GW seismic attenuators on the Moon

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Outline

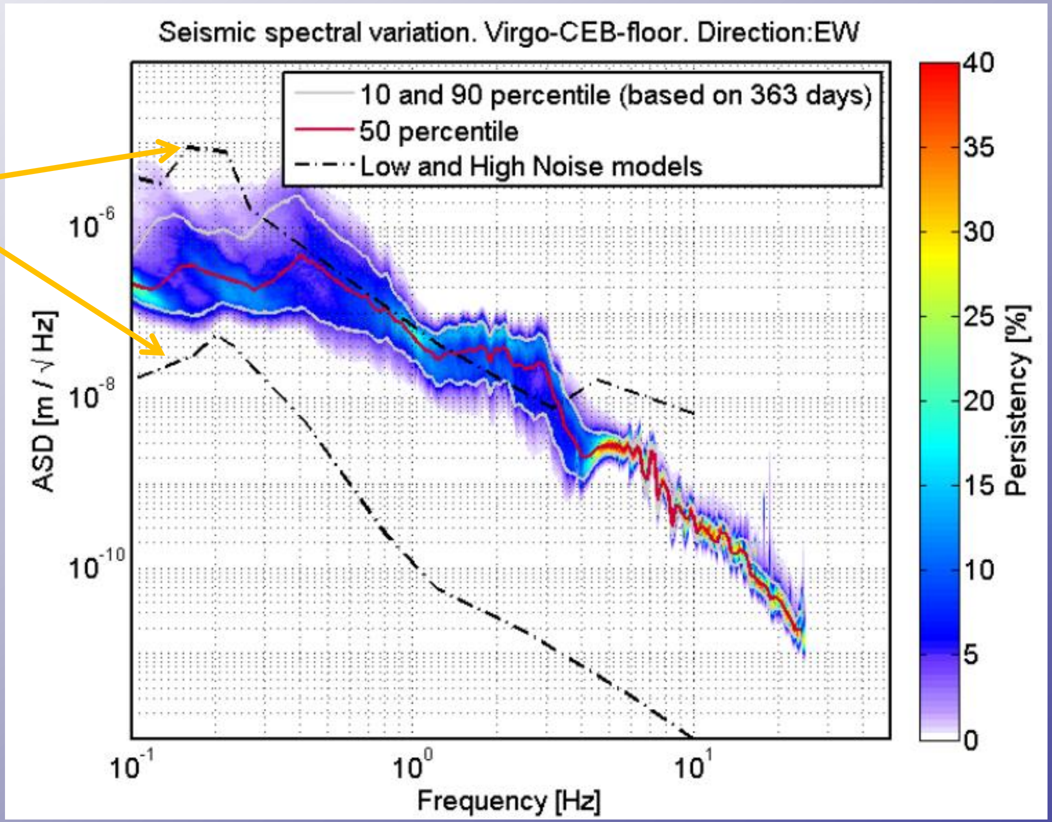
- Introduction
  - How does seismic attenuation works on current GW detectors?
- Going to the moon
  - Simulated performance of a SA on the Moon
- Conclusions

Introduction
Seismic Noise on Earth

- Seismic noise has both natural and human origins and can vary by few orders of magnitude from site to site.
- Al ground motion displacement spectra observed worldwide share some common characteristics: they have essentially the same amplitude in all three orthogonal space directions and they exhibit a low pass behavior that follows the empirical law for f > 0.1 Hz

$$x(f) \sim A\ (1\ \mathrm{Hz/f})^2\ \text{m/sqrt(Hz)}$$

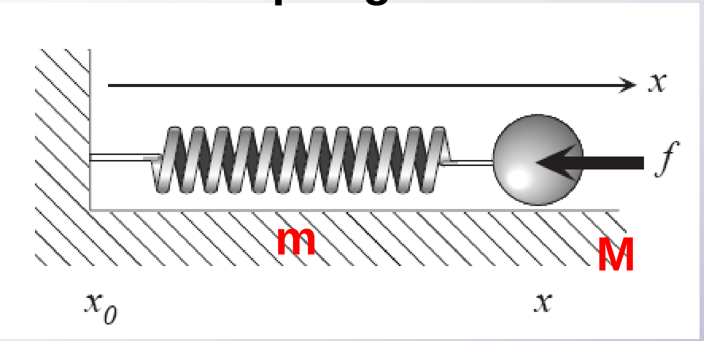
Peterson's High and Low Noise Models



Introduction
Harmonic Oscillators as Mechanical filters

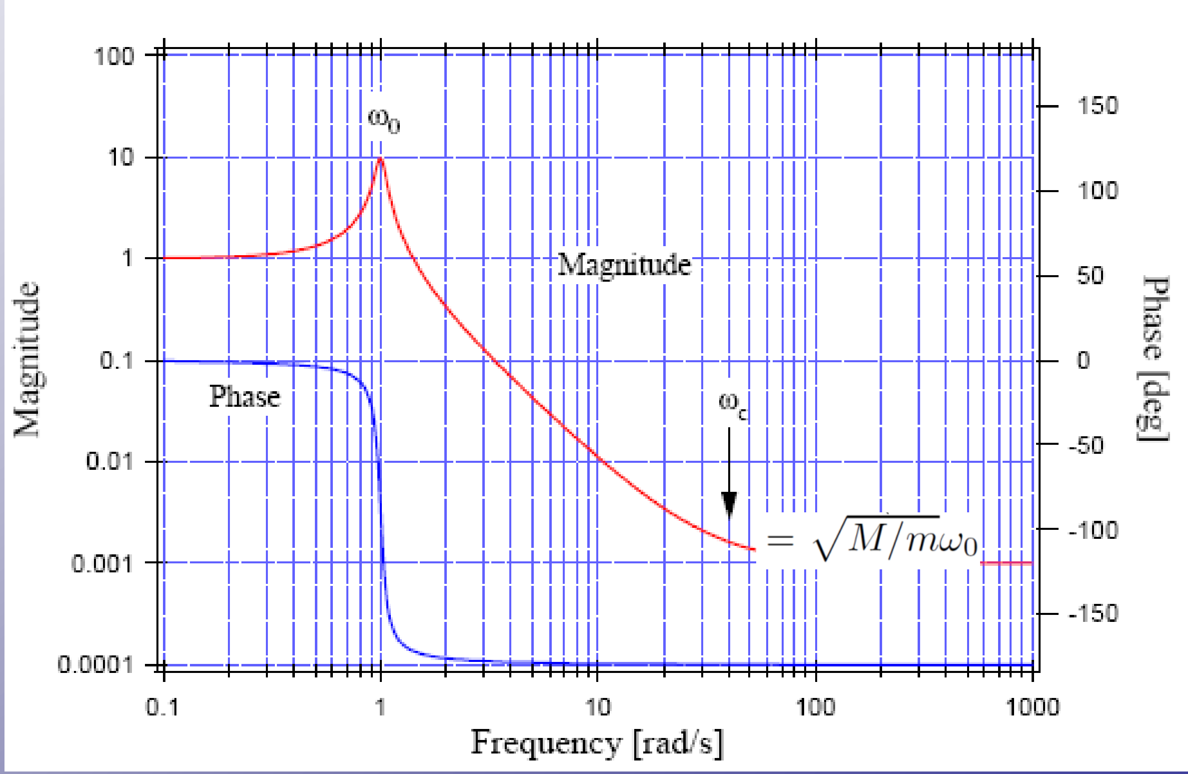
At frequencies higher than the oscillator resonance, the transfer function of an harmonic oscillator is equivalent to a second-order low pass filter.

Massive Spring

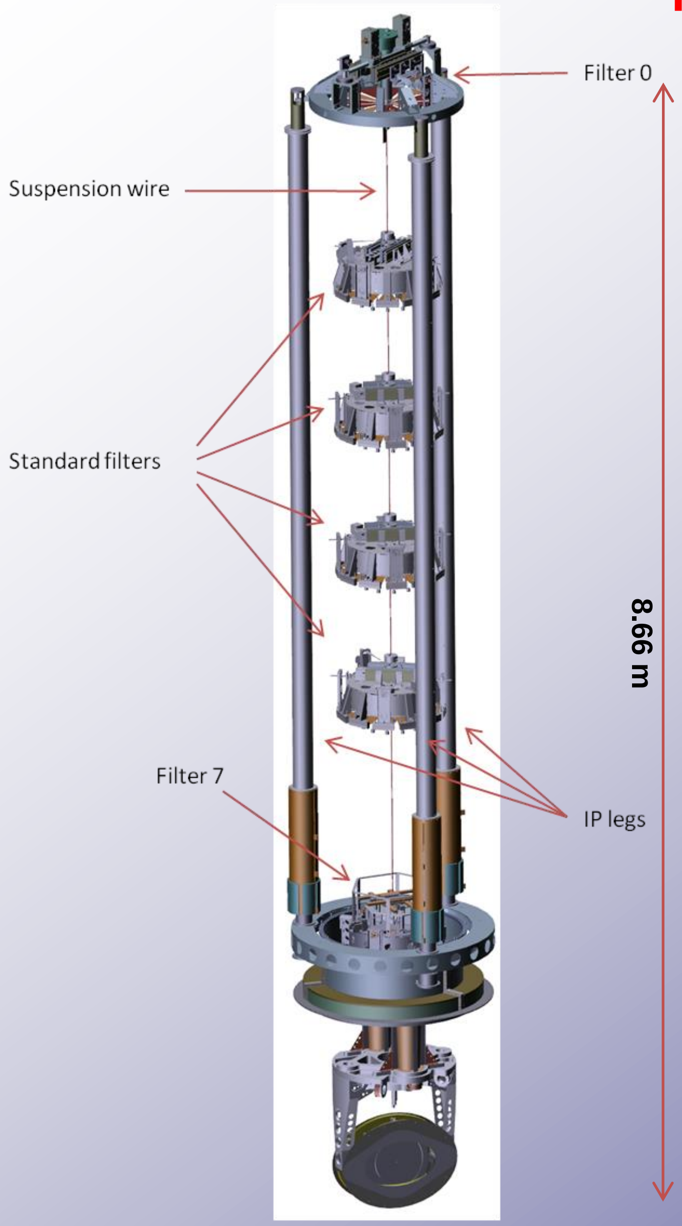


$$H_X = \frac{\omega_0^2(1+i\phi)+\frac{m}{M}\omega^2}{\omega_0^2(1+i\phi)-\omega^2+i\frac{\gamma}{M}\omega}$$

Transfer Function

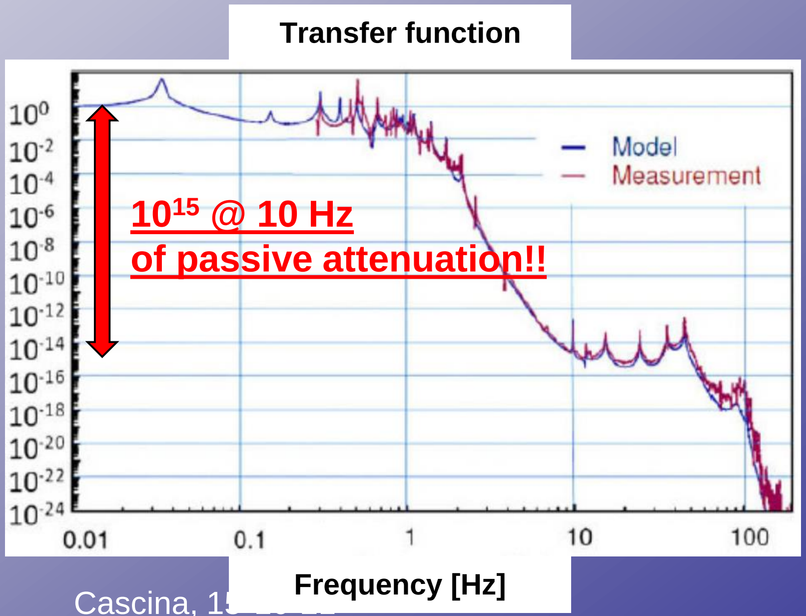


Introduction
The superattenuator (SA)



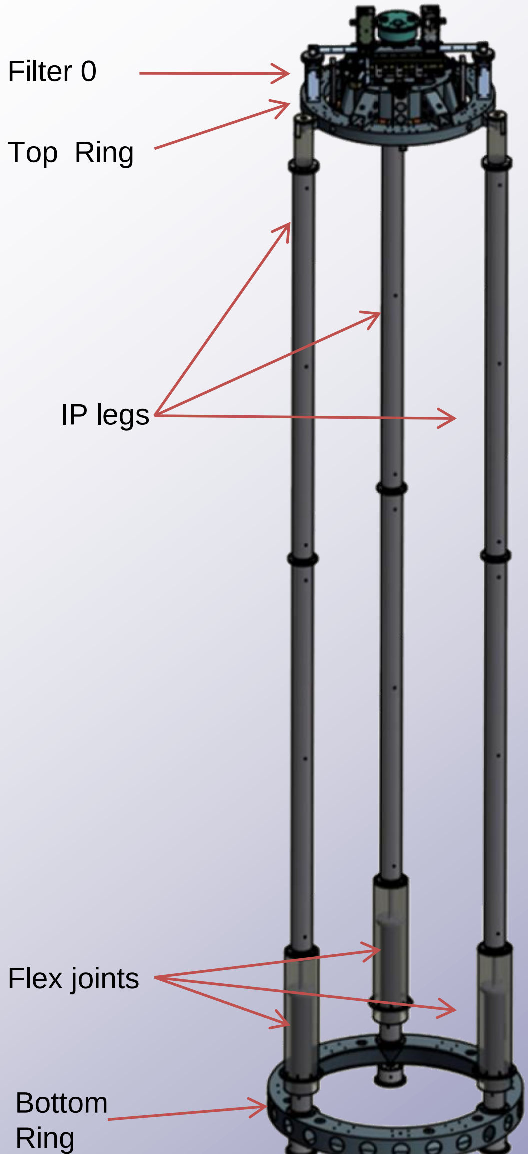
The AdVirgo superattenuator (SA) is a complex mechanical device capable of providing more than 10 orders of magnitude of passive seismic isolation in all six degrees of freedom above a few Hz

- The SA is a passive mechanical system constituted by a 5 stage pendulum supported by a 3-leg elastic pre-isolator called inverted pendulum (IP).
- All the normal mode resonance frequencies of the SA are kept below 2 Hz.
- The SA mechanical structure, consists of three fundamental parts: the inverted pendulum, the chain of standard filters, the payload.
- Mechanical design for AdVirgo is essentially the same of Virgo except for the payload.



Introduction

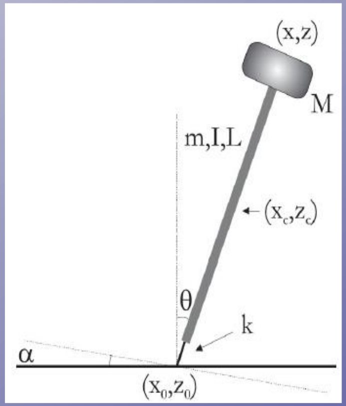
The inverted pendulum



- A low frequency pre-isolator constituted of three 6 m-long hollow legs, each one connected to the ground through a flexible joint and supporting an interconnecting structure (the top ring) on its top.

- The structure horizontal normal modes are tuned at about 30-40 mHz.

- A simple mechanical model such as this



Gravitational Anti-spring

gives

$$\omega_0 = \frac{k - (M + m/2)g/L}{M + m/4 + I/L^2}$$

- Since the system is very soft, it requires very low forces to be moved:

for f<<f0 $F \simeq M\omega_0{}^2 x$

- The top ring is a mechanical support for an additional seismic filter, called filter 0, similar to those used in the chain.

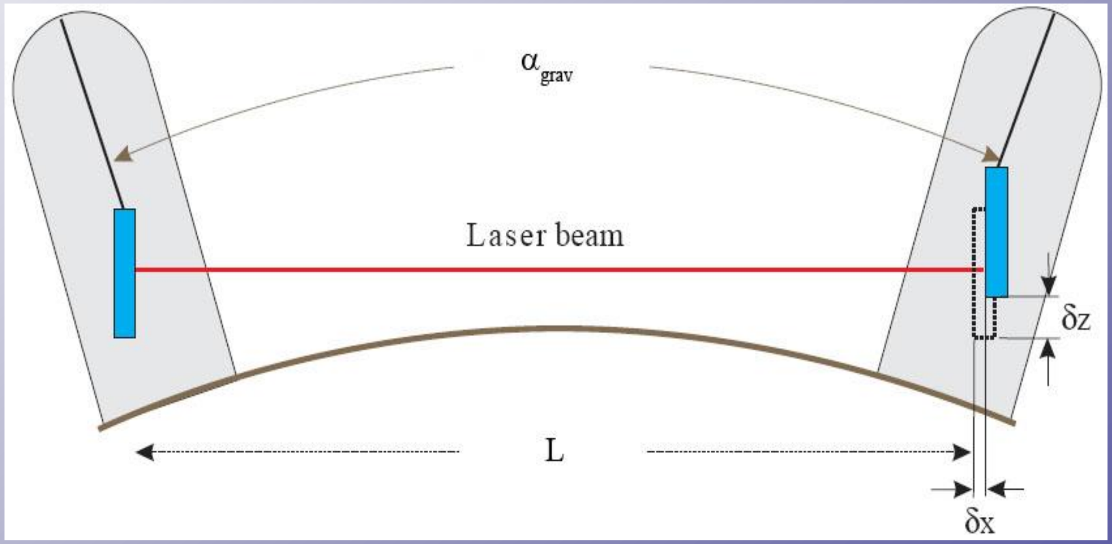
- The filter 0 is equipped with a set of sensors and actuators, placed in a pinwheel configuration, that are used to actively damp the IP resonance modes.

Introduction

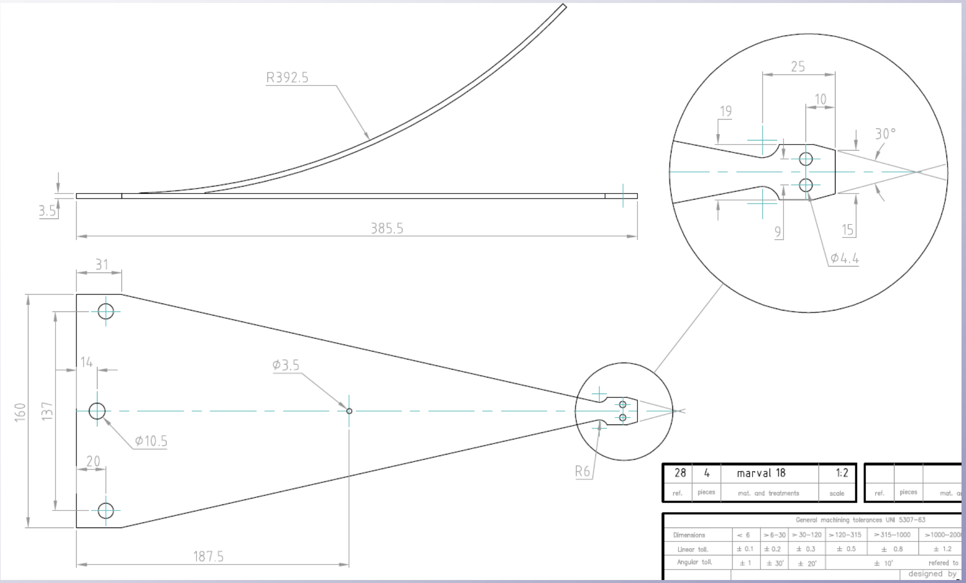
Why vertical attenuation ?

- The input and output mirrors of a Fabry-Perot cavity form an angle alpha_grav = L/r = $5*10^{-4}$ rad (where L = 3 km is the cavity length and r is the Earth radius) with the global vertical direction. Therefore vertical displacement Δz has effect along the beam direction, producing a variation alpha_grav*Δz of the optical path.

- The suspension system causes even larger mechanical couplings (1%), due to structural reasons.



Introduction
Vertical attenuation: Blades

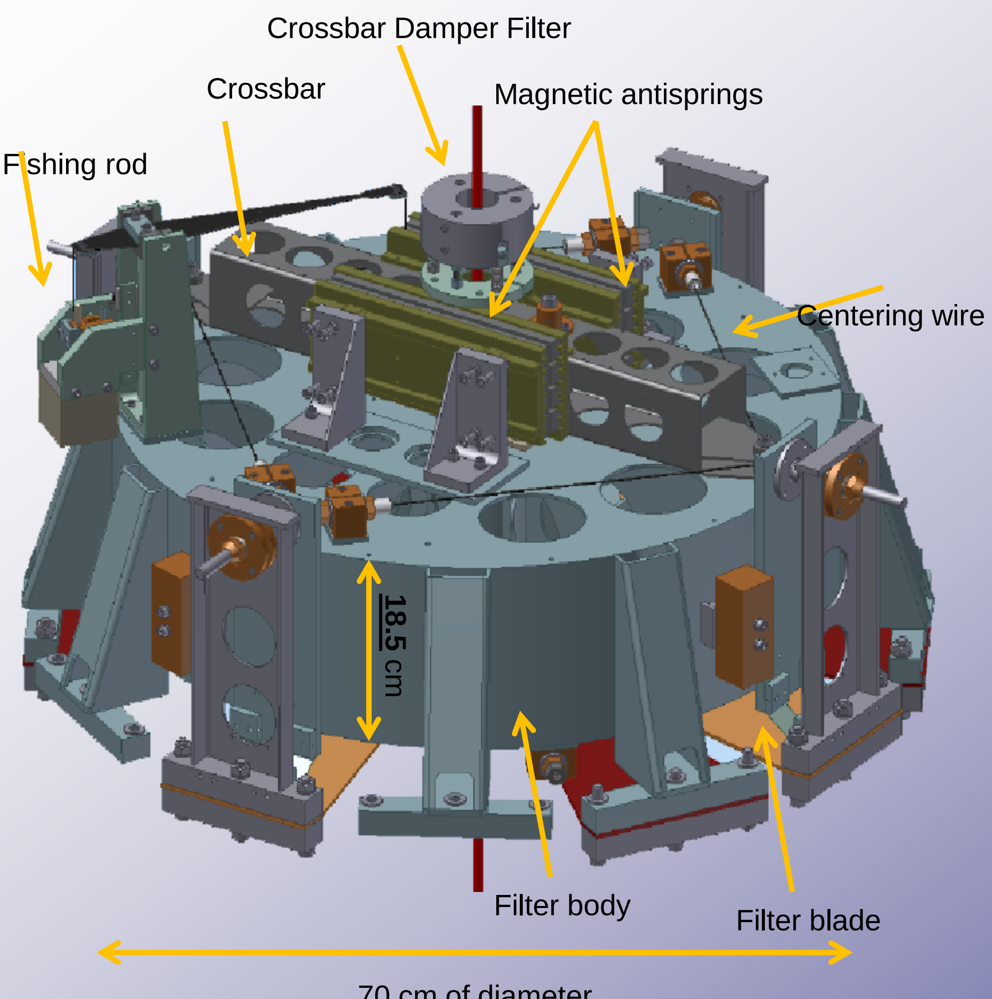


- All the maraging steel blades have a thickness of 3.5 mm, a length of 385.5 mm, while the width of the triangular base changes according with the load to be supported.
- The number of blades ranges from 12 (in the first filter of the chain) to 4 (in the filter 7) according to the suspended load. A total of 52 blades is needed for a long tower.
- The load M depends by the base width b, by the thickness t and length l with this law

$$M = \frac{Ebt^3}{12R_c gl}$$

Introduction

Vertical Attenuation: Standard filters

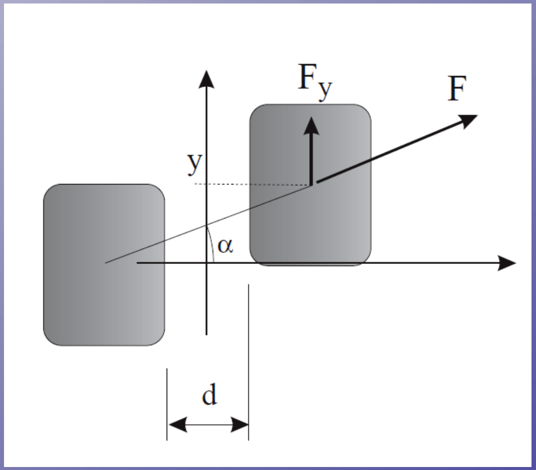


10^2 for *f* > 2 Hz of passive attenuation in both horizontal and vertical direction !!

The first four pendulum stages of the SA are denominated Standard Filters (SFs).

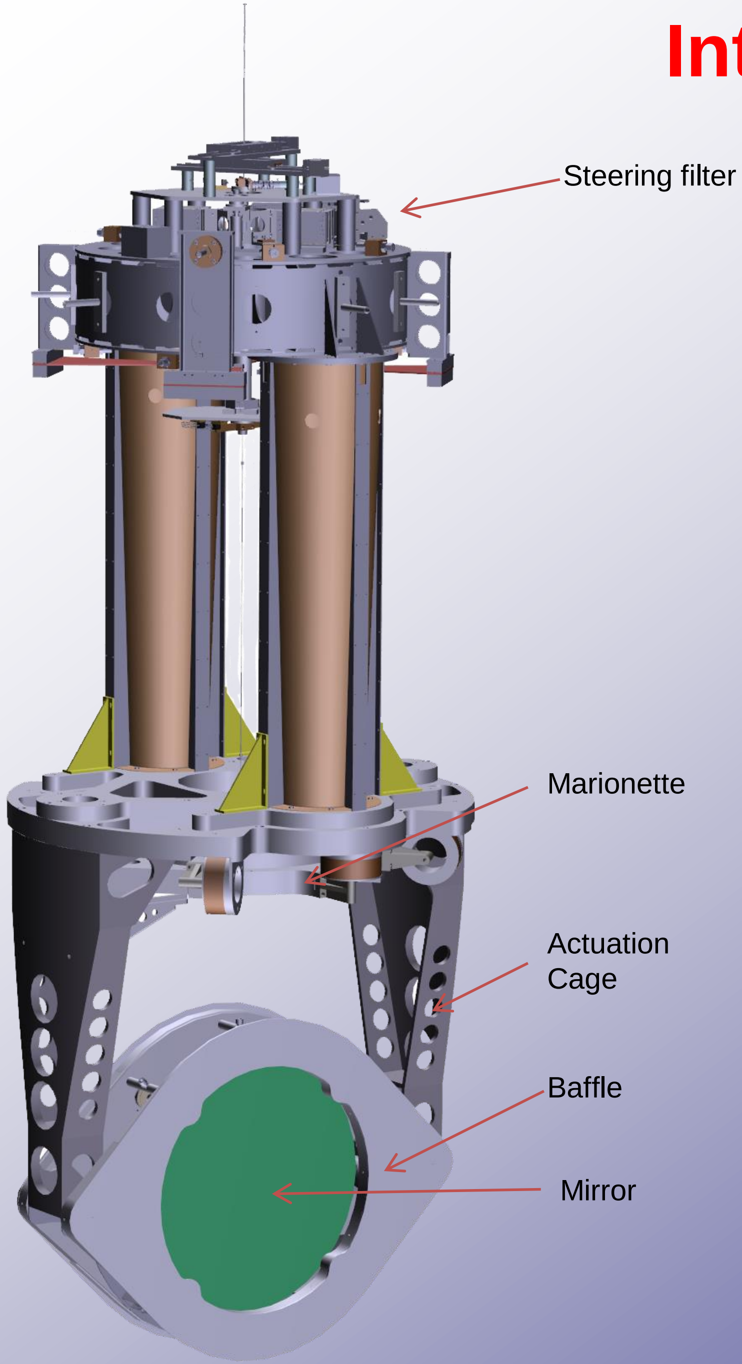
The SF is essentially a rigid steel cylinder supporting a set of maraging steel cantilevered triangular blades clamped along the outer surface of the filter body.

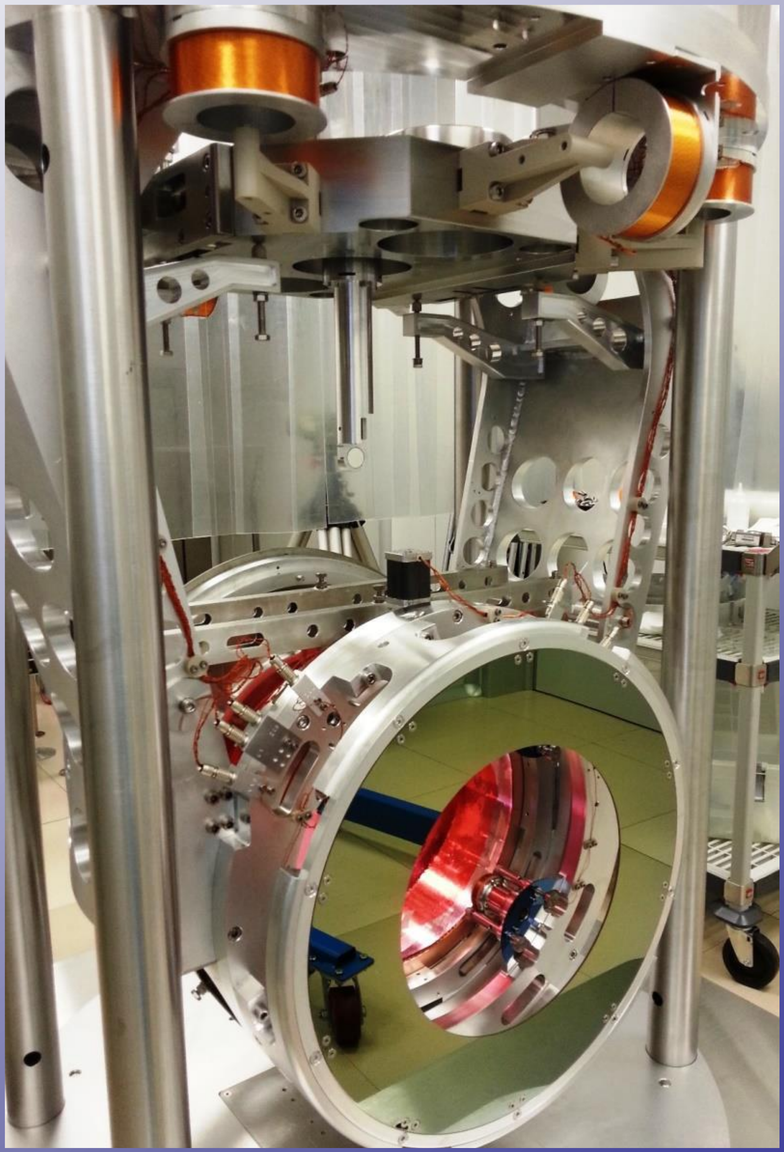
A magnetic anti-spring system, assembled on each filter, is designed to reduce its fundamental vertical frequency from about 1.5 Hz down below 0.5 Hz.



Magnetic antispring working principle

Introduction
The payload





Introduction

Control system setup

On long superattenuators (BS, NI, NE, WI, WE, PR, SR) are installed:

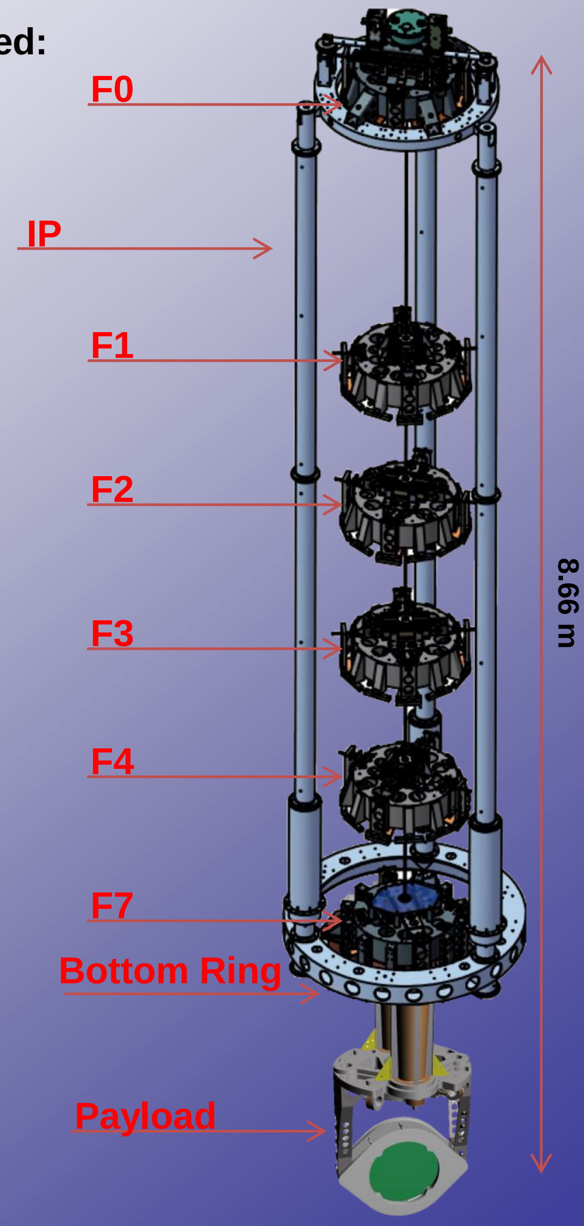
- **18 LVDTs** of 3 different types
  - 9 Vertical LVDTs (F0 – F7 Crossbar, Bottom Ring)
  - 3 F0 Horizontal LVDT
  - 6 F7 LVDTs

- **5 Accelerometers** of 2 different types installed on F0:
  - 3 Horizontal Accs
  - 2 Vertical Accs

- **23 Coils** of 4 different types
  - 5 F0 Coils
  - 6 F7 Coils
  - 8 Marionette coils
  - 4 Mirror coils

- **3 Piezos** on bottom ring

- **21 Motors**
  - 1 Top screw F0 vertical motor
  - 3 F0 trolley motors
  - 6 Fishing rod motors
  - 2 Marionette motors
  - 4 F7 motors
  - 5 Accelerometer motors

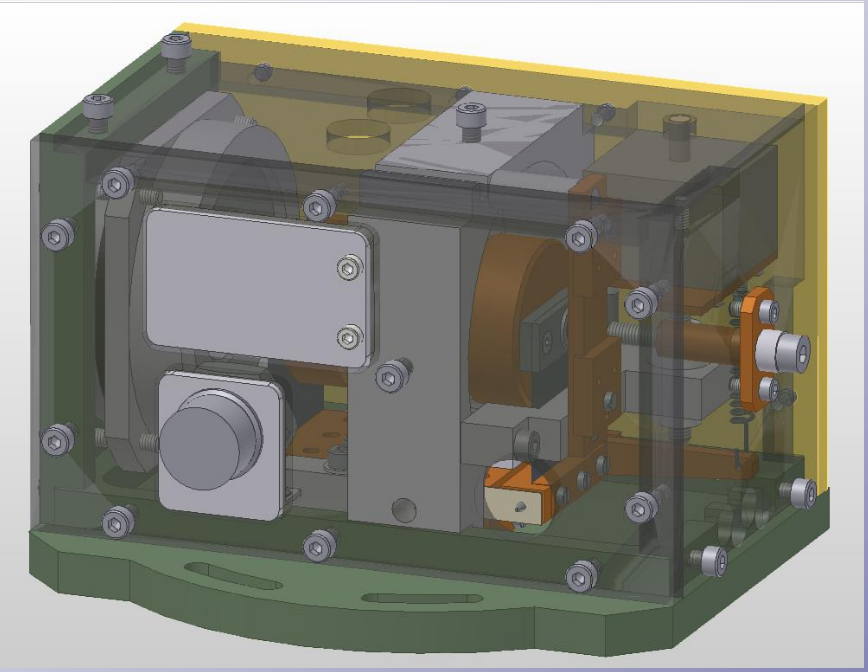


Introduction
Sensors

• There is a total of 5 Accelerometer (Accs) installed on the suspension F0 of 2 different types with sensitivity of about $3*10^{-10}$ $m/s^2/sqrt(Hz)$ for f < 3 Hz

• There are 18 LVDTs installed on long tower suspensions of 3 different types with a sensitivity of about 10^{-8} m/sqrt(Hz) for f > 0.1 Hz

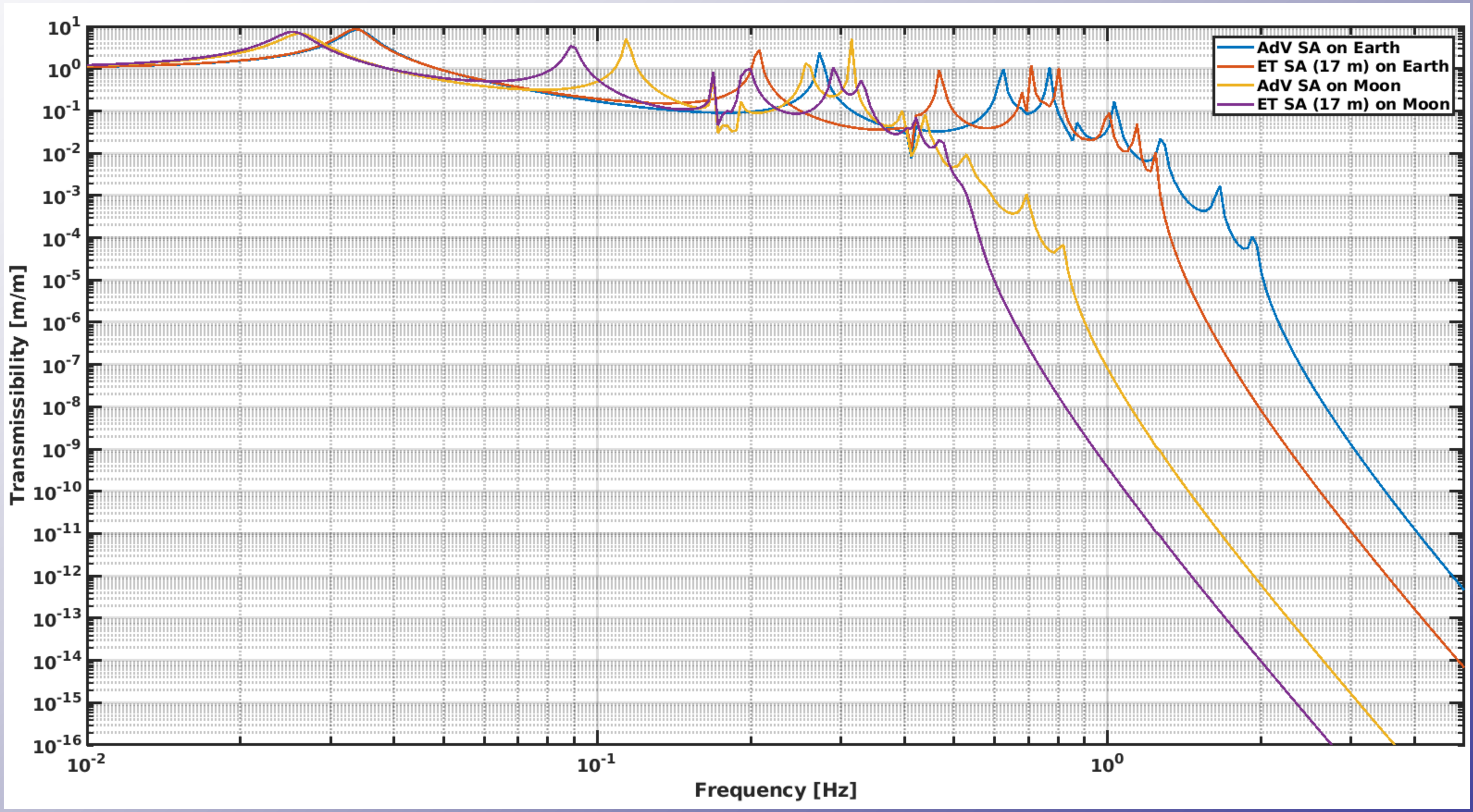
• All the LVDTs are operated using a digital demodulation scheme at 320 kHz sampling frequency



Going to the Moon
Horizontal Transmissibilities

• Octopus simulations of the superattenuators (SA) open-loop horizontal transfer function (Mirror Motion/Ground Motion), along the beam axis, in different configurations. Advanced Virgo SA and ET SA attenuation performance on Earth and on Moon are compared.

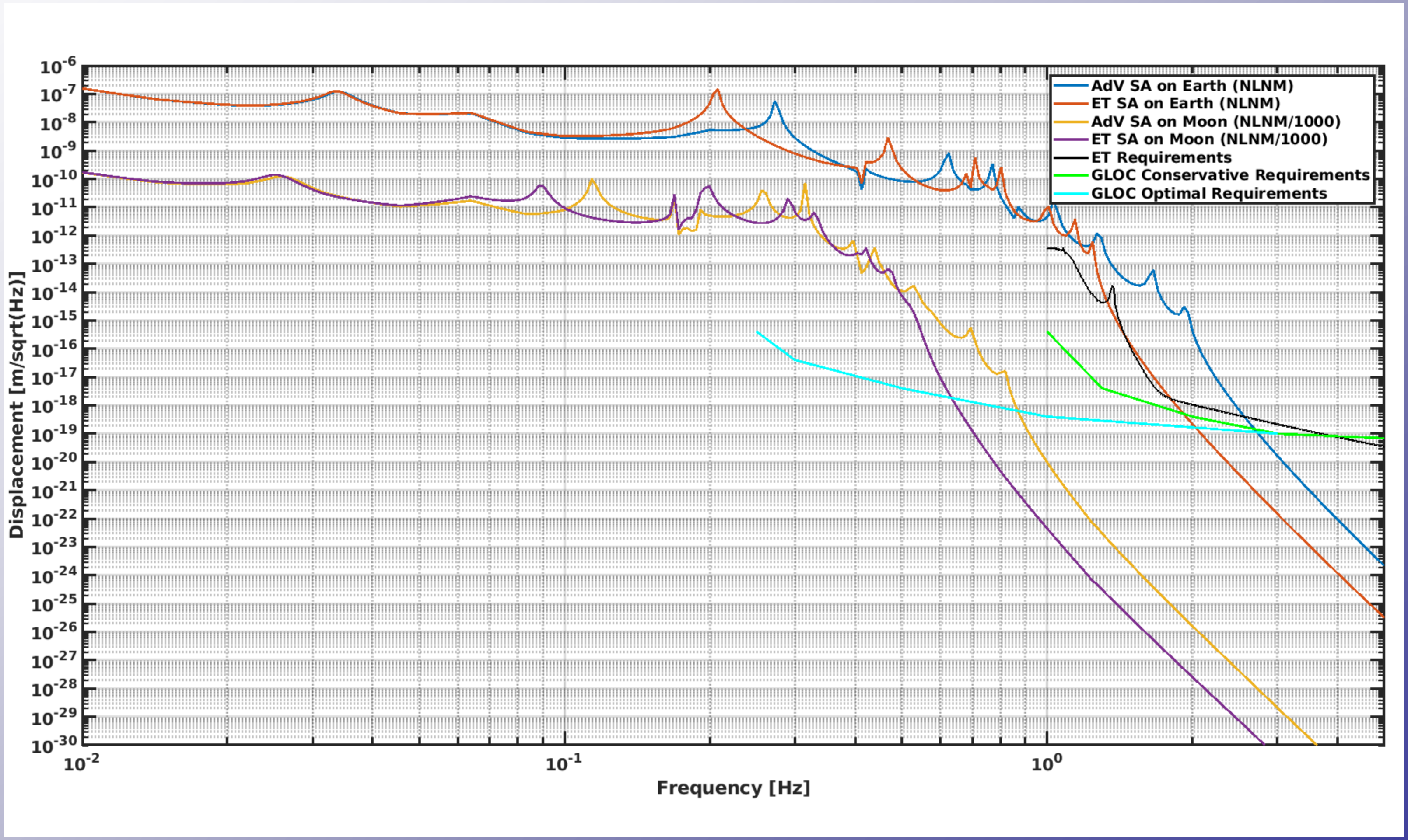
• The only mechanical parameter that has been changed is the lower diameter of the IP flex joint.



Going to the Moon
Displacement Spectra

- Octopus simulations of the superattenuators (SA) displacement spectra (Mirror Motion/Ground Motion), along the beam axis, in different configurations. Advanced Virgo SA and ET SA attenuation performance on Earth and on Moon are compared with ET and GLOC requirements (K. Jani, 2021).

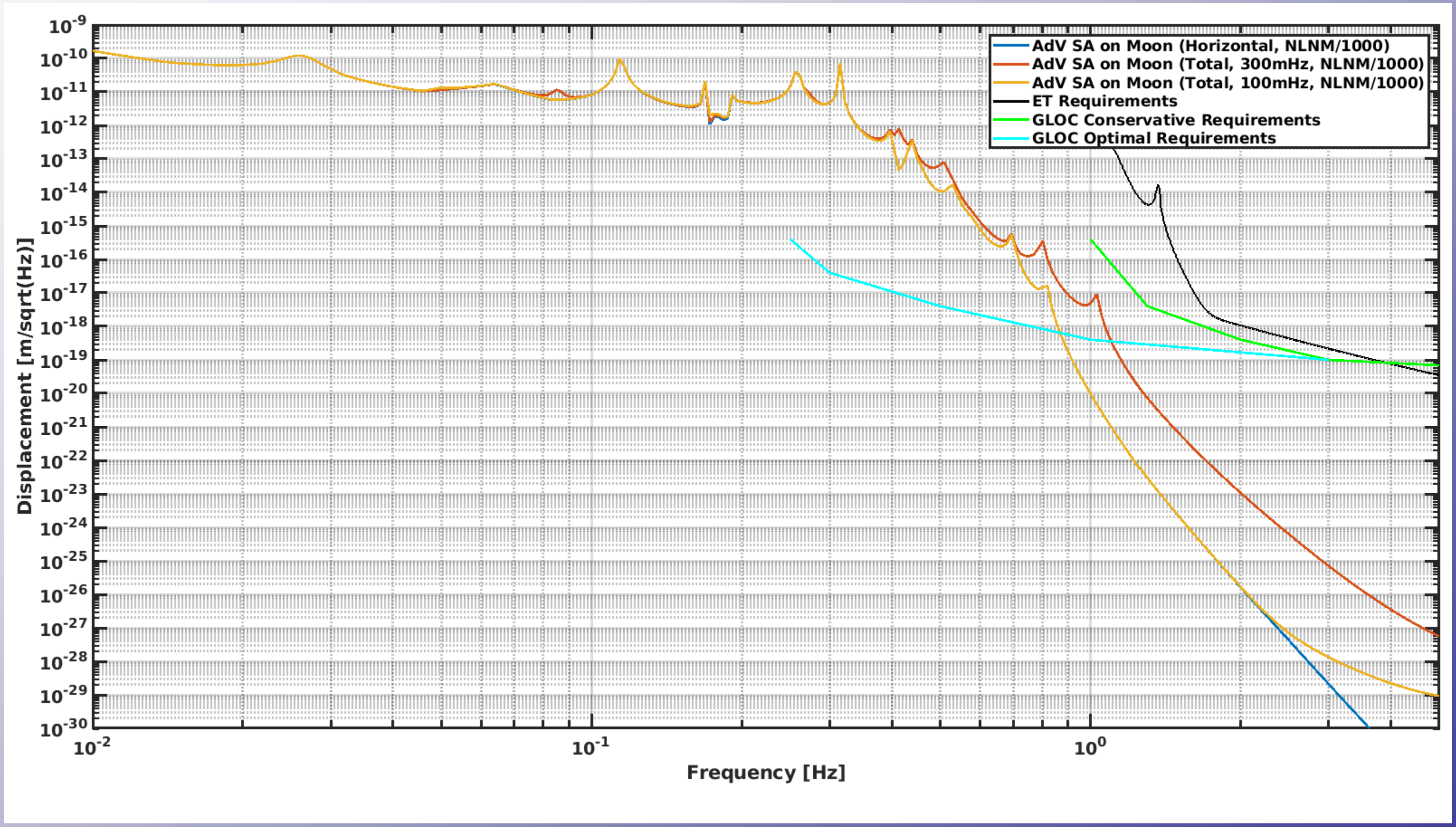
- Seismic noise model used are Peterson's NLNM and Peterson's NLNM/1000 (Lognonné, 2009)



Going to the Moon
Vertical Cross-coupling

• Vertical frequencies, typically 300 mHz in current SA, does not scale down with g since the they depends only by k and m. However since the blades will be loaded a factor 6 less, the could be made thinner and therefore tuning to lower frequencies will be much easier.

• In the simulations the H/V cross-coupling due to Moon curvature (2.3 % for GLOC) has been taken into account.



Going to the Moon
Problems

• **Sensors**: To implement inertial damping, both current displacement and inertial sensors will have to be improved by a factor 1000. Several groups are working on that in the ET perspective (see Joris' talk).

• **Tilt**: Angular ground motion is an open question on suspension control because accelerometers on SA top stage are sensitive both to tilt and acceleration. Depending on the tilt level on the Moon, high sensitive gyroscopes would be mandatory.

• **Thermal changes**: thermal variations of more 0.1 C impact suspension length. Thermal stabilization will be much more complex on the Moon.

Thank you for your attention!!