A nested inverted pendulum for ET suspensions: preliminary studies

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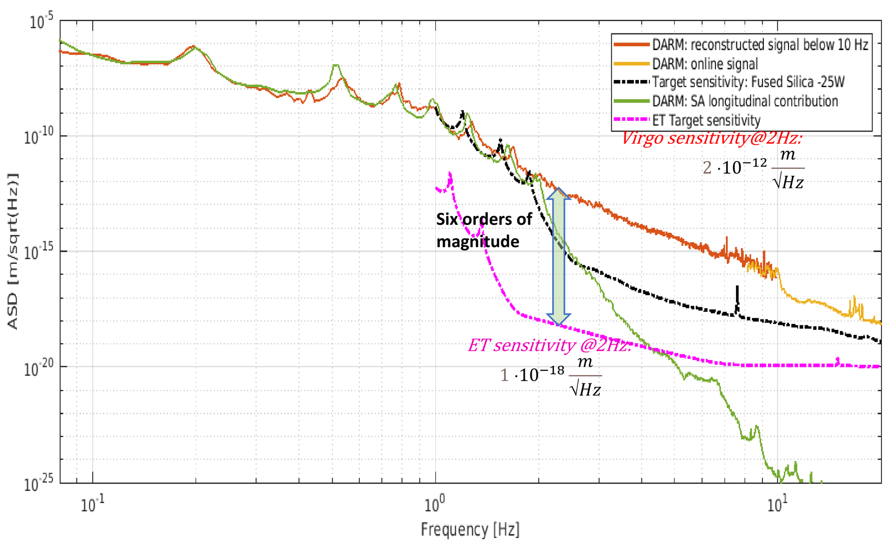
Introduction

For ground-based GW detectors, seismic vibration is the dominating source of noise in the low-frequency region, limiting both sensitivity and duty cycle. The plan for future 3rd generation detectors, like the Einstein Telescope (ET), aims to further extend the detection band down to 2-3 Hz. This requires underground locations, where seismic noise is about 100 times smaller than on the surface, together with other technological improvements like cryogenic payloads and reduced thermal noise.

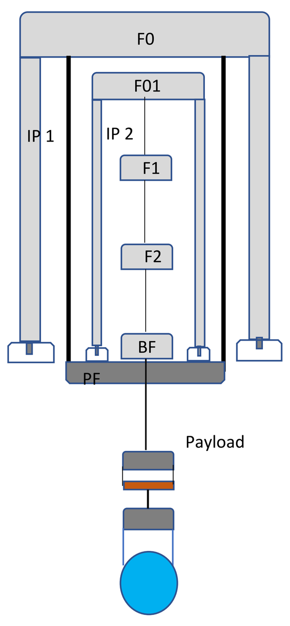


To achieve the attenuation value of $10^{-18} m/sqrt(Hz)$ at few Hz, the suspensions of the optical components must be upgraded with respect to the 2nd generation ones, in order to improve seismic attenuation in low frequency and reduce as much as possible the frequency of mechanical resonances below the detection band.

Double nested inverted pendulum as a possible solution

A seismic isolation system adopting a nested, double inverted pendulum could permit a large improvement in seismic isolation keeping total suspension length comparable with the AdV superattenuator.

Schematic view of a suspension adopting a double nested inverted pendulum



A possible layout could be:

- Double nested inverted perndulum (IP1 and IP2)
- Passive filters chain (F1, F2 and BF)
- Platform (PF)
- Payload

Crucial points are the confinement of the SA resonances below 1 Hz, the crosstalk of vertical and angular noise, the feasibility and noise level of control loops.

Simulations

During the last twenty years a MATLAB code, based on the impedance matrix approach [1], has been developed and applied for studying and upgrading the VIRGO seismic attenuators [2, 3]. This code together with the mass optimization method described in the paper [4], will be extensively used to study the coupling terms between degrees of freedom so that to define a suitable layout and parameters that optimize the performance of the system.

Here preliminary **longitudinal**, **tilt coupling**, and **vertical transfer functions** from ground to mirror, of a suspension adopting a double nested pendulum in the following cases will be shown:

Case A:

I. **Total lenght :8 m**
II. **Total mass: 2650 Kg**

Case B:

I. **Total lenght :10 m**
II. **Total mass: 2650 Kg**

Case C:

I. **Total lenght :10 m**
II. **Total mass: 3250 Kg**

Vertical transfer function, from ground to mirror, is calculated assuming four standard filters like those of Virgo's SA (F01, F1,F2,BF) [2,3].

Reference

[1] S. S. Rao. Mechanical Vibrations. N.J: Prentice Hall, 2010.

[2] P. Ruggi, *L'attenuazione del rumore sismico nel rilevatore di onde gravitazionali Virgo*, thesis (2003). https://tds.virgo-gw.eu/ql/?c=16268

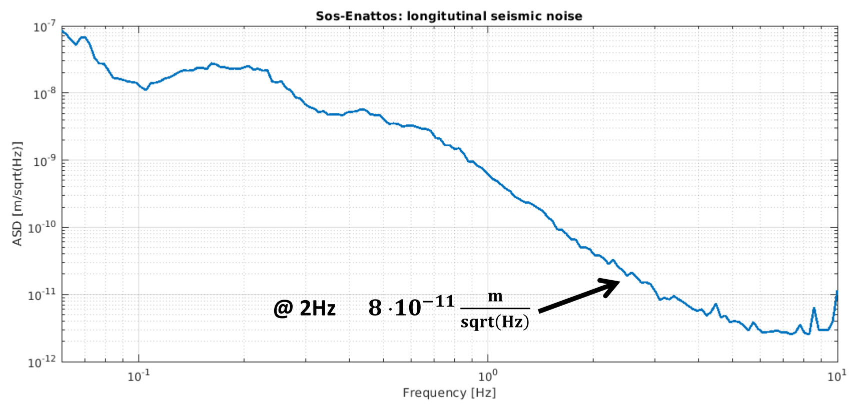
[3] L. Trozzo, Low Frequency Optimization and Performance of Advanced Virgo Seismic Isolation System , PhD thesis (2018). https://tds.virgo-gw.eu/ql/?c=13271

[4] A. Bove et al 1997 EPL 40 601

Measured Seismic noise at Sos-Enattos site

It is a well-known result that in underground locations seismic noise can be about 100 times smaller than on the surface. In particular here, let's focus the attention on the seismic noise measured at the Sos-Enattos site (Sardinia, Italy).

Longitudinal contribution



Tilt contribution

At the moment, there is no direct measurement of tilt ground, but it is possible to estimate a lower limit by using the following empirical formula:

$$\alpha_0 = \frac{\omega}{v} \cdot x_0$$

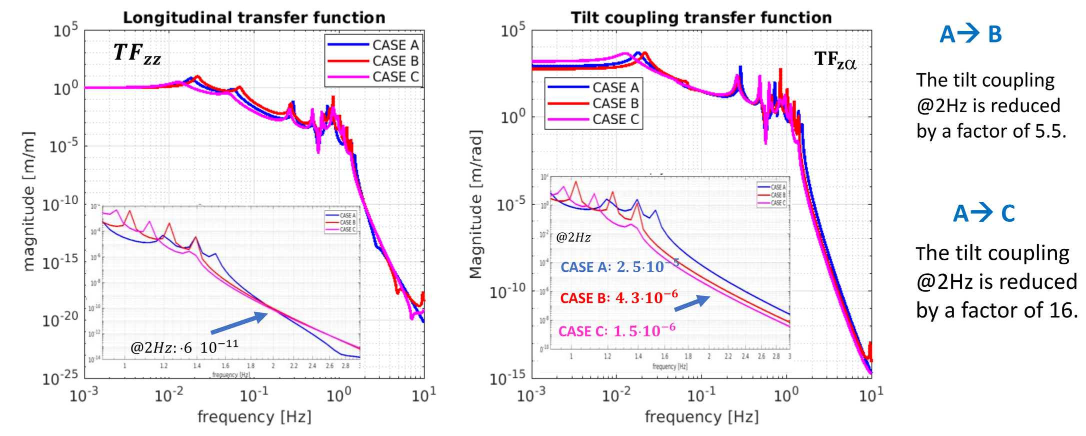
Assuming the values of **v** (seismic wave speed) and x_0 (longitudinal ground motion) to be about 2000 m/s and $\mathbf{8 \cdot 10^{-11}} \frac{m}{sqrt(Hz)}$ respectively, the estimated value of α_0 is about

$$3 \cdot 10^{-13} \frac{rad}{\sqrt{Hz}} \quad @2Hz$$

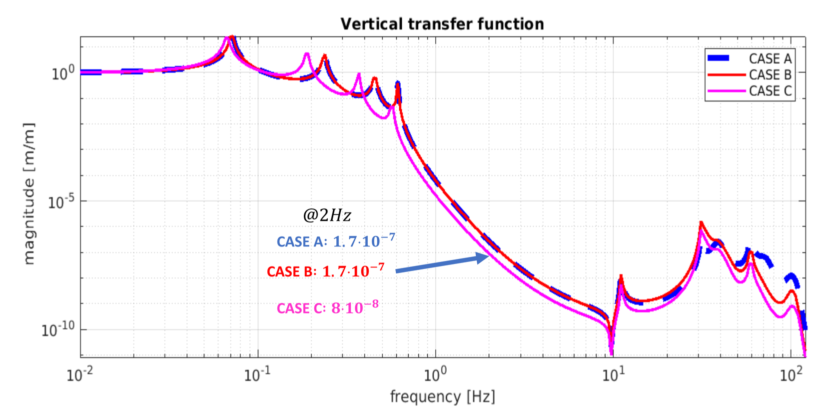
[5] Matteo Di Giovanni et al., A seismological study of the Sos Enattos Area the Sardina candidate site for the Einstein Telescope, Seismological Research Letters, 2020.

Simulation's results

Here the simulated transfer functions from ground to test mass are shown.



Are these attenuations enough to reach the target sensitivity @2 Hz? …

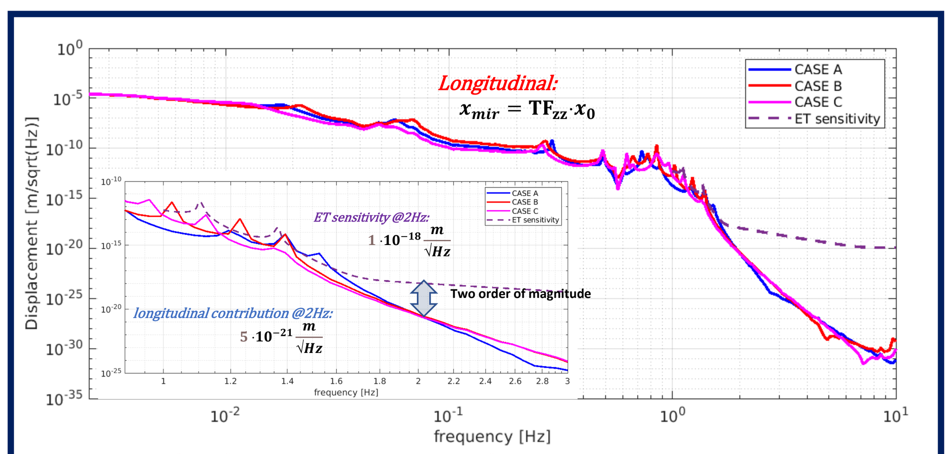


Let's see if vertical passive mechanical attenuation is enough above 10 Hz…

Projection on the ET's sensitivity curve (I)

Both transfer functions and seismic noise are used to estimate the residual motion of the test mass, compared with respect to the ET's sensitivity for evaluating benefits, limits, and defining requirements for sensors and control strategy.

Here residual seismic noise, from longitudinal and tilt contribution is shown.



Longitudinal contribution is not limiting the sensitivity anymore.

Tilt contribution @2 Hz, is calculated as following :

$$x(f = 2Hz)_{mir} = \mathrm{TF}_{z\alpha} \cdot \alpha_0$$

Case A: $8 \cdot 10^{-18} \frac{m}{\sqrt{Hz}}$ → Tilt contribuition is limiting the sensitivity

Case B: $1 \cdot 10^{-18} \frac{m}{\sqrt{Hz}}$ → Tilt contribuition compatible with the sensitivity curve

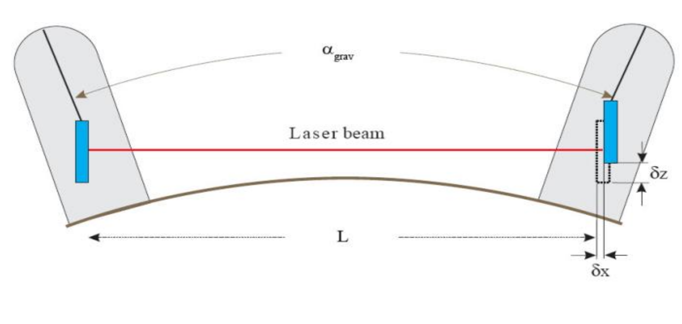
Case C: $3 \cdot 10^{-19} \frac{m}{\sqrt{Hz}}$ → Tilt contribuition is a factor of 3 below the sensitivity curve at 2 Hz.

Projection on the ET's sensitivity curve (II)

Here residual seismic noise, from vertical contribution, trasmitted to the test mass and compared with respect the ET's sensitivity is shown.

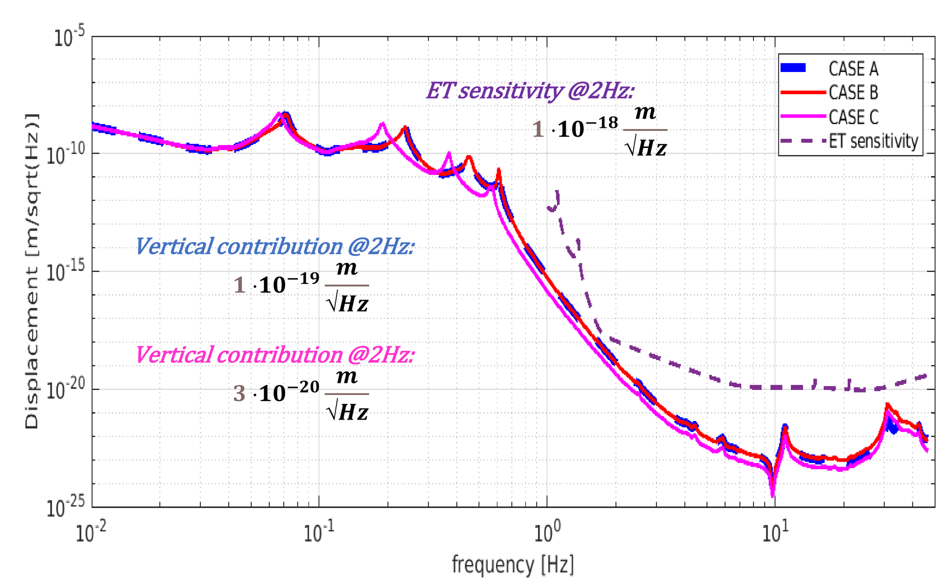
Vertical contribution

Due to Earth curvature, on distance of about 10 Km, the impact of the coupling between the horizontal and vertical directions is not negligible.



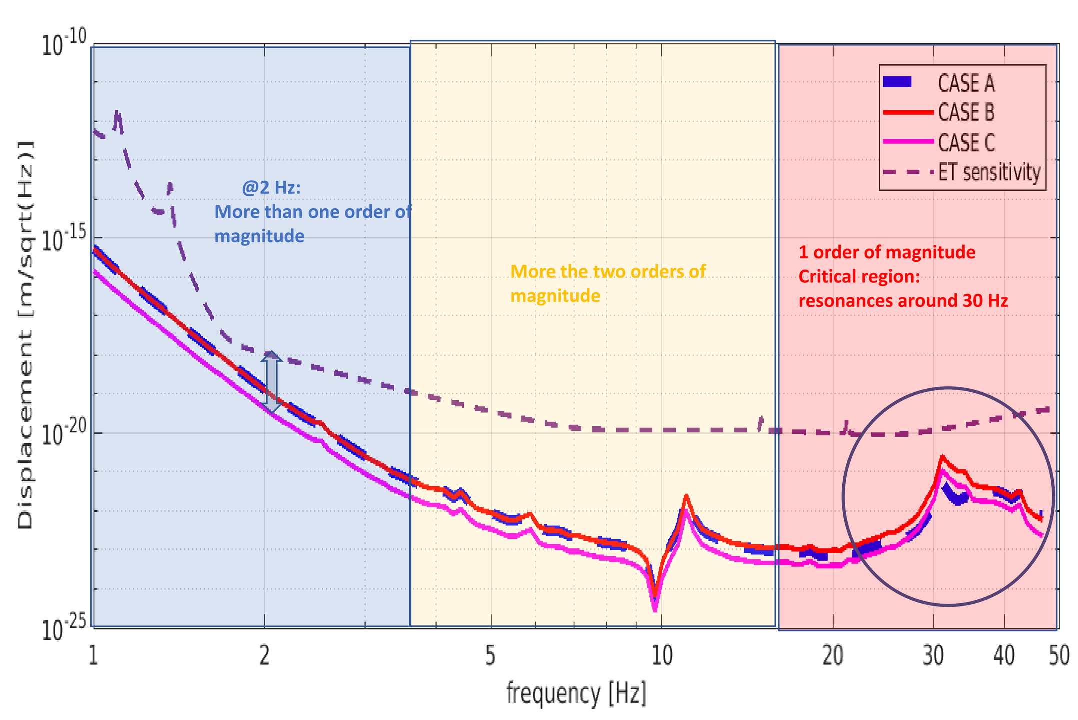
Assuming the value of α_{grav} to be about $\mathbf{3 \cdot 10^{-3}}$, the vertical contribution can be calculated as following:

$$x_{mir} = \mathrm{TF}_{yy} \cdot \alpha_{grav} \cdot y_0$$



Above 20 Hz vertical cross coupling could represent an issue

Let's zoom into the region [1÷50] Hz…



Crossbar resonances (@ 30 HZ) can be excited not only by seismic noise but also from other noise sources.

Conclusions

✓ ***Longitudinal is not limiting the sensitivity anymore.***

✓ ***Tilt and vertical contribution could represent an issue.***

These results are a starting point for furthers improvements in the design of the system as well as in the definition of a suitable control strategy.

Next steps

✓ *Further optimization of the whole suspension*

✓ *Increase both the suspension lenght and number of the stages*

✓ *Active tilt control:*
Tiltmeter sensitivity at 2 Hz: $10^{-13} \frac{rad}{\sqrt{Hz}}$

✓ *Reduce the impact of the vertical resonance*

Dedicated R&D project for new vertical filter design

Work in progress….

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