# Development of a nested inverted pendulum for ET suspensions: preliminary studies

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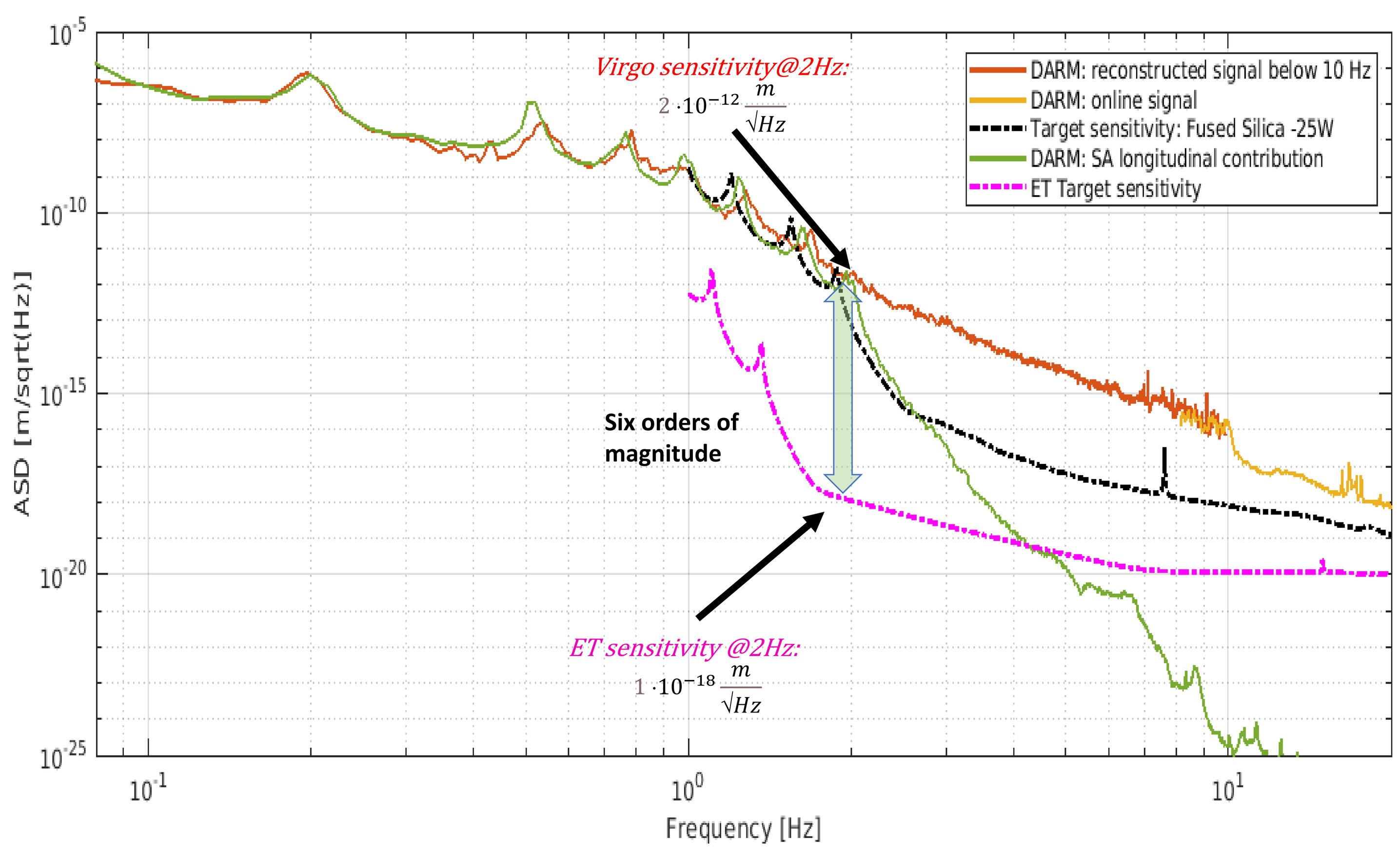
## Introduction

For ground-based GW detectors, seismic vibration is the dominating source of noise in low frequency region, limiting both sensitivity and duty cycle.

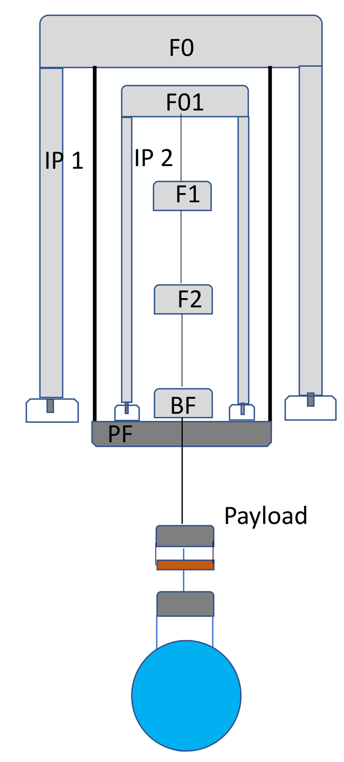
The plan for future 3rd generation detectors, like the Einstein Telescope (ET), aims to further extend the detection band down to 2-3 Hz. This requires underground locations, where seismic noise is about 100 time smaller than on surface, together to other technological improvements like cryogenic payloads 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

**Schematic view of a suspension adopting a double nested inverted pendulum**




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

A possible layout could be:

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

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

## Simulations

In frequency domain, the mechanical response, from any point-to-point and coordinate-to-coordinate, of a such complex system can be computed by using the impedance matrix approach. During the last twenty years, a library of analytic description for any possible mechanical basic elements together with a Matlab code for the algebraic composition of any complex layout has been developed and applied for studying and upgrading the VIRGO seismic attenuators.

This code togher with the mass optimization method described in the paper [1], will be extensively used to study the coupling terms between degrees of freedom so that to define a suitable layout and parameters that optimize performance of the system.

Here preliminary longitudinal and tilt coupling 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: 1450 Kg**

**Case B:**

I. **Total lenght :10 m**
II. **Total mass: 1450 Kg**

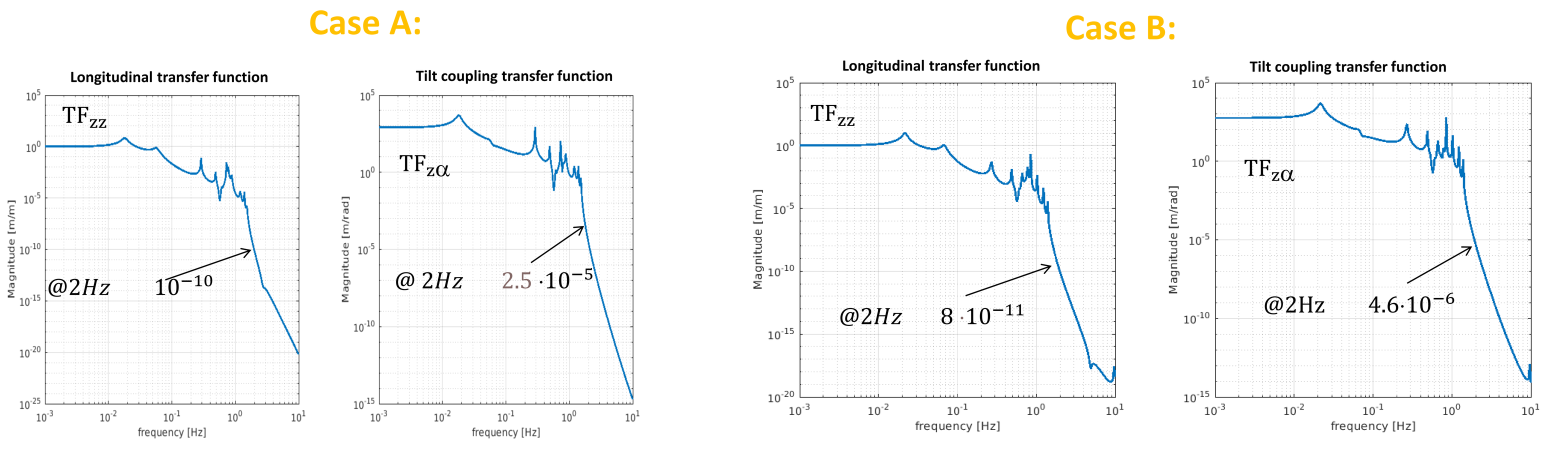

***Reference***

***[1]: A. Bove et al 1997 EPL 40 601***


## Simulation's results

Here the simulated longitudinal and tilt coupling transfer functions from ground to test mass are shown.

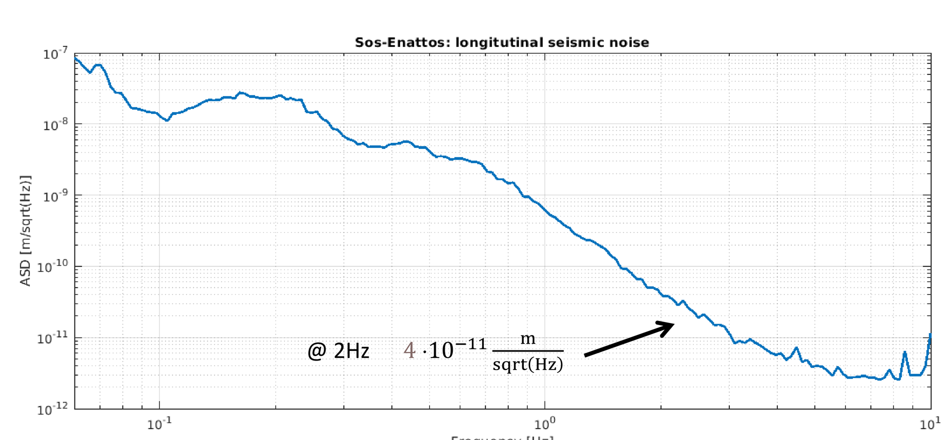
**Case A:** **Case B:**




Just incresing the lenght of the suspension the tilt coupling @2Hz is reduced by a factor of 5.5.

## Measured Seismic noise at Sos-Enattos site

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



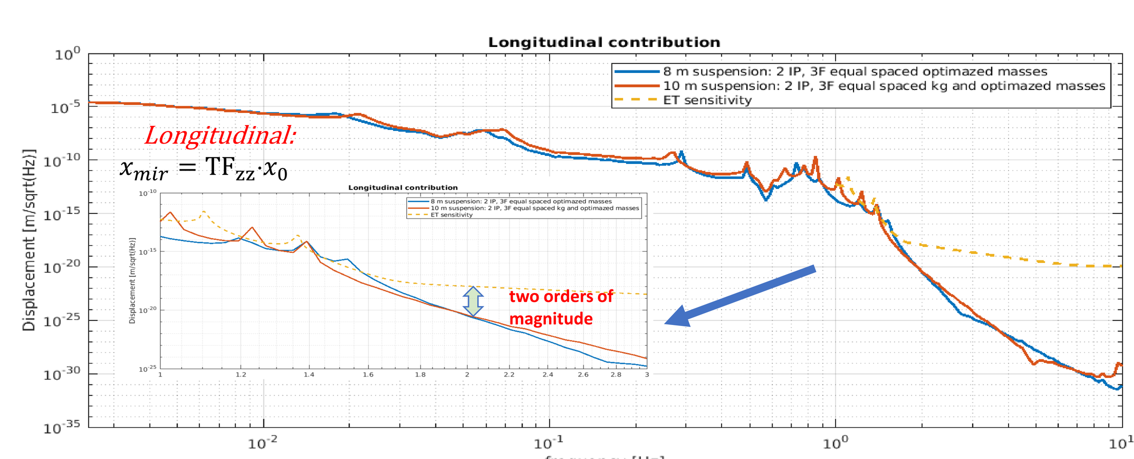

At the moment, there is no direct measurement of tilt groun but it is possible to estimate a lower limit by using the following empirical formula: $\alpha_0 = \frac{\omega}{v}\cdot x_0$

Assuming the values of **v** (seismic wave speed) and $x_0$ (longitudinal ground motion) to be about 2000 m/s and $4\cdot10^{-11}\frac{m}{sqrt(Hz)}$ respectively, the estimated value of $\alpha_0$ is about $1\cdot10^{-13}\frac{rad}{\sqrt{Hz}}$ @2Hz

## Projection on the ET's sensitivity curve

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

Residual seismic noise, from longitudinal contribution, trasmitted to the test mass is shown here:




Longitudinal contribution, in both cases, is not limiting the sensitivity anymore.

The tilt contribution @2 Hz, in both cases, can be calculated as following : $x(f = 2\,Hz)_{mir} = TF_{z\alpha}\cdot\alpha_0$

Case A: $2.5\cdot10^{-18}\frac{m}{\sqrt{Hz}}$

Case B $4.6\cdot10^{-19}\frac{m}{\sqrt{Hz}}$ → The tilt contribution, in the case B, is a factor of 1.5 below the sensitivity curve at 2 Hz.

## Conclusions and next steps

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 to suppress more the tilt contribution:**

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

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

➢ **Study of the vertical attenuations and crosscoupling with respect to the longitudinal degree of freedom**

**Work in progress….**

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