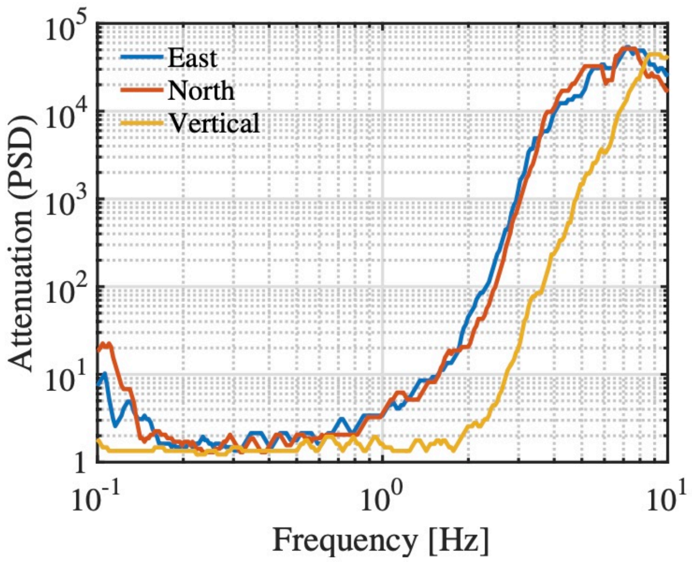

Figure 1: Surface-to-underground seismic noise power attenuation measured at the Terziet borehole site as a function of frequency [plot reproduced from [1]). Between 1-10 Hz horizontal (East and North) vibrations (the most dangerous for the observatory) are attenuated more strongly than the vertical ones, which is expected from Rayleigh waves generated by human activities on surface.

Vibration isolation and Newtonian Noise

Engineering design of vibration isolation systems for the mirrors of the Einstein Telescope is at an advanced stage. In particular, within the E-TEST consortium, a novel concept, in which broadband active vibration suppression exploiting ultralow noise seismometers is combined with passive attenuation from low natural frequency mechanical oscillators, is been explored and will soon be prototyped. The block scheme of such an isolator is shown in Figure 2. Simulations, assuming the Terziet noise level as the input, have shown that the Einstein Telescope requirements can be met over the whole sensitive frequency band of the detector, with a safety factor more than 10 at 2 Hz, which becomes 500 at 3 Hz (see Figure 3 – left panel).

Although the performance expected from the vibration isolation systems seems to suggest that a significantly increase in the seismic noise level can be tolerated, Newtonian Noise studies indicate that this is not the case. The plot in Figure 3-right panel shows the estimated NN level in the EMR region compared to the Einstein Telescope requirements as a function of the frequency.

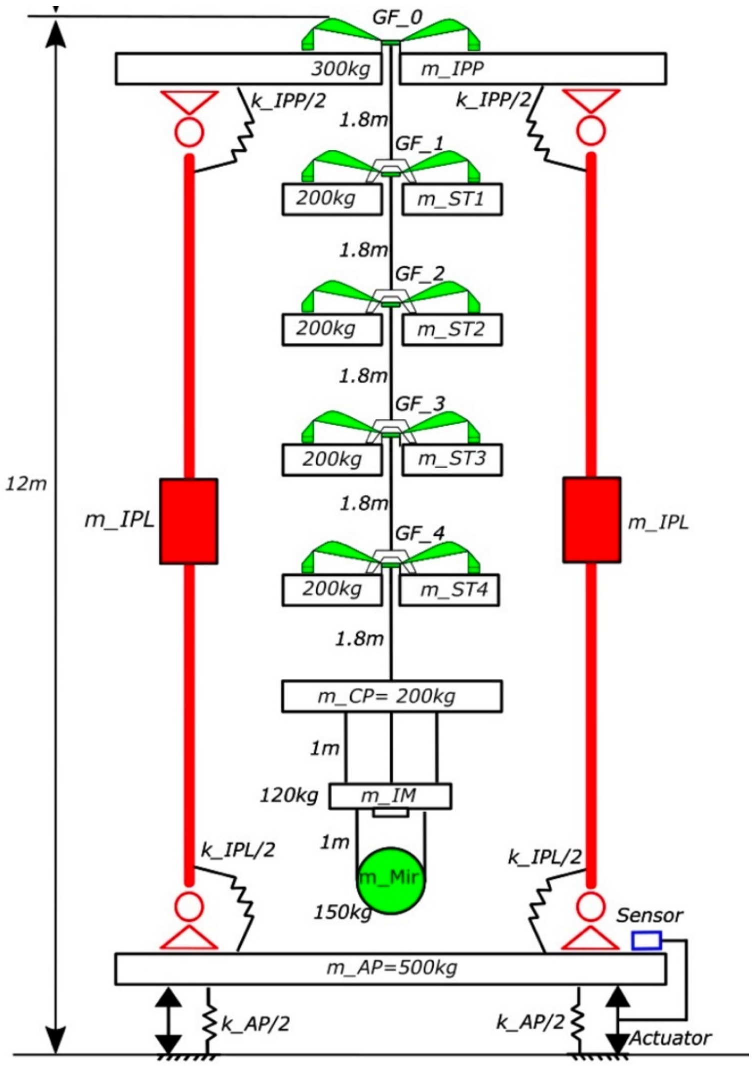

Figure 2: Conceptual scheme of the prototype vibration isolation system for the ET mirrors being developed within the E-TEST consortium. The mirror (m_Mir in green) is shielded from ground vibrations by means of a cascaded multistage pendulum system providing the bulk noise reduction above 5 Hz. ET requirements are met from 2 Hz onwards thanks to the pre-isolator combining an active isolation platform (m_AP) connected to ground and supporting a long inverted pendulum (m_IPP) passive attenuation stage.

The model, based on the Terziet geology and currently observed seismic noise level, shows that only a modest active NN suppression is needed for the site to offer suitable conditions to host the telescope (no active NN cancellation is assumed in the plot in Figure 3). However, it is straightforward how a worsening of the environmental vibration levels around any of the Corner Points of the detector could affect the current scenario.

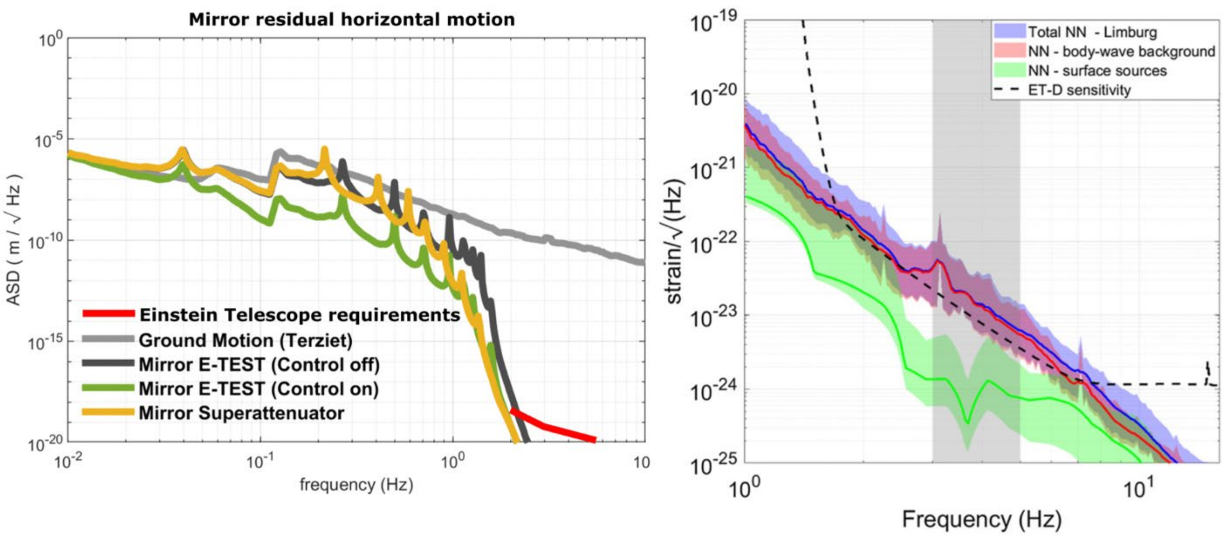

Figure 3: *Right Panel. Estimated residual mirror motion due to the indirect effect of seismic noise. The performance of the E-TEST solution is compared with the one originally envisaged in the Einstein Telescope design study from 2010 that required 50% taller suspension structures. The ET requirements (red line) can be met with a large safety factor when one assumes the measured Terziet noise level as the input. Left Panel. Newtonian Noise level calculated for the EMR region based on the data from the borehole site in Terziet and on the knowledge of the local geology. The shaded violet area takes into account temporal variations of the seismic noise amplitude within its 90th percentile. The shaded grey area indicates that the shown estimated NN between 3-5 Hz should be taken as an upper limit. The plot is reproduced from [2].*

Alongside the expected further progress in NN active reduction methods, the mitigation of this risk goes through a careful selection of the location of the Corner Points of the telescope in quiet areas without noise sources in the surroundings.

Furthermore, the potential impact of any proposed new civil infrastructure in the area on the seismic noise level will have to be assessed in advance with dedicated scientific studies.

In this regard, besides heavy industries, highways, railways and densely populated urban neighborhoods, wind turbines are major cause of concern since they are known to be powerful generators of ground vibrations, at frequencies between 1 and 10 Hz, that are easily measurable tens of km away from the source.

For this reason, a preliminary study has been carried out within the E-TEST consortium [3] that led to the definition, around the candidate sites to host the Einstein Telescope Corner Stations, of Safe Buffer areas within which the installation of new wind turbines is strongly undesirable.

References

[1] Maria Bader, "Seismic and Newtonian Noise modeling for Advanced Virgo and Einstein Telescope", PhD Thesis, VU Amsterdam (2021).

[2] M.Bader, S.Koley, J. van den Brand, X.Campman, H.J.Bulten, F.Linde, B.Vink, ''Newtonian noise characterization at Terziet in Limburg – the Euregio Meuse-Rhine candidate site for Einstein Telescope", Class.Quant.Grav. 39 (2022) 2, 025009.

[3] S.Shani-Kadmiel, "Safe buffers around Einstein Telescope Corner Points with regards to wind turbines", E-TEST internal report, January 14th (2022).

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