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Environmental noises in current and future gravitational–wave detectors

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Abstract. Gravitational–wave (GW) detectors are very sensitive instruments that suffer from a huge number of noises. If we aim to observe gravitational waves with earthbound detectors, we need to take care of every source that can prevent the observation. Seismic noise poses a huge challenge to the sensitivity in the the low–frequency band and it is tackled with suspensions and active controls. The low–frequency band can also be threatened by the so–called Newtonian noise, generated by the fluctuations of the gravity field. If this has not been a problem in the first generation gravitational-wave detectors, it will be so in the next runs and especially in the third–generation detectors, like the Einstein Telescope. We need then to be prepared to suppress as much as possible these noises, otherwise they might become the last wall for the sensitivity of our detectors. This manuscript will explore environmental noises with a particular detail on Newtonian and seismic noise and the techniques that we can employ to reduce their effects.

1. Introduction

Future gravitational–wave detectors will enhance their sensitivity which, in the low–frequency band ($< 10 - 20$ Hz), is dominated by the thermal, quantum, seismic and Newtonian noises. However, improving the sensitivity of earthbound detectors in this frequency region is more challenging due to two Earth–related environmental noise sources: the seismic and the Newtonian noise (NN) [1]. Seismic noise couples with the test masses passing through its suspensions. These are constituted by a chain of pendulums that are natural low–pass filters and can suppress all the seismic vibrations at frequencies greater than their frequency of resonance [2].

NN is instead generated by induced gravity fluctuations which bypass everything and couple directly to the test masses. It can be distinguished into seismic and atmospheric NN. The gravity perturbation is written as [3]:

$$\delta\phi(\vec{r}_0, t) = -G \int dV \frac{\delta\rho(\vec{r}, t)}{|\vec{r}_0 - \vec{r}|} \tag{1}$$

Where $\rho(\vec{r}, t)$ represents the density variation at the position $\vec{r}$ and at the time t. Every mechanism that produces a density variation in the media surrounding the test masses represents a source of Newtonian noise. In the atmosphere, these density variations can be caused by pressure and temperature fluctuations [4]. Density fluctuations can be also produced in the soil by passing seismic waves [5]:

$$\delta\rho_{seis}(\vec{r},t) = -\nabla\cdot(\rho(\vec{r})\xi(\vec{r},t)) \tag{2}$$

Here $\xi(\vec{r},t)$ is the displacement caused by the passing seismic wave, and it is solution of the wave equation. For what concerns NN, the solutions representing body and Rayleigh waves are the most important. Body waves are divided into shear and compressional waves and represent a solution to the wave equation propagating in the bulk. Rayleigh waves, instead, are surface waves and arise when an interface between media is present (such as soil/air). For a formal dissertation on seismology the Reader is referred to [6].

2. Seismic Newtonian noise cancellation in Virgo

Rayleigh waves dominate the seismic spectrum in GW detectors located on the Earth surface (like Virgo and LIGO). Therefore, they represent the main contribution to NN in such detectors. Since this noise directly couples with the test masses through gravity fluctuations, physically shielding the detector would require major changes to the already existing infrastructure [7]. However, Newtonian noise can be reduced by employing active noise cancellation techniques [8]. Given that seismic NN is linear with respect to the seismic displacement, it is possible to feed a linear filter with the signals recorded by an array of seismometers to provide an estimate of the NN in the test masses and then cancel it from the GW data stream. In order to achieve a good cancellation, it is important to find the optimal position of the array [10], which can be really challenging when the seismic field cannot be modelled [9].

Figure 1 shows the optimal array found for the Virgo Central Building (CEB). Both the two input test masses must be considered in the optimization. In fact, they are close enough to be correlated. The optimization was performed starting from seismic data collected in the CEB and the result shows interesting patterns: the accumulation of sensors along the edge of the platform between the two test masses creates a super–sensor with improved SNR and a similar result can be obtained by simulating a perfectly isotropic and homogeneous seismic field. Of course, the seismic field in Virgo is nor isotropic nor homogeneous. For this reason, other sensors are needed to optimally cancel the NN. The position of the sensors reflects the sources of noise present in CEB. This suggest that the seismic field might be described as isotropic and homogeneous plus some source of noise.

The optimization is the first step towards a complete system for the NN cancellation. The procedure used for Virgo will be also employed for ET, where however it will be necessary to consider the different nature of the NN. In fact, underground NN is mainly generated by shear and compressional waves instead of Rayleigh waves. As it will be explained in the next section, this will cause additional difficulties to be faced.

3. Seismic Newtonian noise in underground environments

Building an underground detector, like the Einstein Telescope (ET), has certainly the advantage of reducing both the seismic and the NN: indeed, surface Rayleigh waves decay exponentially with depth [6]. In an underground environment instead, body waves are always present. This implies that underground GW detectors will still be affected by some NN with respect to a surface GW detector, even if greatly reduced.

Depending on the site characteristics, NN will need to be suppressed by a factor 3 to 10, which will represent a major challenge for ET. Indeed, in underground environments the mixing of compressional and shear waves makes more difficult the NN cancellation [11]. This means that ET will still require a NN cancellation system. It will be also important finding a way to disentangle compressional wave signals from shear wave ones in order to reduce the number

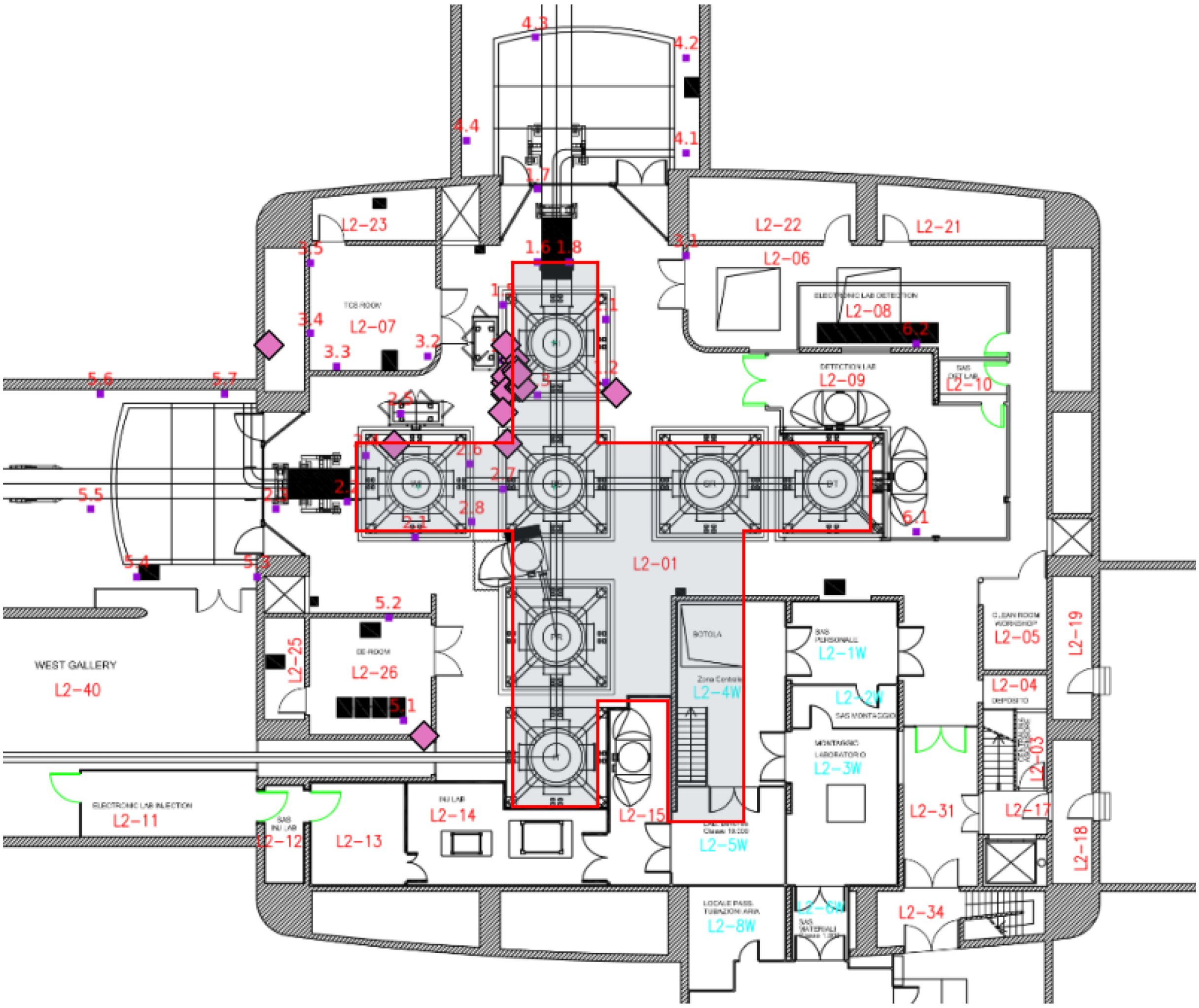

Figure 1. Optimal array composed by 16 sensors (pink squares) found for the Central Building in Virgo. The optimization was made following the technique of Ref. [9]. The red line shows the edges of the platform covering a lower ground level. The small violet squares instead represent the seismic sensors previously placed in the CEB to collect the data used to find the optimal array.

of sensors needed and to enhance the cancellation performances. This is important especially because the sensors will be located into boreholes, thus having a too high number of sensors would not be feasible.

4. Seismic noise in underground environments

Building an underground detector is mainly done with the purpose of having a quiet seismic environment. However, we must be careful here. Indeed, the underground environment requires many infrastructures that a surface detector may not have (like water pumps). ET will also employ cryogenic technologies to reduce the thermal noise [12]. This, together with all the other needed infrastructure, might produce unwanted excess of seismic and acoustic noise in the vicinity of the test masses. A study carried in KAGRA [13] showed that the seismic noise produced by all the machinery rapidly attenuates with increasing distance from the noise source. Moreover, also the related acoustic noise produced inside the caverns is negligible compared to

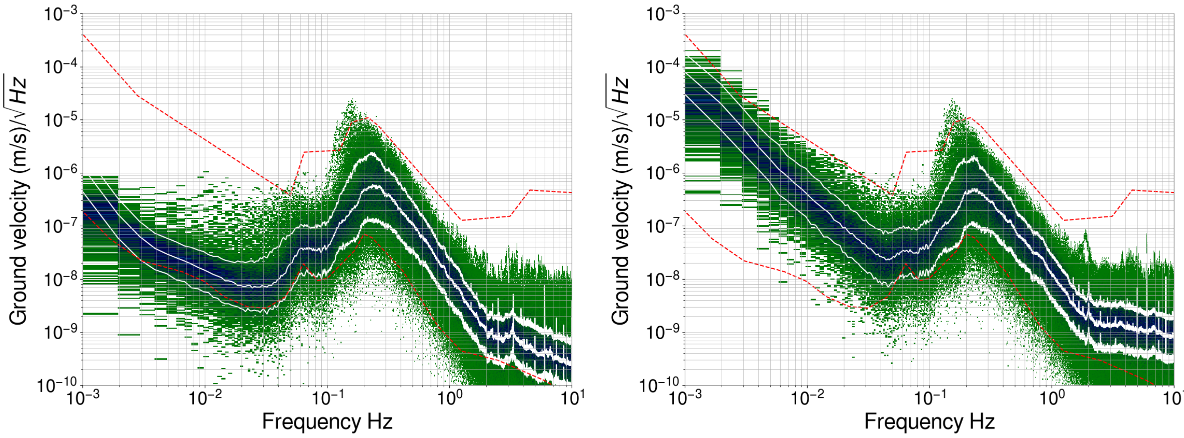

Figure 2. Comparison between the vertical (*left*) and the x horizontal (*right*) channels in the input chamber of KAGRA. An excess noise in the horizontal channel is clearly visible below 50 mHz.

KAGRA and ET sensitivity curves. More careful studies should be run to investigate induced seismic and acoustic noise for ET, especially once the site will be selected. A good norm would however be that of placing all the noisy machinery at least 100 m from the ET test masses. This will probably suffice to avoid unwanted excess noise in the detector.

Another important point, is about the presence of excess horizontal displacement below 50 mHz. It is a long–known fact that some pressure fluctuations (or thermal induced effects) can produce seismic tilt [14, 15] that can couple with horizontal seismic channels. A recent work showed a connection between local air pressure and seismic strain in KAGRA [16] and this noise excess is also well visible in Figure 2, where the seismic spectra of the x horizontal seismic channel recorded in KAGRA was plotted. This must be investigated more, since tilt might be a problem for the active seismic isolations of interferometric GW detectors.

5. Final remarks

ET will be a third generation GW detector which aims to be sensitive to GWs down to 2-3 Hz. Reaching such a performance requires to build the detector underground and to be careful in not producing artificially induced extra noise. The efforts required to reach such sensitivities in the low–frequency band are legitimized by the possibility of observing binary neutron stars from hours to days before their final merger, thus increasing the SNR and enhancing the parameter estimation [17]. Beside this, a greater sensitivity in the low–frequency band could provide answers about fundamental cosmology like the nature of dark matter or modifications of gravity theory [18].

The past experience of detectors like Virgo and KAGRA is of fundamental importance in order to reduce as much as possible noises in ET where particular care will be needed to avoid artificially induced seismic noise and to reduce the NN still present in an underground environment.

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