IV INTERNATIONAL WORKSHOP ON GRAVITOMAGNETISM AND LARGE-SCALE ROTATION MEASUREMENT

PISA, 15/06/2023

Large-band tiltmeters for Newtonian Noise studies in Virgo and ET detectors

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EGO

Outline

- The tiltmeter: from the prototype to the first upgrade
- Akìnetos: two months of data taking and first experimental results
- Towards the optimal seism-to-tilt decoupling: center of mass raising

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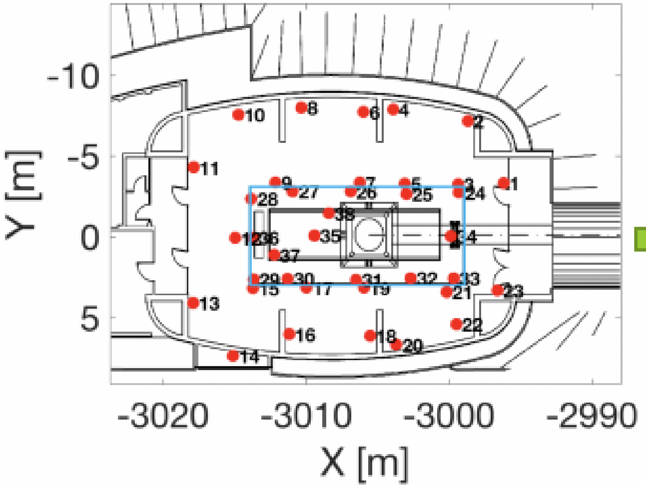
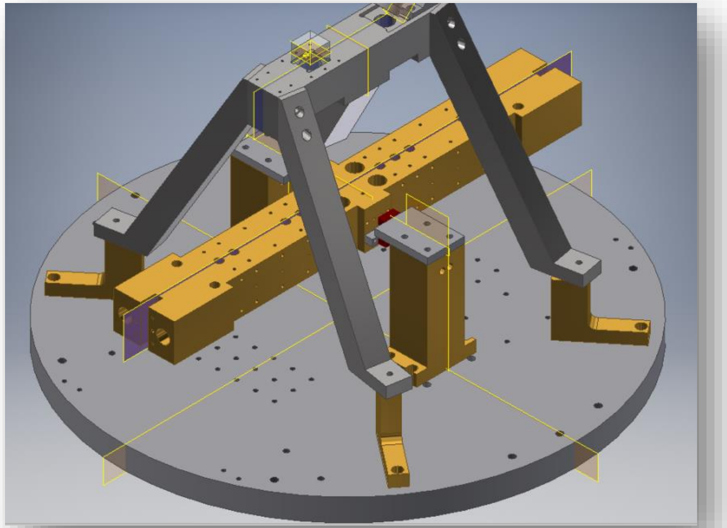
Tiltmeters in GW detectors

Newtonian Noise (NN) is predicted to limit the sensitivity of GW detectors in the future at frequencies **below 20 Hz**.

Its cancellation is based on a coherent estimate of NN using data from seismometer array **+ tiltmeter**

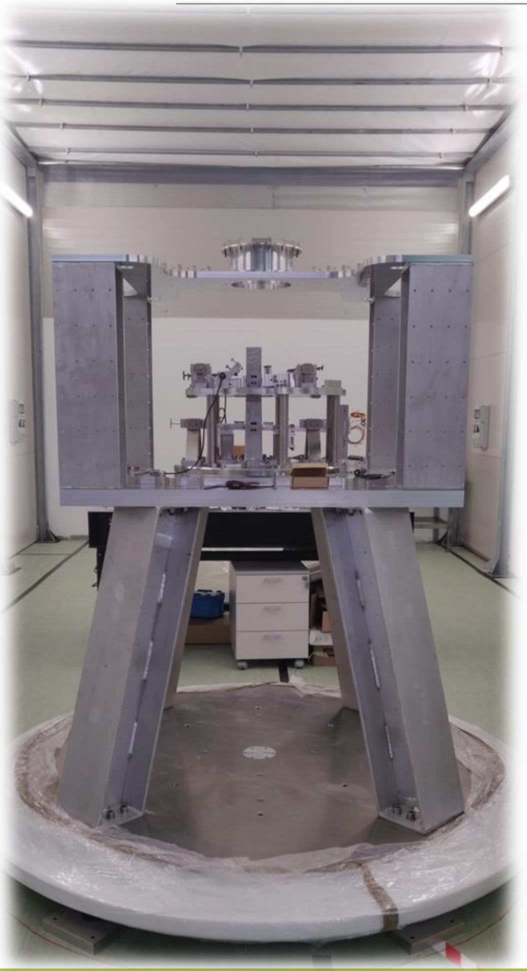




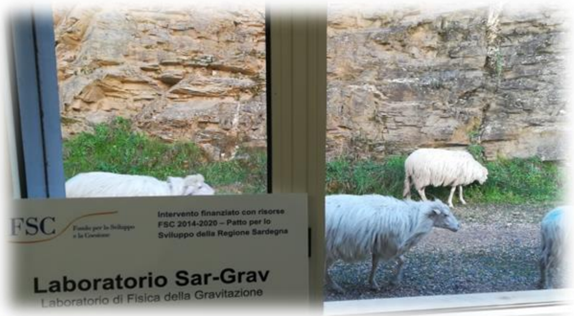
Tiltmeter
Proof-mass suspended by flexural joints. For a center of mass located close to the suspension bending point, torques from horizontal acceleration can be minimized

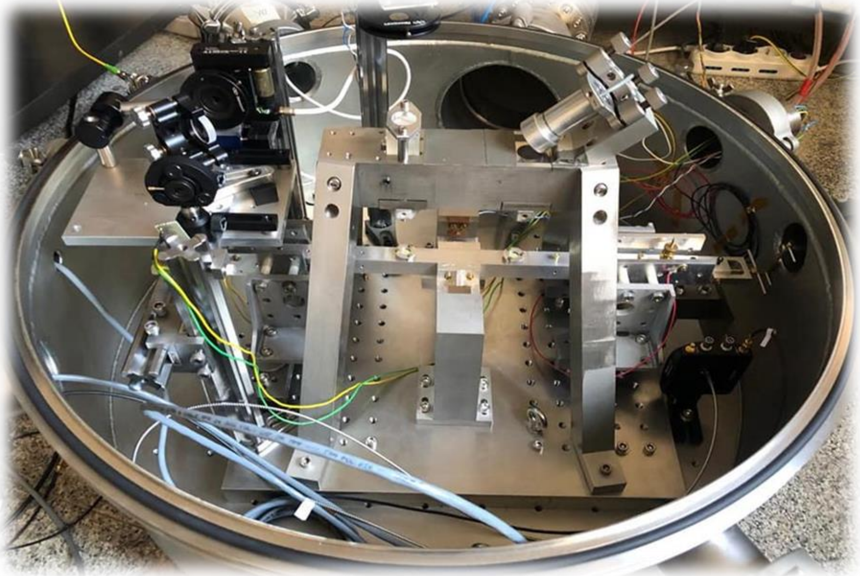
J. Harms - Class. Quantum Grav. ***33*** *(2016) 234001*
Maria C. Tringali et al 2020 Class. Quantum Grav. ***37*** *025005*

Tiltmeter prototype

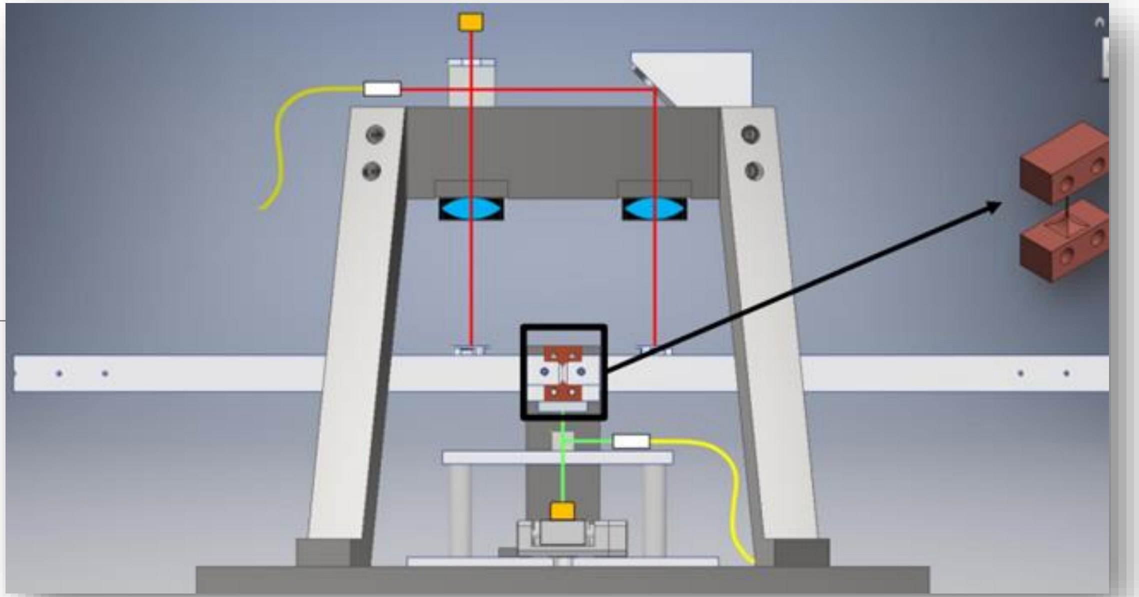


The first tiltmeter was thought to be a prototype of the **Archimedes** experiment, aiming to the measure of the interaction between quantum vacuum energy and gravity, currently installed in the Sar-Grav laboratories in Sos-Enattos – Sardinia.

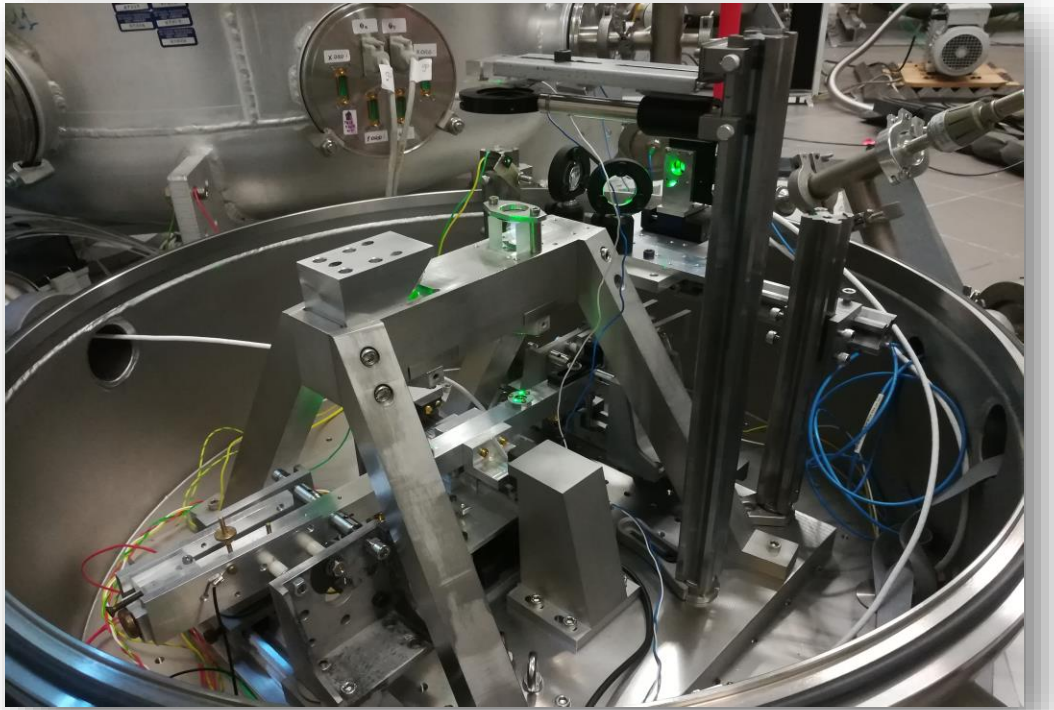




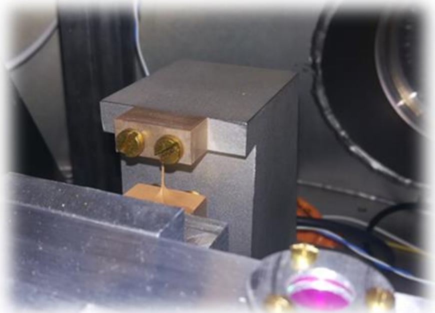
Tiltmeter prototype - mechanics



- **Beam balance,** 50 cm long aluminum arm with brass cylinders 11 cm long inside, with low momentum of inertia (0.02 kg*m^2)



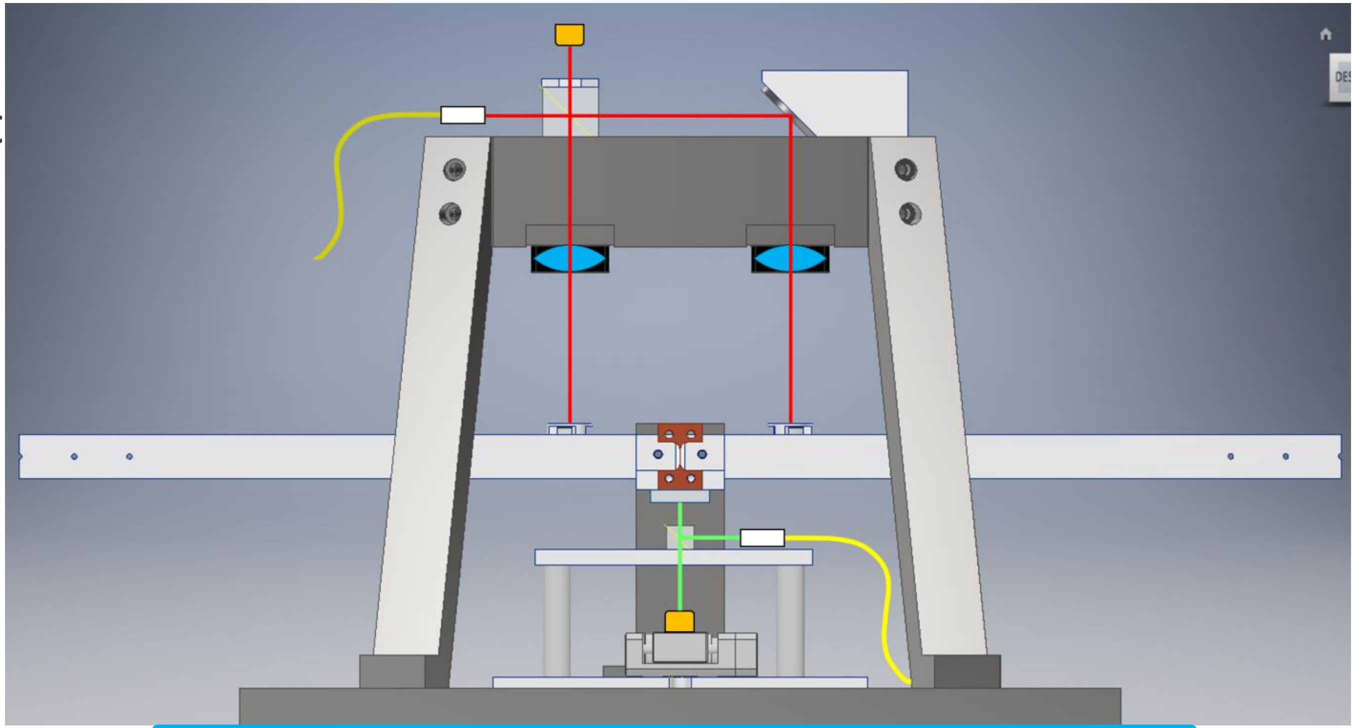
- Tiltmeter arm is suspended through **Cu-Be flexible joints**, **100μm x 500μm in section,** very similar in design to LIGO tiltmeters (*Venkateswara et al., 2014*) which allow to keep **the resonance frequency below 20 mHz**



Tiltmeter prototype – optical readout

The tiltmeter is equipped with two different optical readout systems, providing an error signal for the feedback control and damp low frequency tilts (drifts):

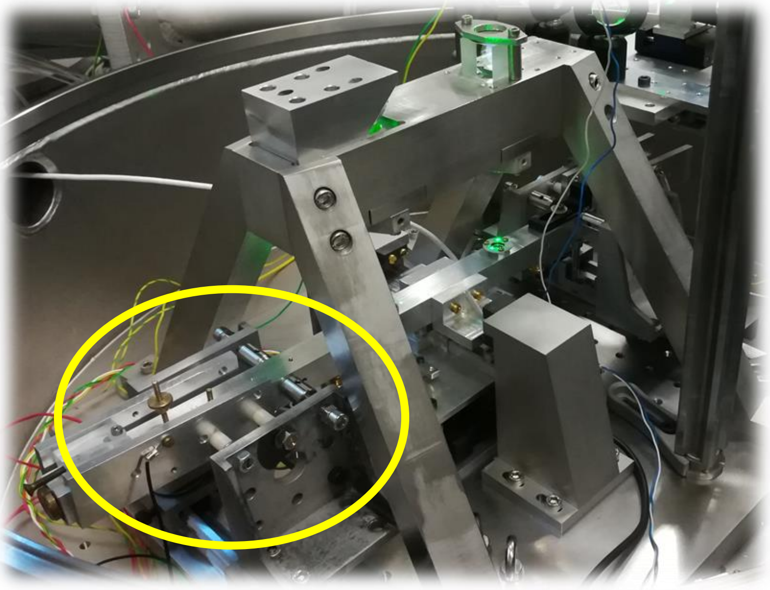
- **Optical lever** (wider dynamic range)
- **Interferometer** (higher sensitivity)

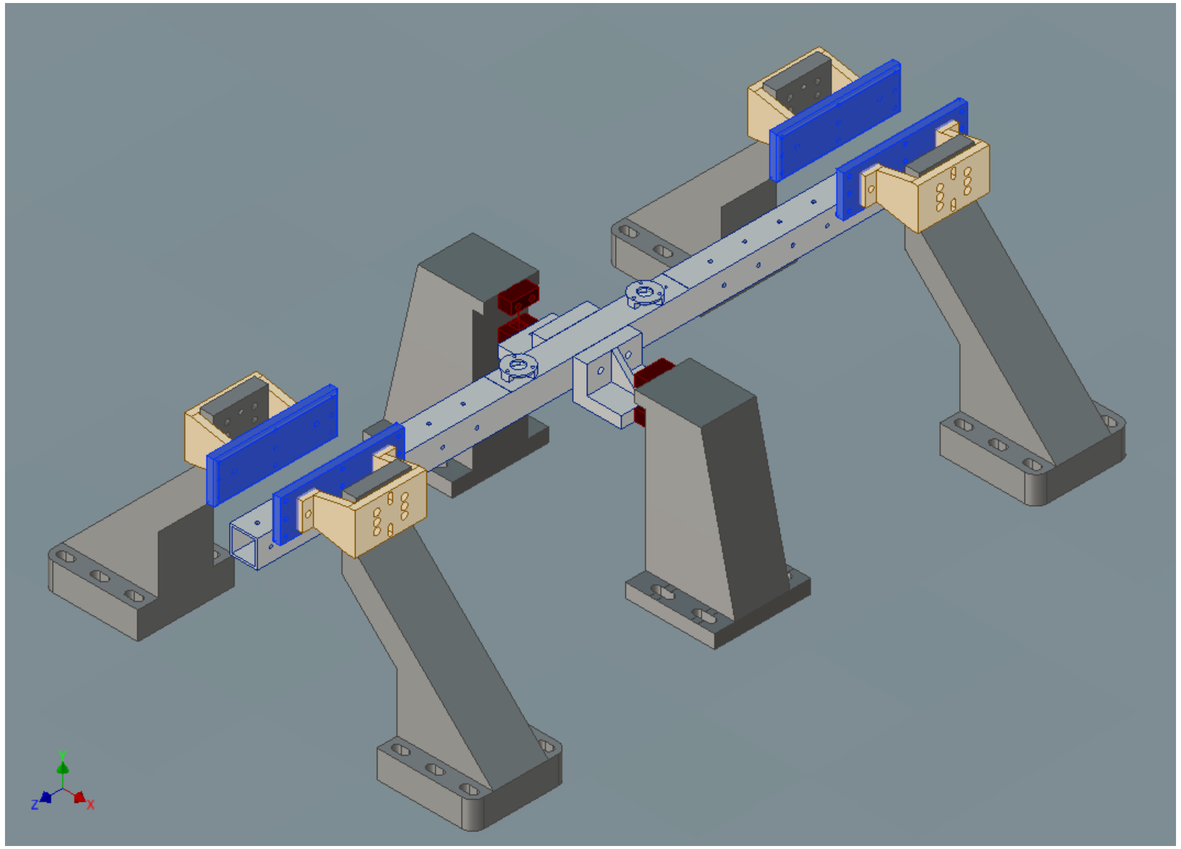


Lenses in the ITF read-out are added to give **robustness against static arm tilts**

Tiltmeter prototype – controls

- Control in feedback performed with **electrostatic actuators** (a couple at the end of each side of the arm – blue in figure)





First installation in Virgo

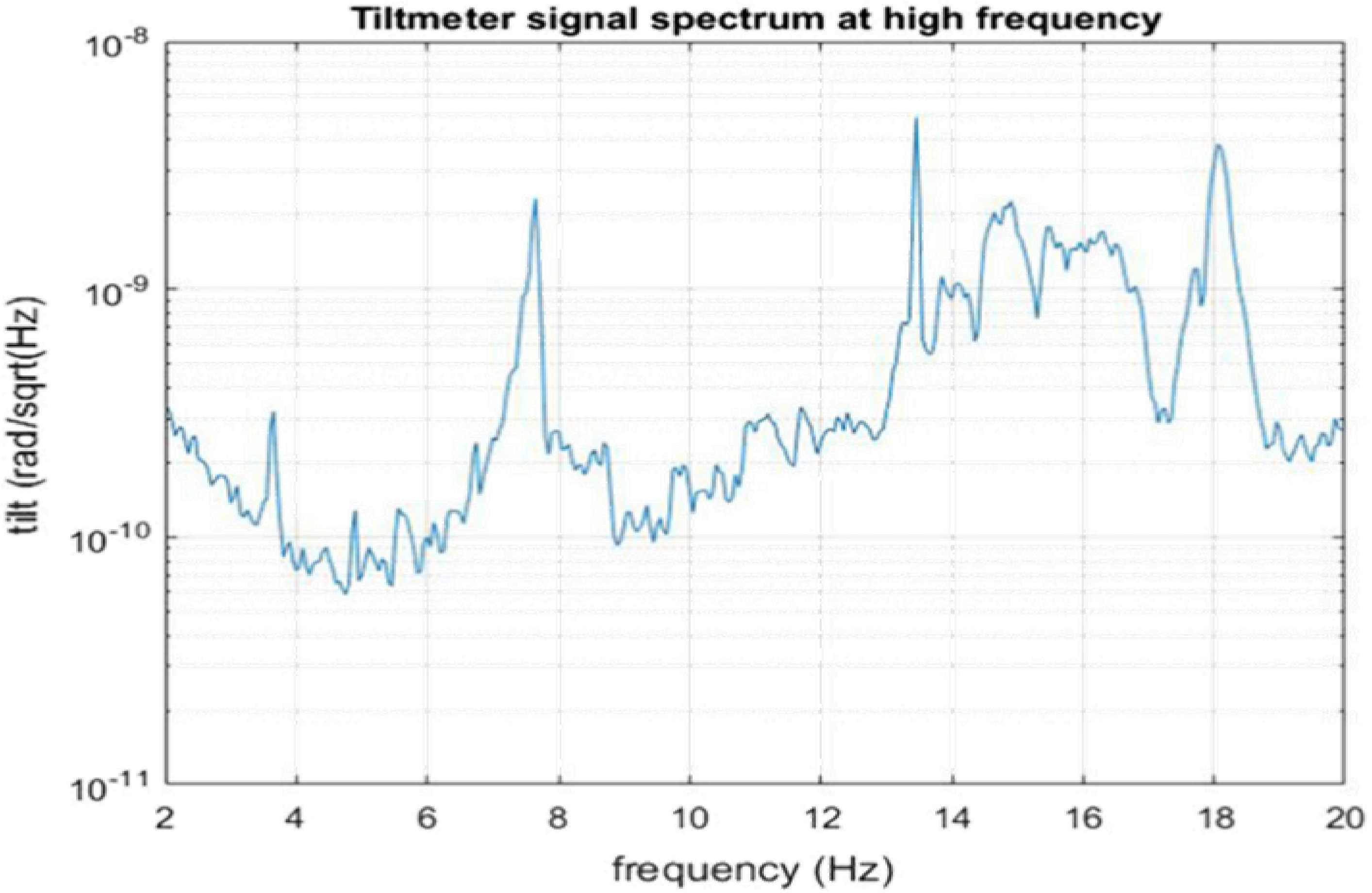
- Installed by the Virgo-Napoli group in Feb 2019. Data acquired during part of O3

- Oriented to be mainly sensitive to **ground tilts along the direction of the North Arm**

- **Digital acquisition and control system was completely Virgo-like** (same modules used to control the superattenuators – developed by **Virgo-Pisa group**)

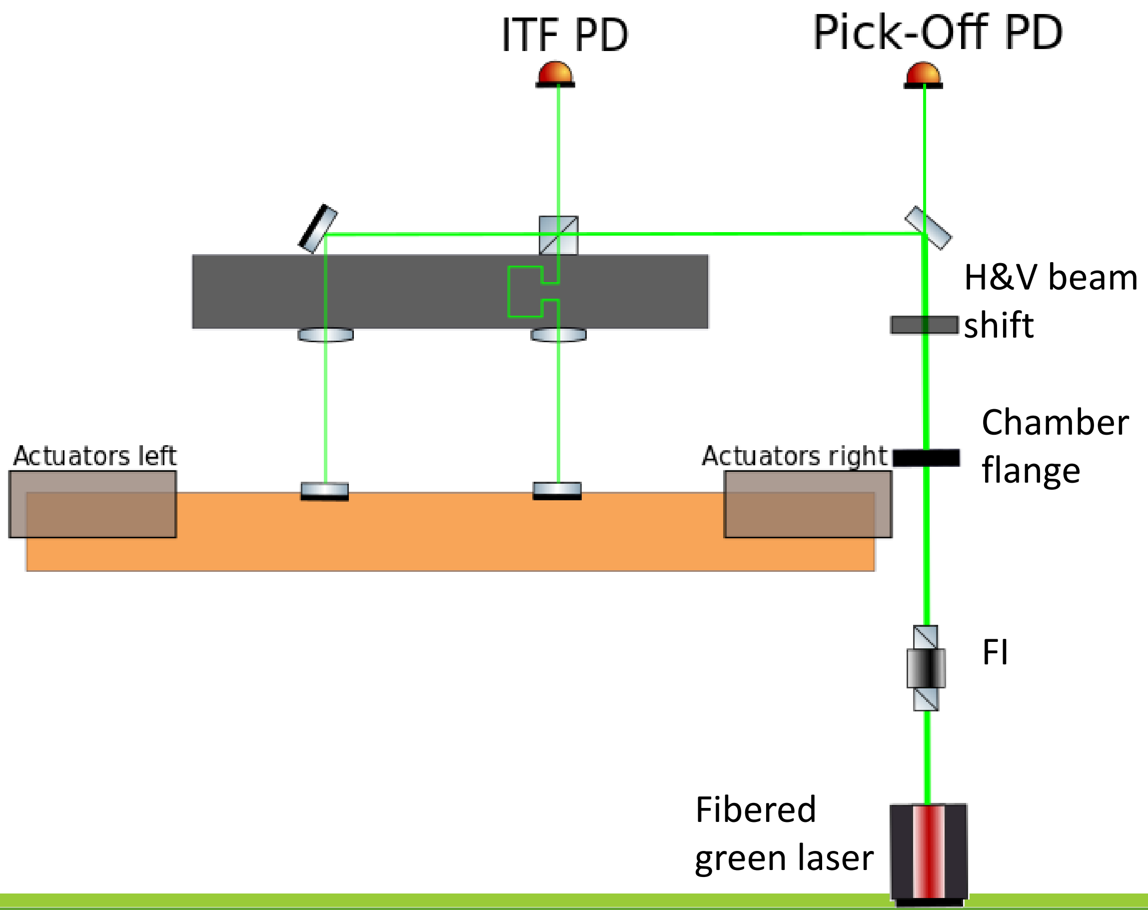
- Tilt measurements compared to tilt reconstruction by seismometer array @NE reported in *Ayatri Singha et al 2021 Class. Quantum Grav. 38 245007*

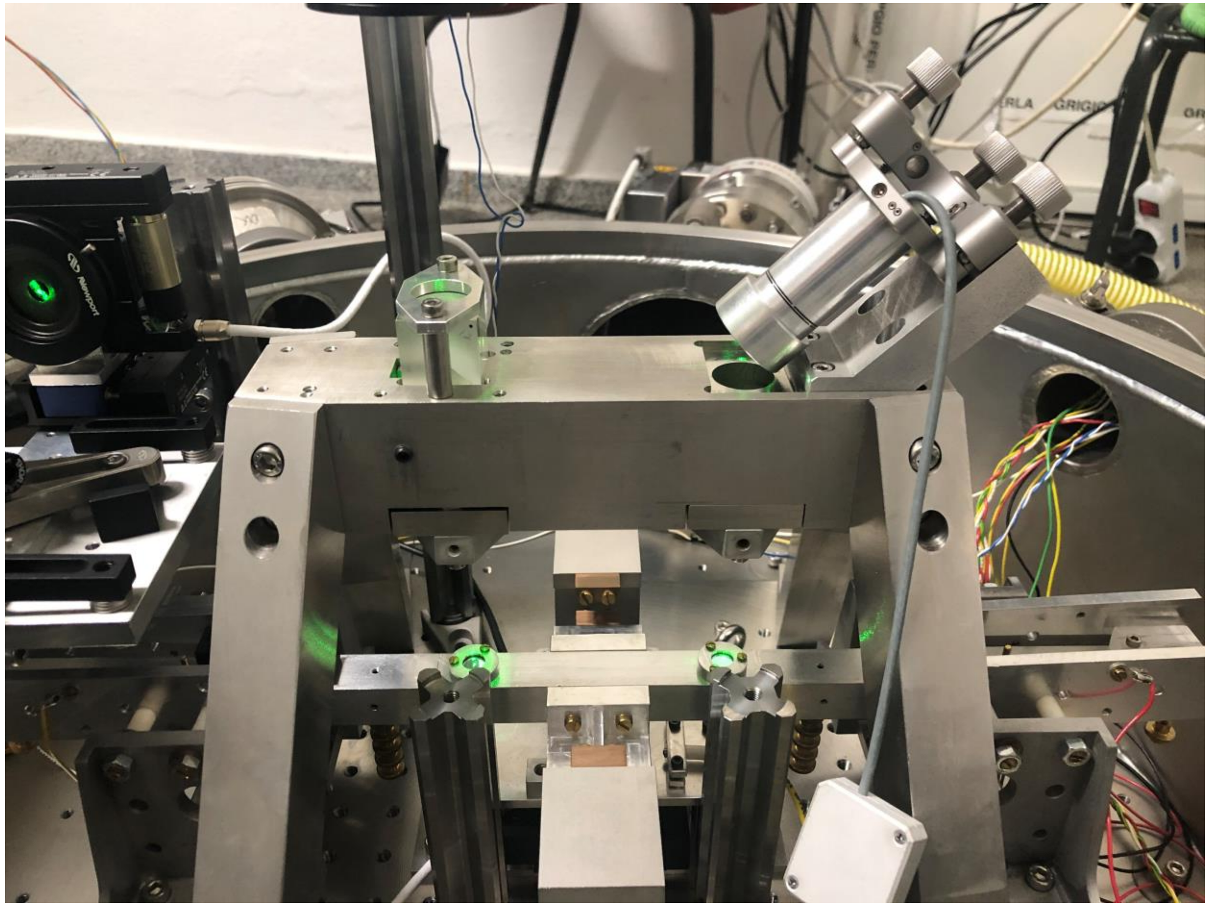
Tiltmeter sensitivity in Virgo 2019



E. Calloni - Eur. Phys. J. Plus **136**, 335 (2021)

Tiltmeter – first improvements





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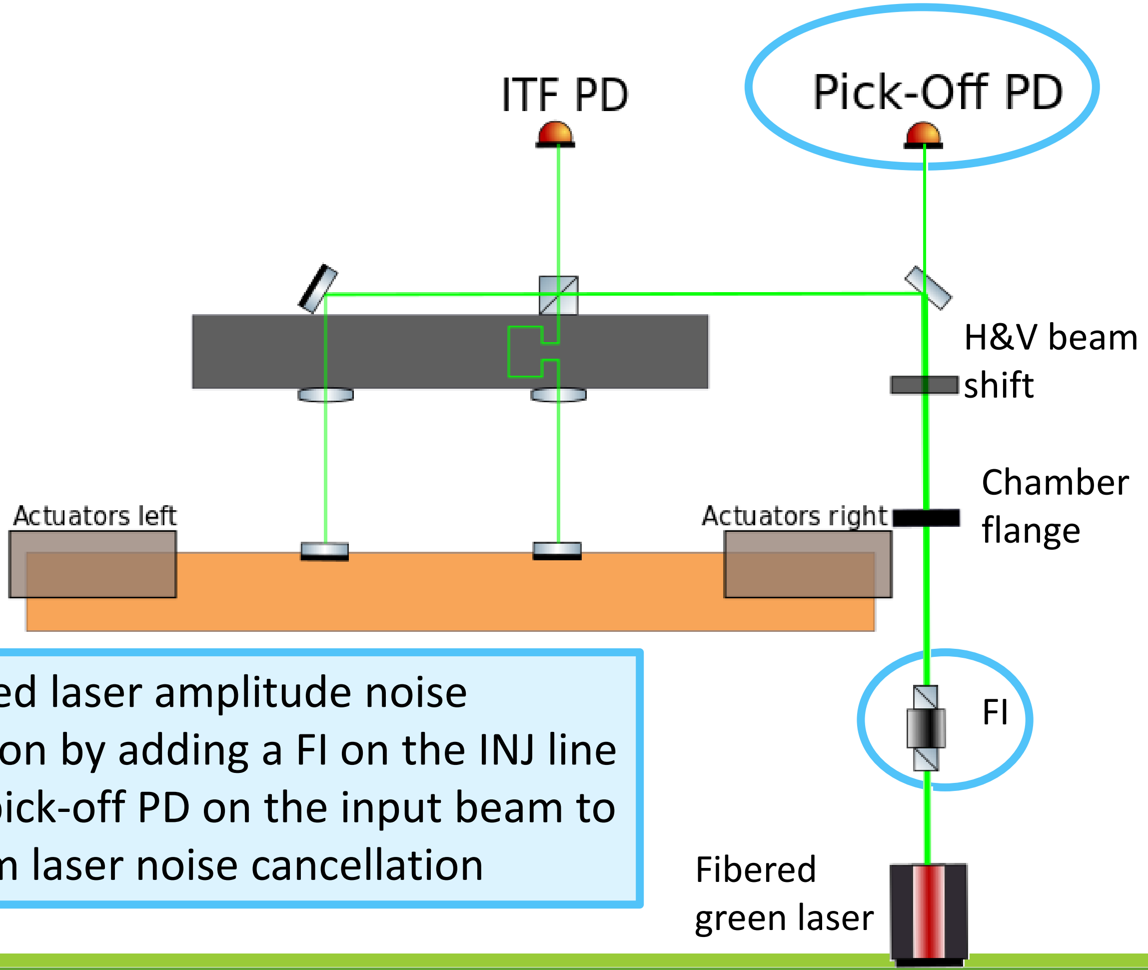
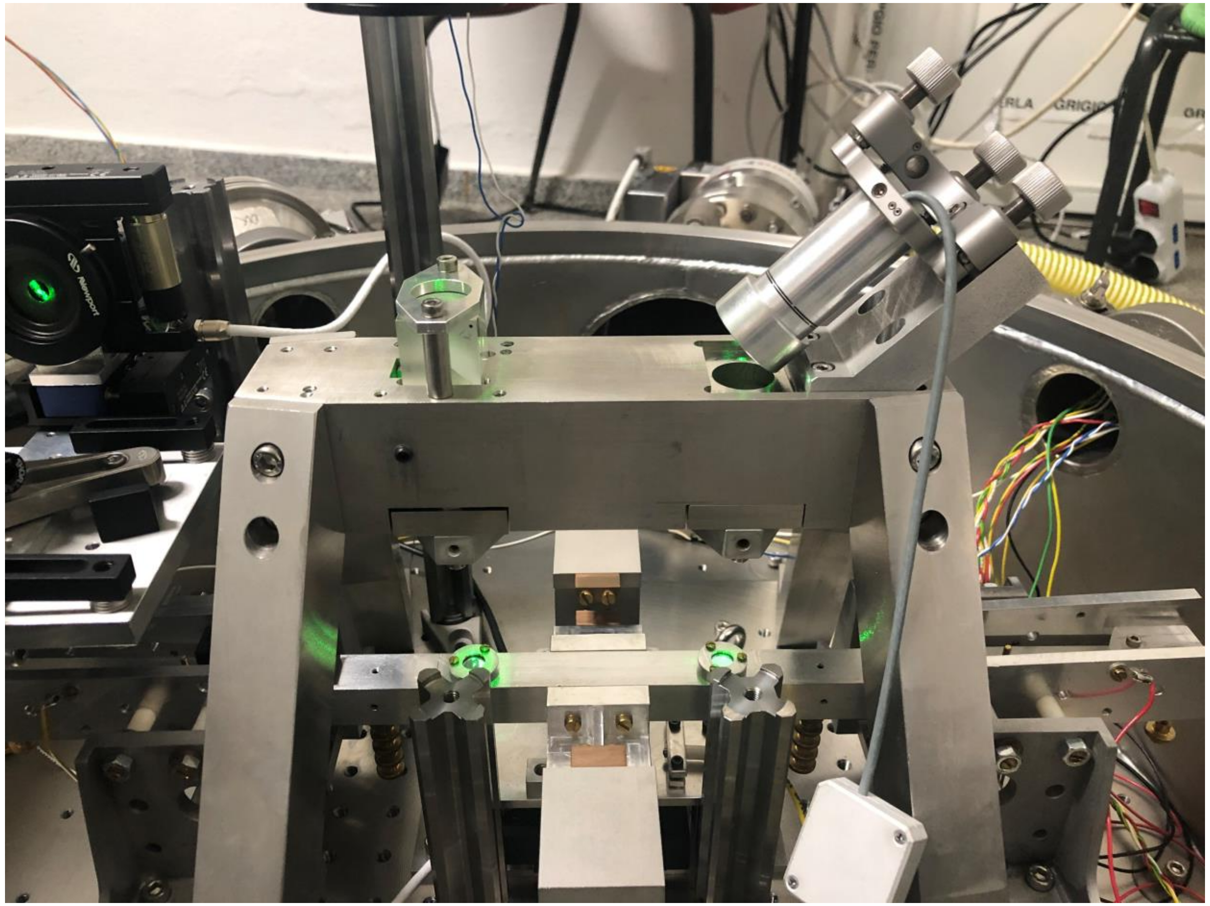
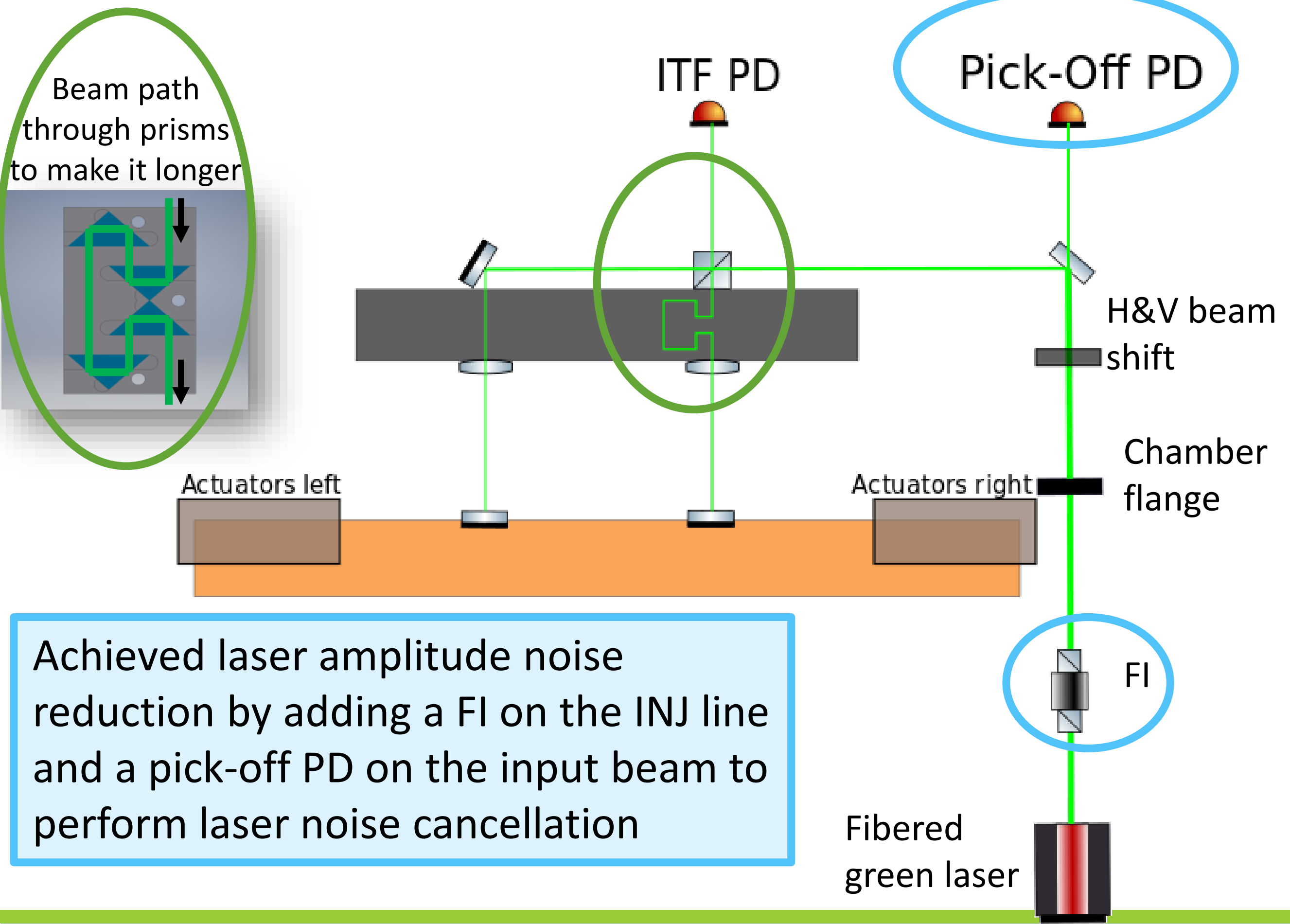


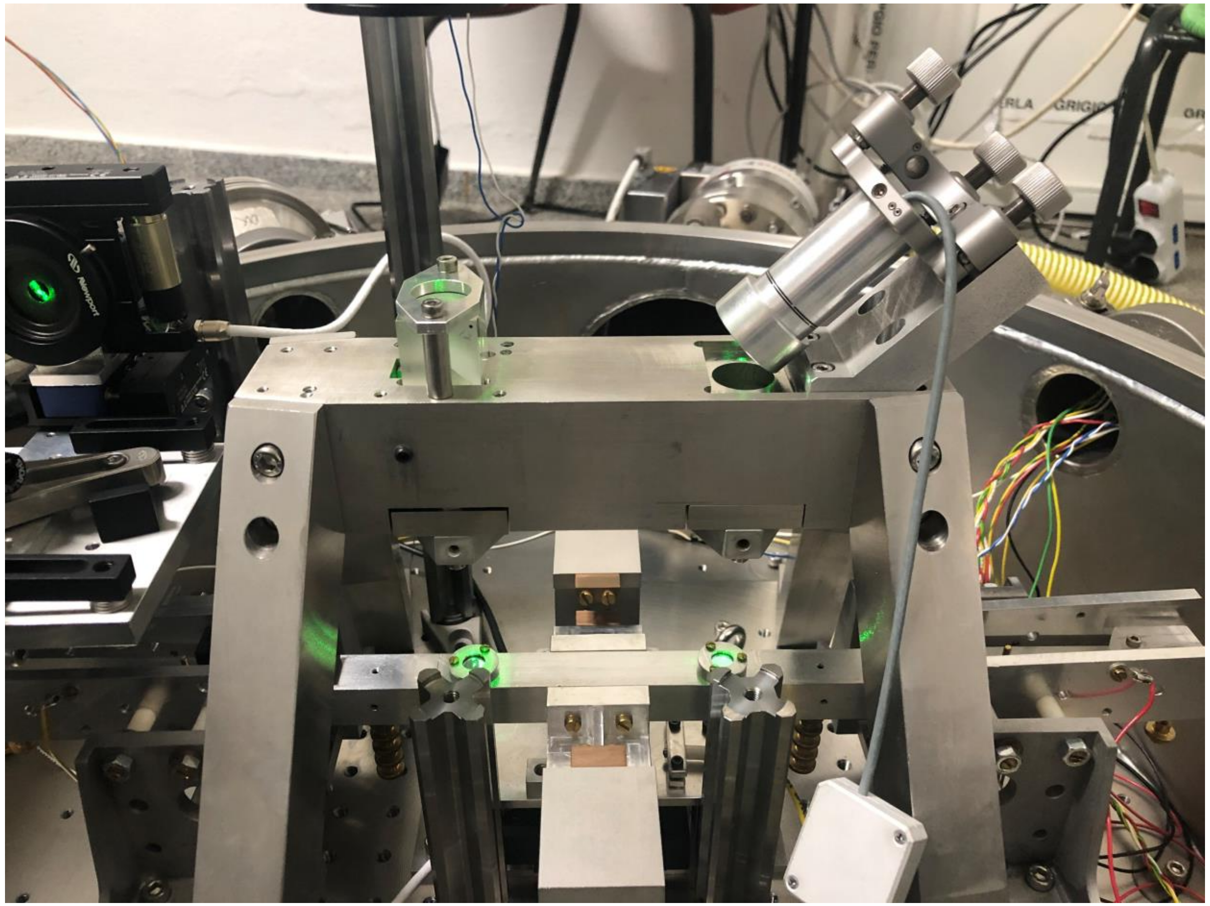
Achieved laser amplitude noise reduction by adding a FI on the INJ line and a pick-off PD on the input beam to perform laser noise cancellation



Tiltmeter – first improvements

Reduced frequency noise coupling by equalizing interferometer arms (from $\Delta L = 10\ cm$ to $\Delta L \approx 2\ mm$)





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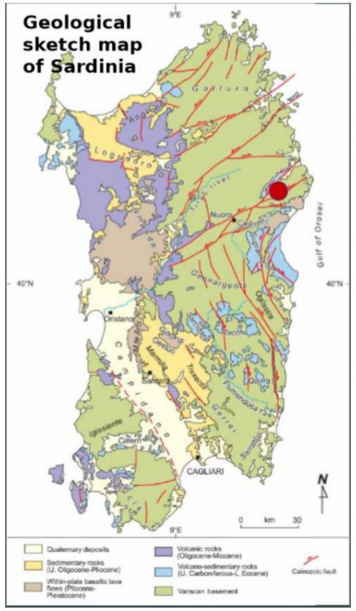
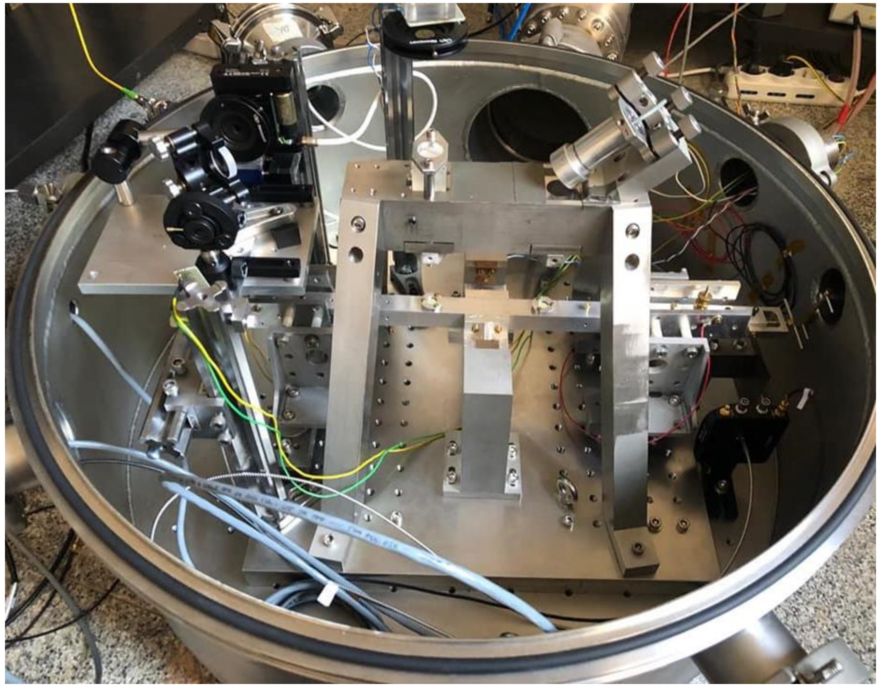




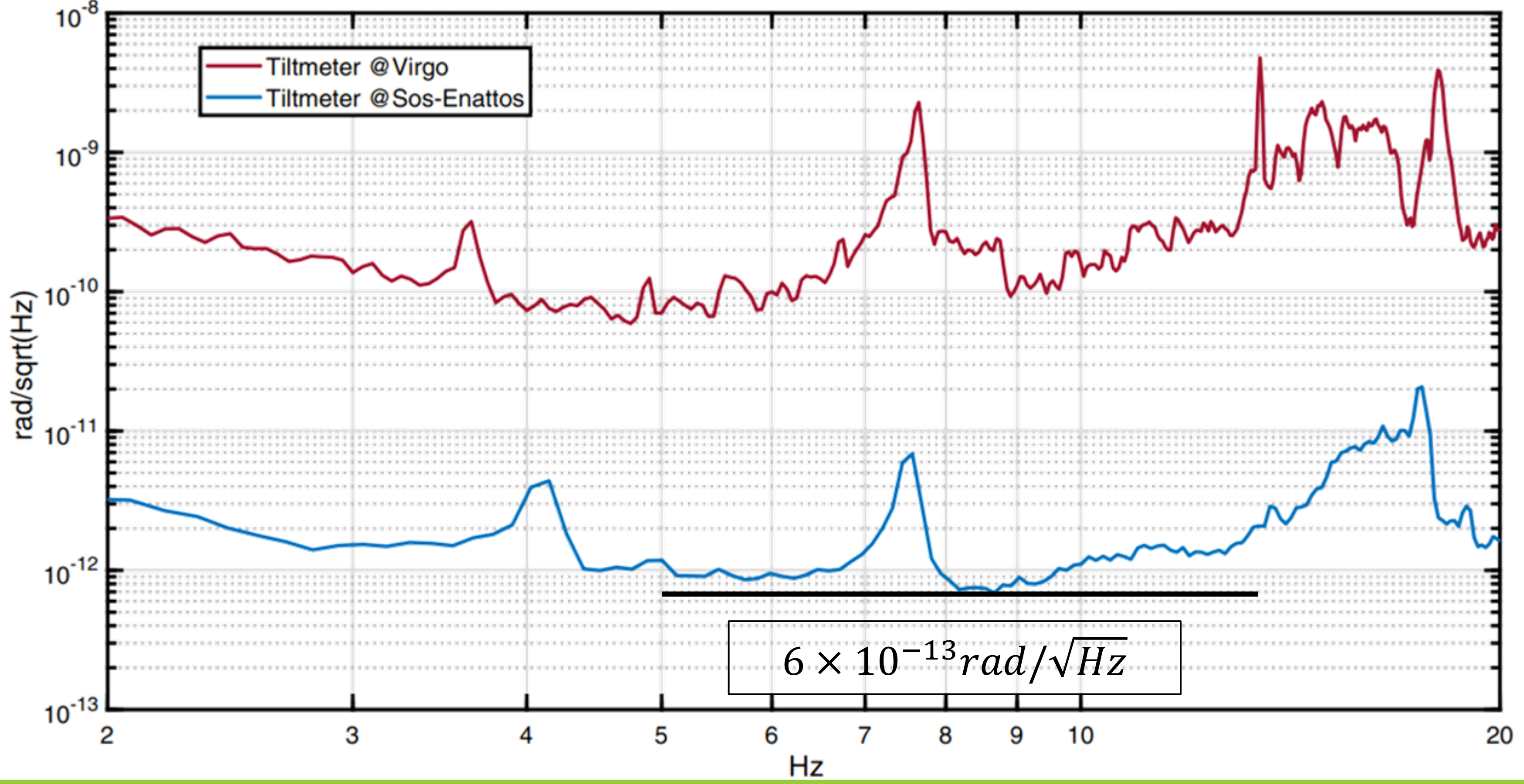



Tiltmeter in Sos-Enattos

INSTALLED IN THE SAR-GRAV LABORATORIES AT THE SOS-ENATTOS MINE IN FEB 2020

Tilt measurement comparison between Virgo and Sos-Enattos

Most sensitive tiltmeter in the world in the frequency band 2-20 Hz



L. Errico et al, Eur. Phys. J. Plus (2021) 136:1069

Tilt measurement comparison between Virgo and Sos-Enattos

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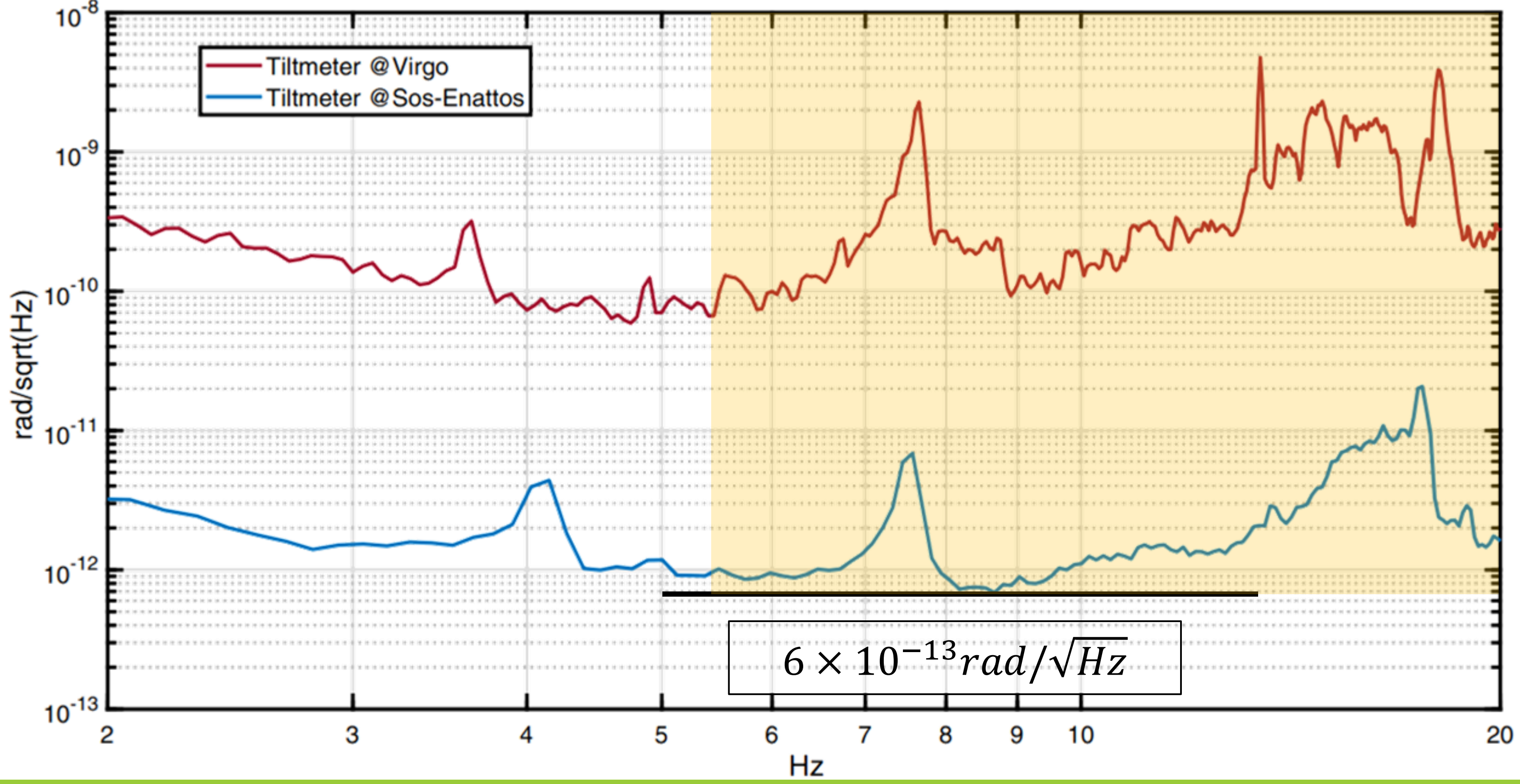

Above 5 Hz frequency noise coupling was reduced between the two tiltmeter versions

L. Errico et al, Eur. Phys. J. Plus (2021) 136:1069

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- The tiltmeter: from the prototype to the first upgrade
- **Akìnetos: two months of data taking and first experimental results**
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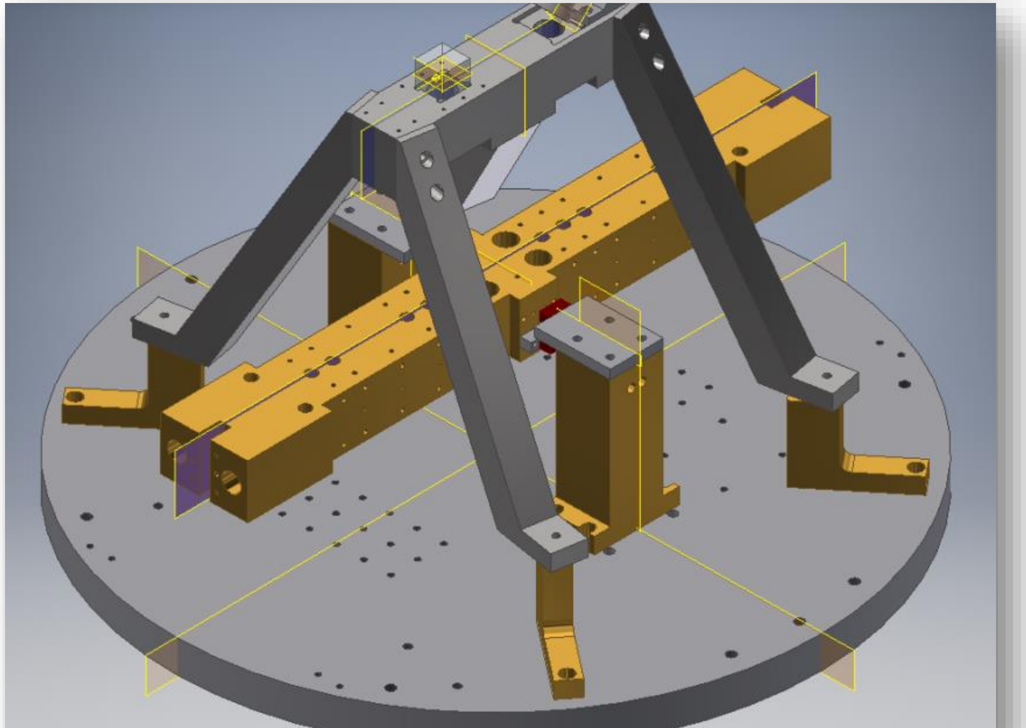
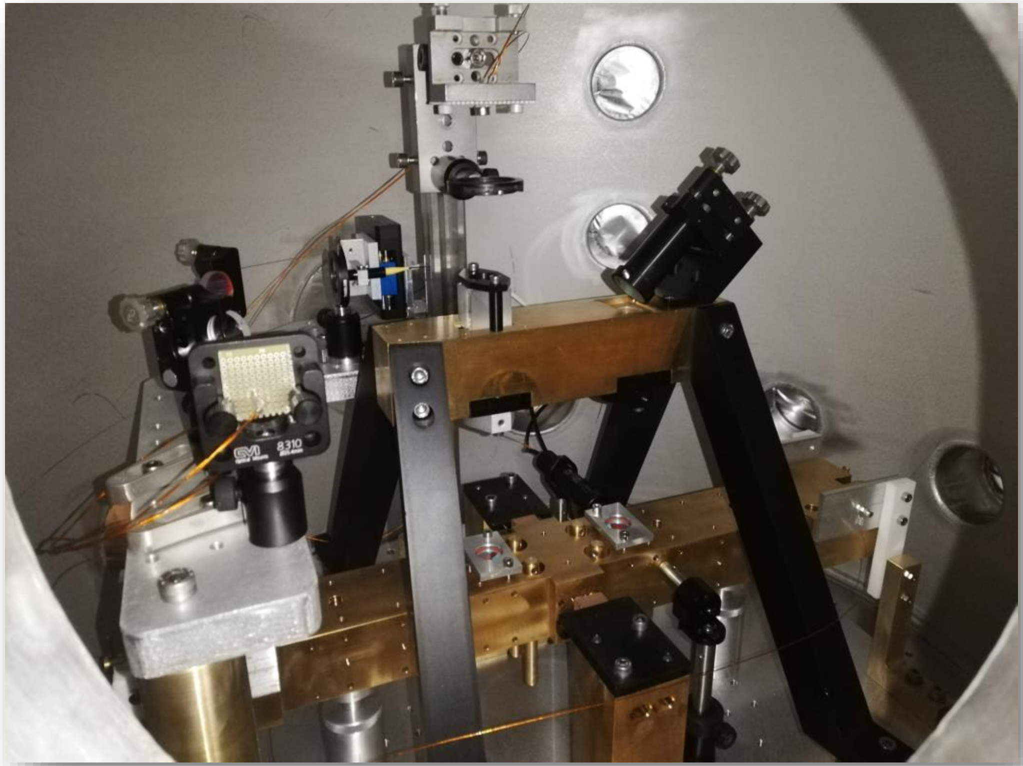
᾿Ακίνητος: the new tiltmeter

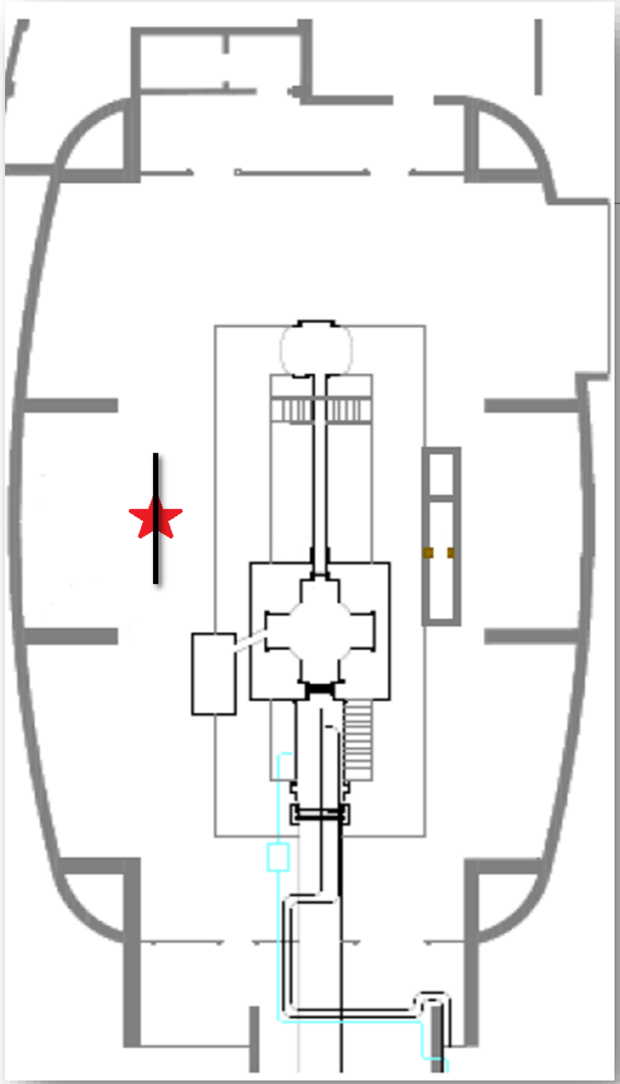
The new tiltmeter exploits the same working principles as the prototype.

Main improvement: arm with much higher momentum of inertia: 13 kg of brass, I = 0.33 kg*m^2, more than one order of magnitude bigger than the previous version, joint size: 0.1x3mm



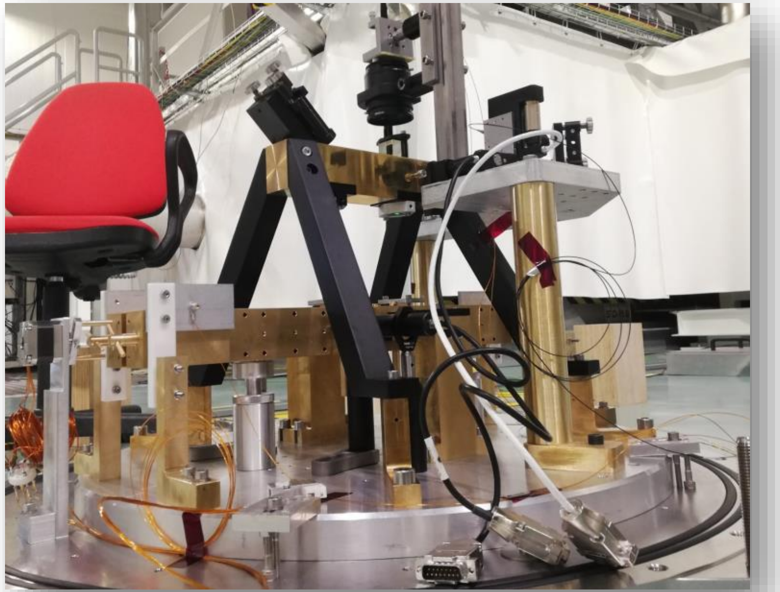
CAD sketch by L.Errico





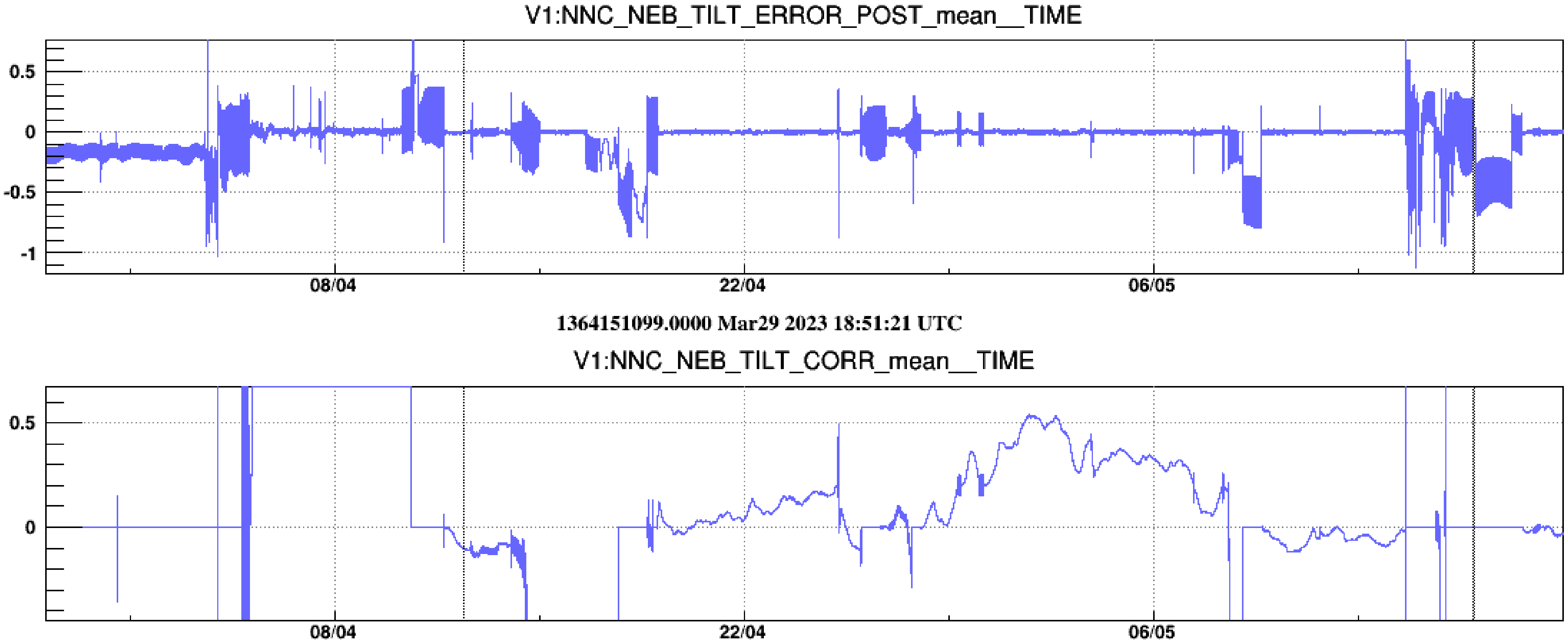
’Ακίνητος: the new tiltmeter

Installed in the NEB, along the arm direction at the end of March 2023



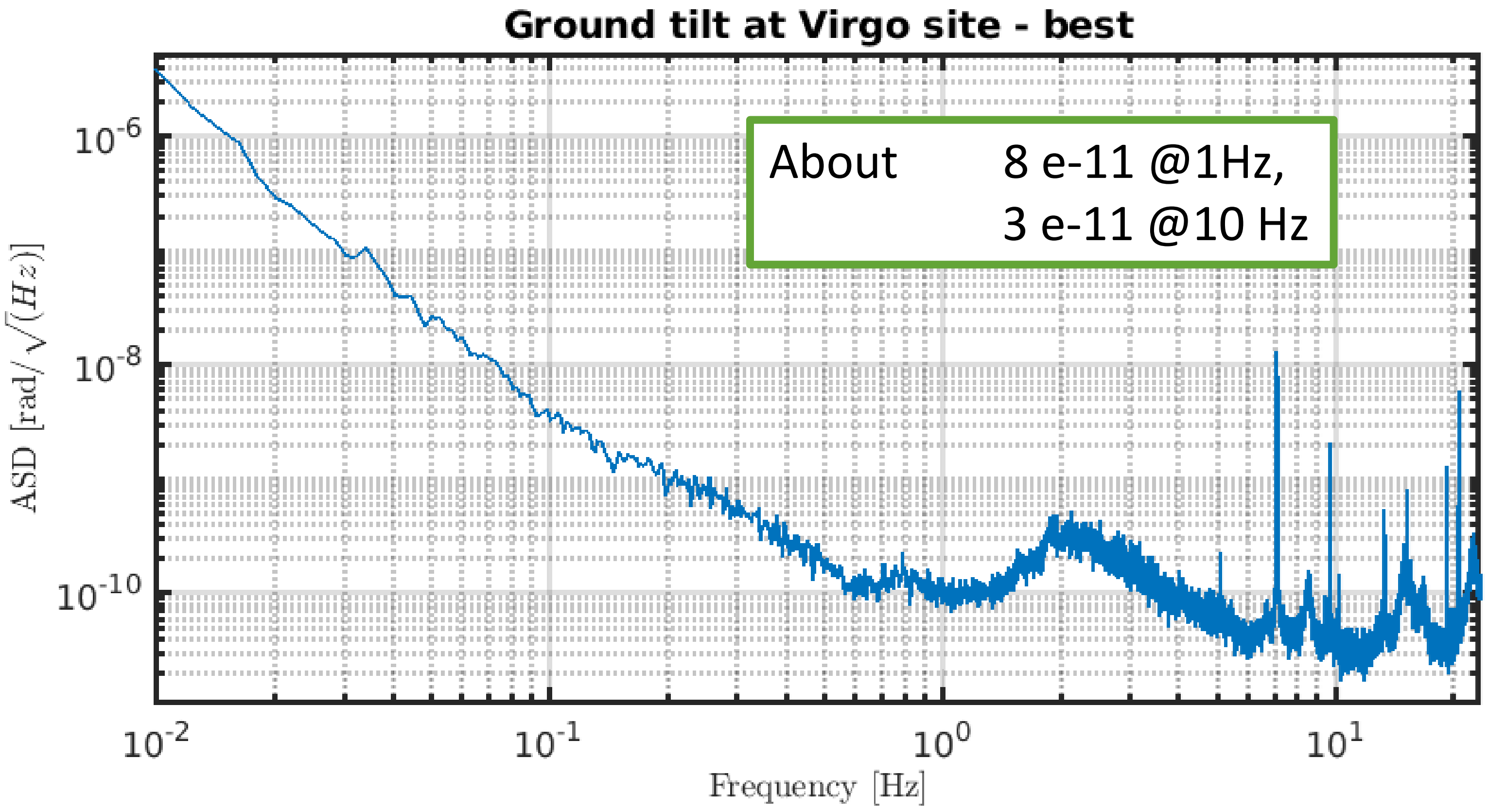
First 2 months of data

Installed during the week of March 20th, first arm lock at the end of March

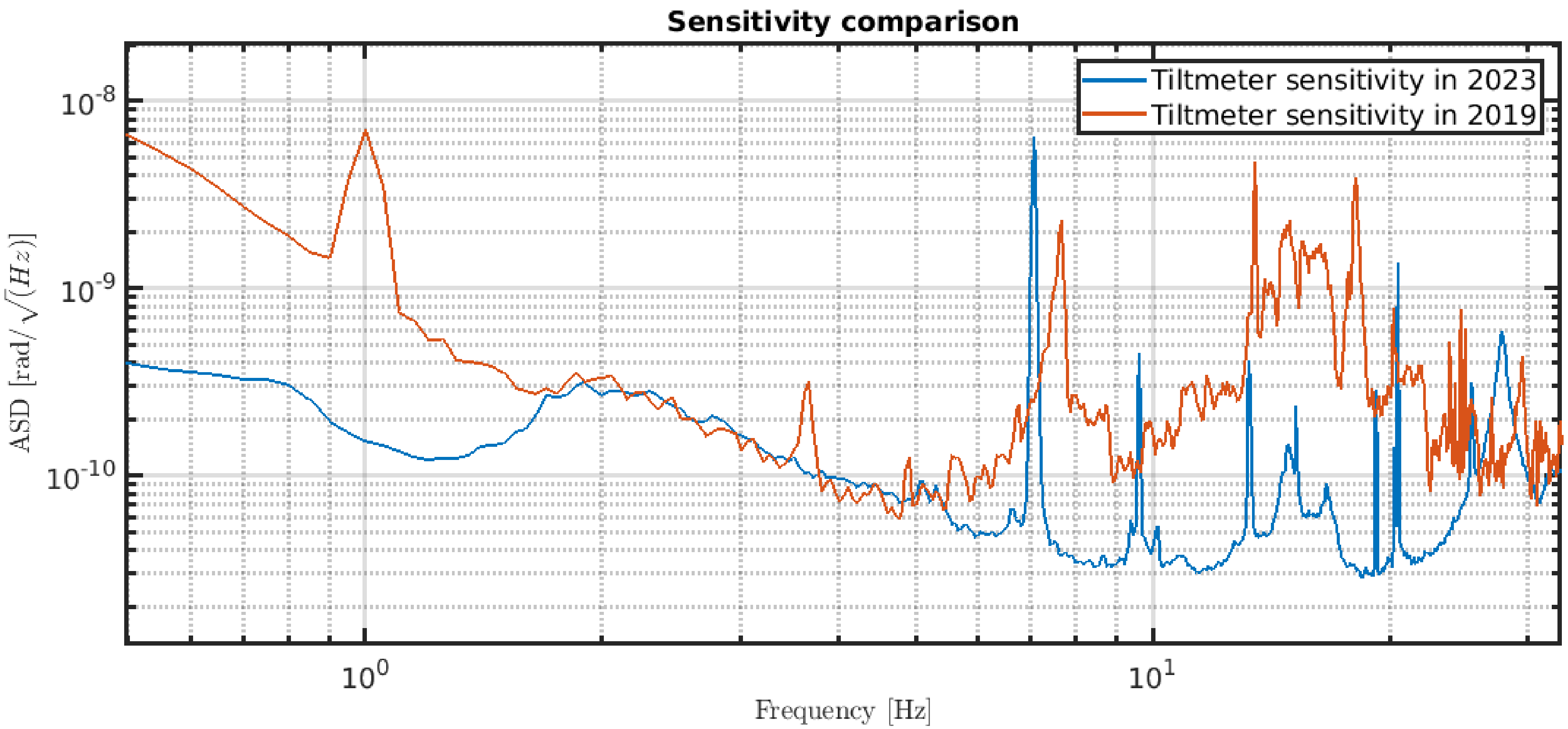


- Good duty cycle (more than 70%)
- Low correction to hold the beam in position using ITF readout

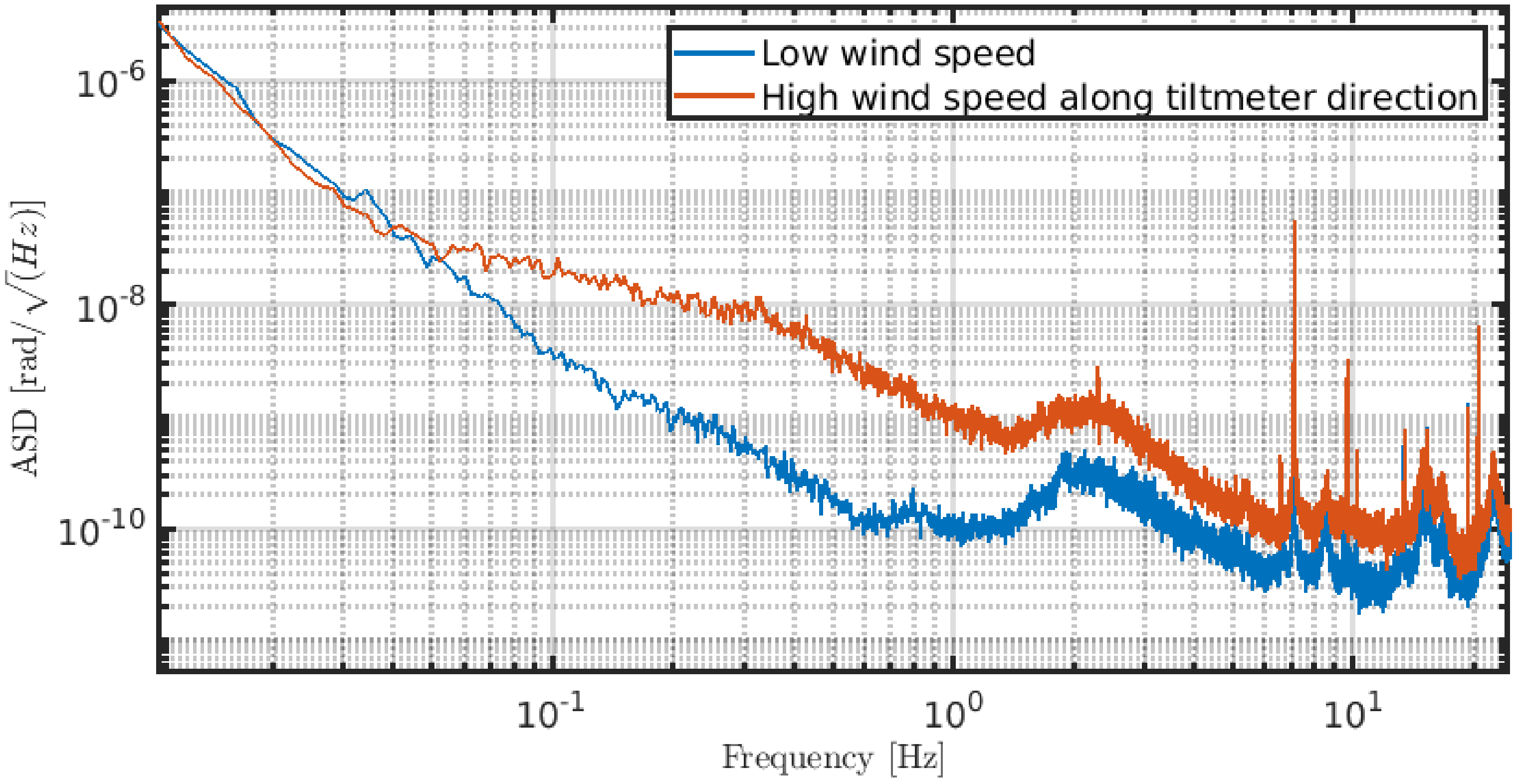
Best sensitivity curve in the first month of operation



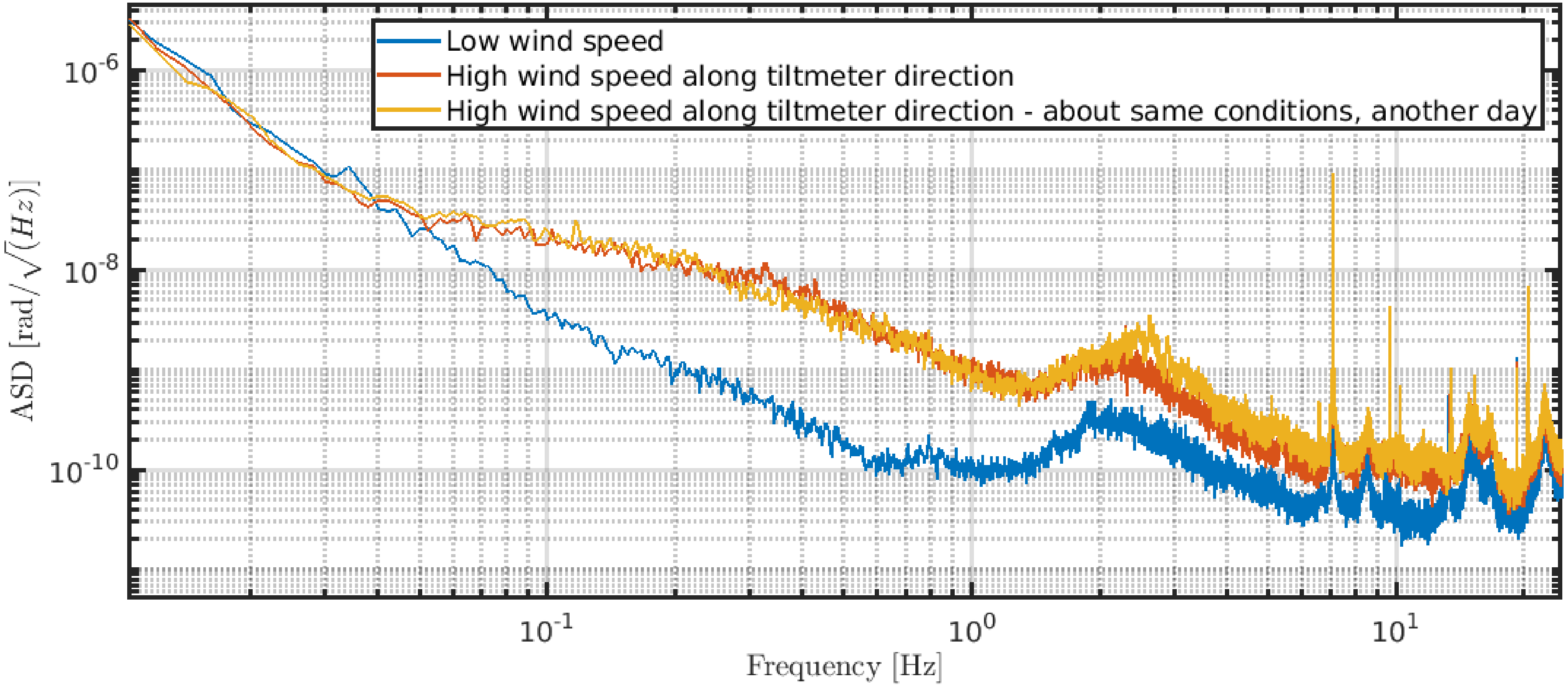
Comparison between tiltmeters sensitivity in 2019 vs 2023



Ground tilt measurement in different wind conditions

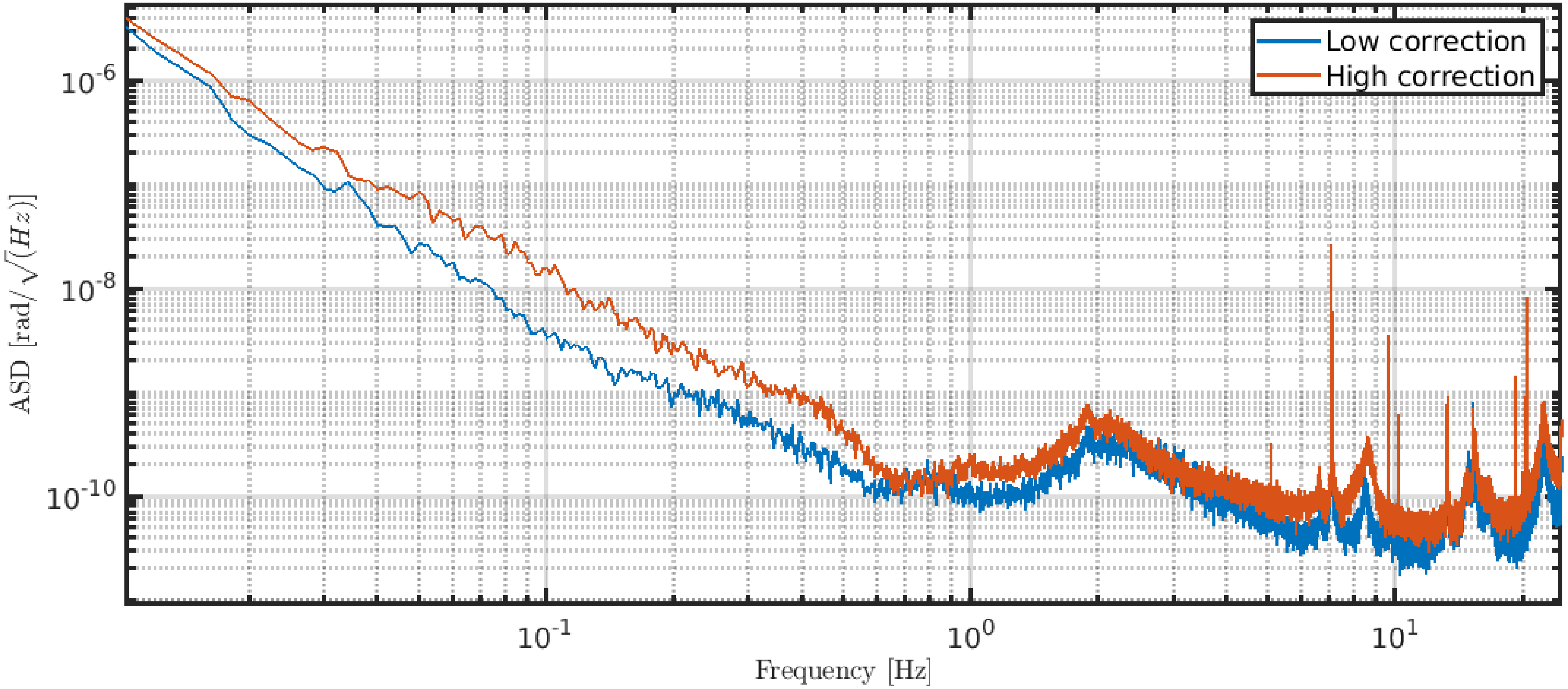


Ground tilt measurement in different wind conditions - repeatability



Same spectrum in similar conditions: further confirmation that tilt is actually measured

Effect of actuation noise @low frequency



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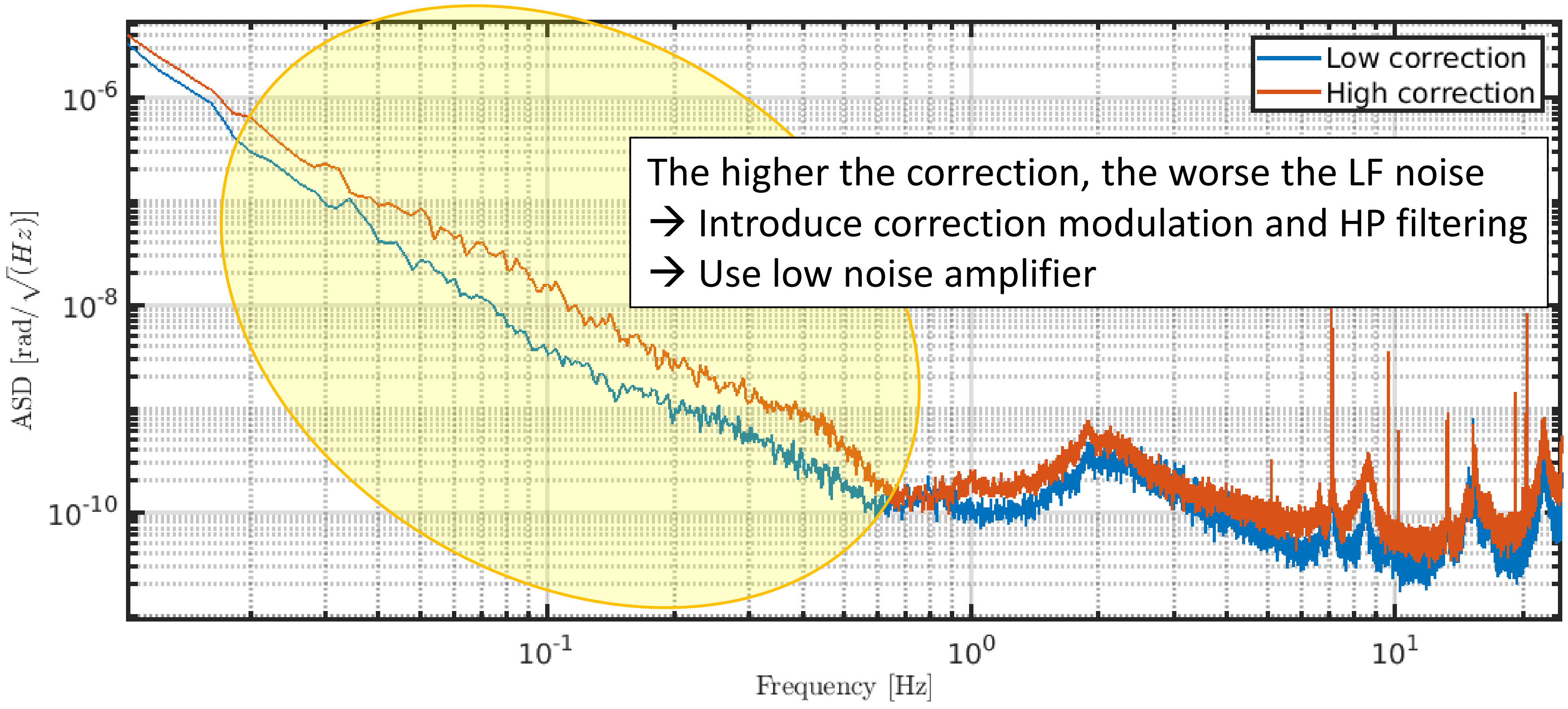

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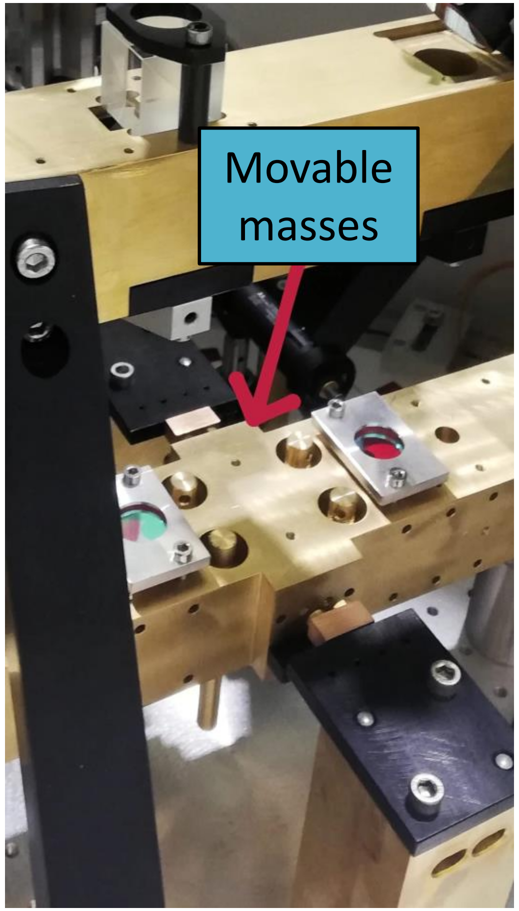
Center of mass raising to reduce the seism-to-tilt coupling

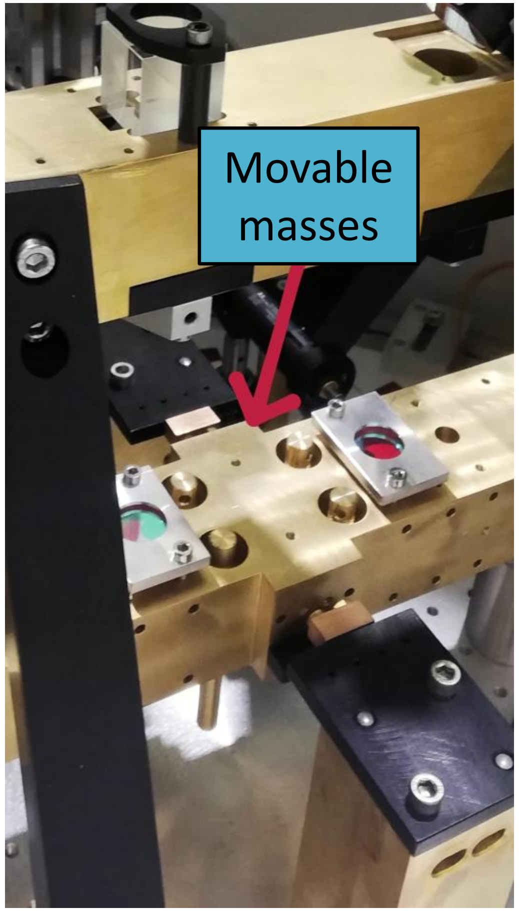


- The tiltmeter behavior was simulated with OCTOPUS, a Matlab simulation tool developed by P Ruggi based on impedence matrices approach (see L. Trozzo talk) and tuned in order to match the measured transverse resonance frequencies – pretty reliable model

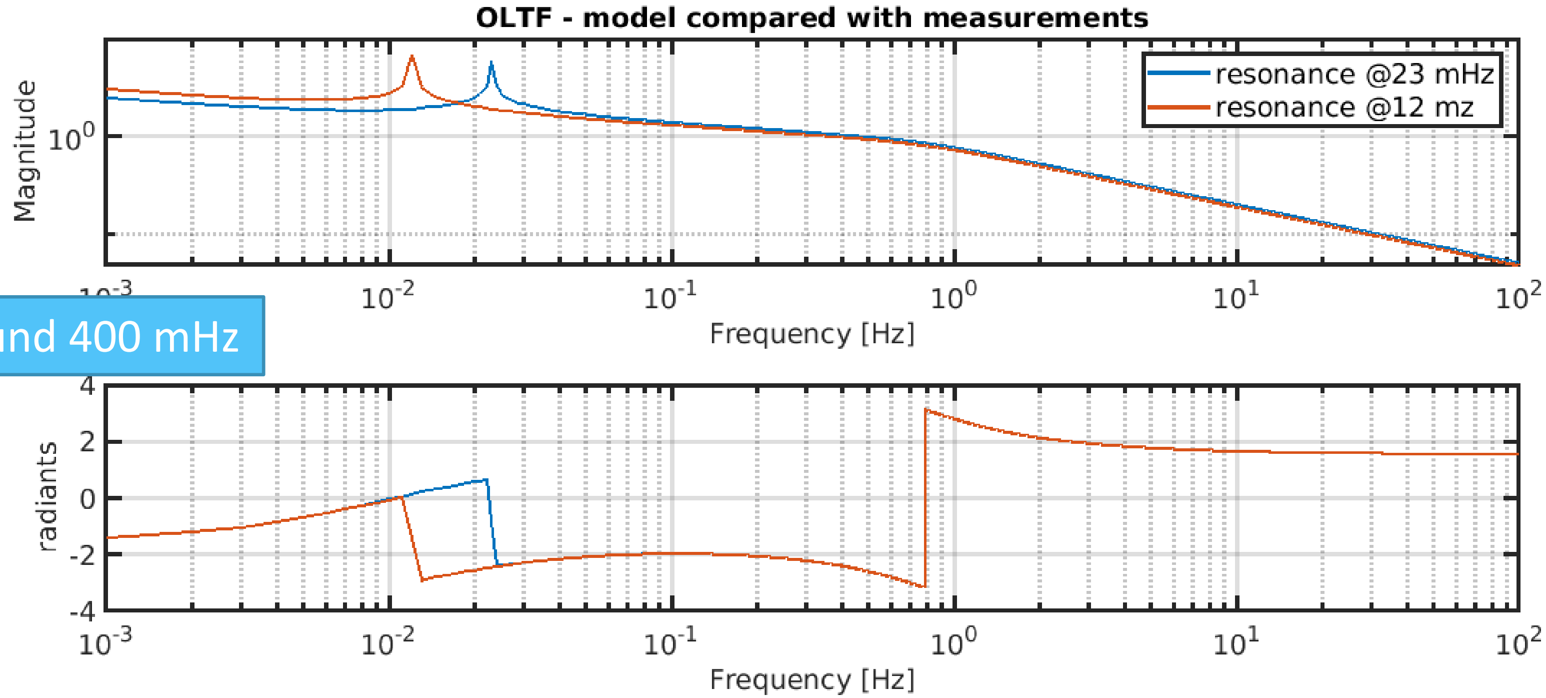
- A residual seism-to-tilt coupling along the arm direction has estimated to be a factor of about 1e-3, corresponding to a residual distance between bending point and center of mass of about 50 µm.

- This distance has also been estimated looking at the coherence between the seismometers and tiltmeter signal

Center of mass raising to reduce the seism-to-tilt coupling



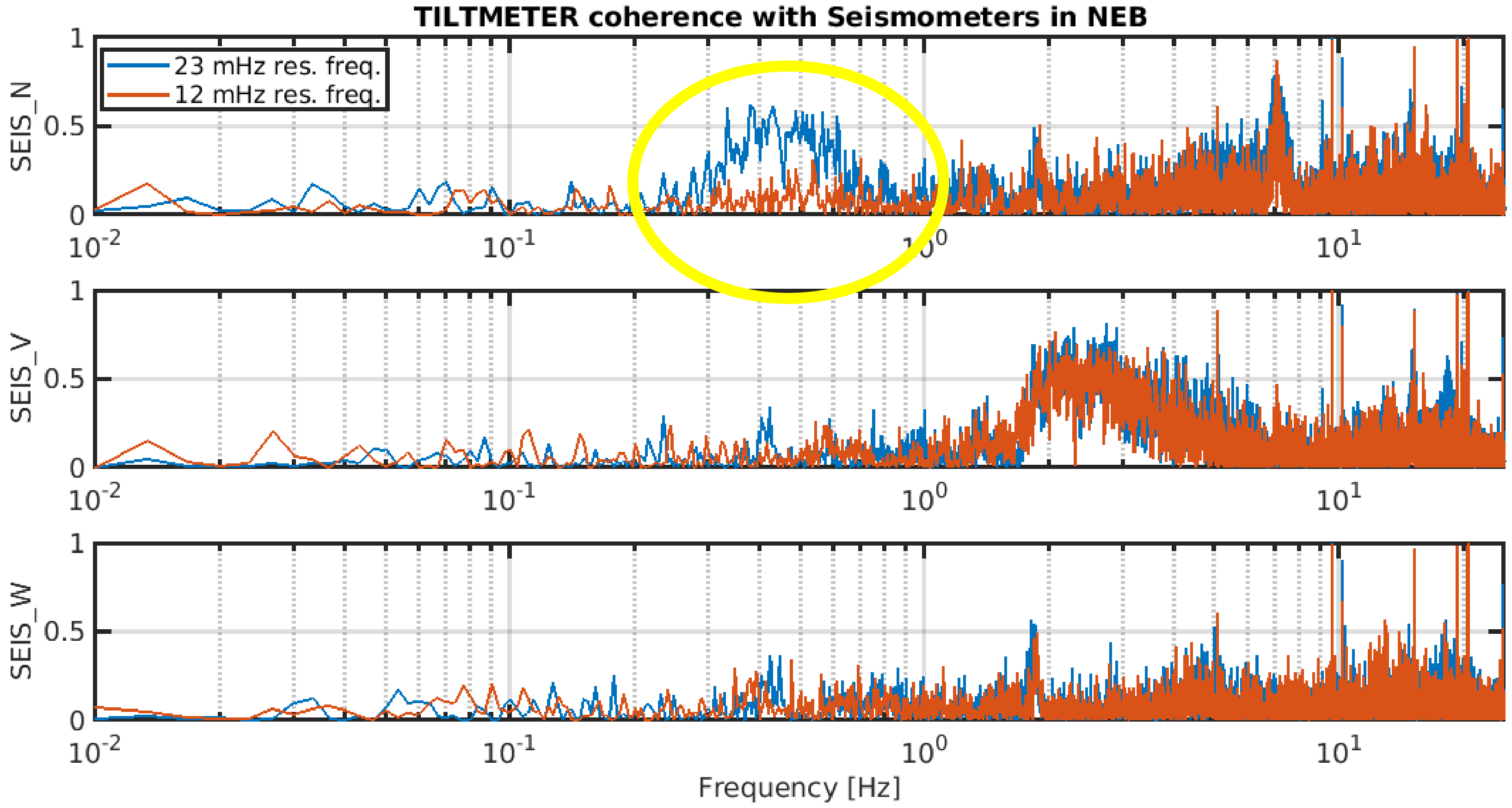
The center of mass was raised by about 35 μm to reduce its distance from the bending point and therefore reduce the seism-to-tilt coupling.
Resonance frequency changed from 23 mHz to 12 mHz



Change made few days ago, loop still to be well tuned, work in progress

PRELIMINARY ANALYSIS

Coherence with surrounding seismometers



After center of mass raising, coherence with the seismometer measuring accelerations in the same direction of tiltmeter beam is highly reduced (for comparable microseismic and wind conditions)

→ **better decoupling**

ANALYSIS ONGOING

OCTOPUS simulations can reproduce the new configuration and foresee a coupling decrease by about a factor 4

An unexpected outcome: dark photon search with tiltmeters

A tiltmeter equipped with weights and counterweights made of different materials **is sensible to the B-L dark-photon field, namely with the dark photon that couples with opposite sign with barions and leptons**

$$\mathcal{L} \equiv -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_A^2 A^\mu A_\mu - \epsilon_D e J_D^\mu A_\mu$$

Given the dark photon mass m_A, the force exerted by the dark photon field of amplitude A_0, on a mass that contains the number of charges q_D, in units $\hbar$ = c =1 is given by

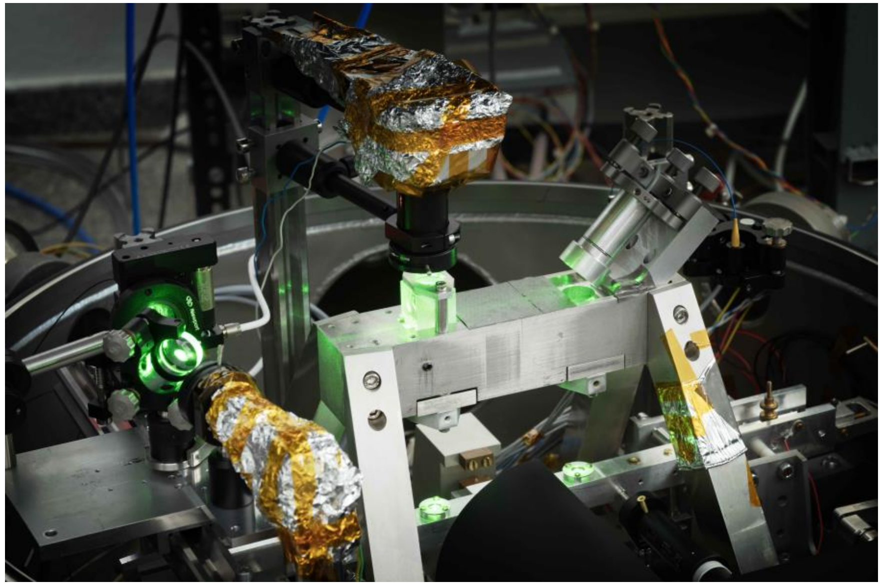
$$\vec{F}(t,\vec{x}) = \epsilon e q_D \frac{\partial \vec{A}}{\partial t} = A_0 \epsilon e q_D m_A \vec{e} cos(m_A t - \vec{k}\vec{x} + \phi(t))$$

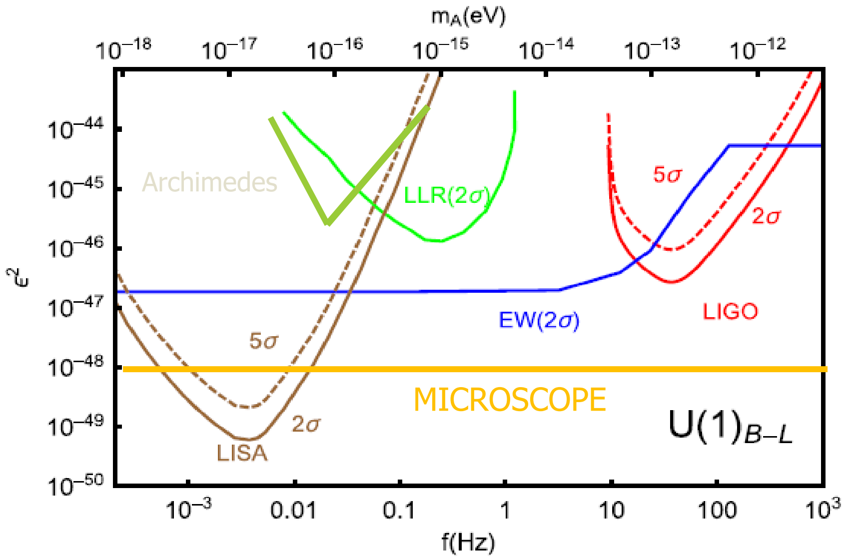
The signal is a monocromatic noise at the frequency m_A and under the hypothesis that all the dark mass is due to the dark photon the amplitude of the field is

$$A_0 = \frac{\sqrt{2\rho_{DM}}}{m_A}$$

Preliminary results

In the tiltmeter prototype we chose Aluminum and Brass as weight and counter-weight. The B-L asymmetry is about 4.5%. With few nights of data taking, promising results have been obtained. In order to reach better limits we plan both to increase the measurement time and to use the final Archimedes balance that will be more sensitive with respect to the prototype.





Very preliminary: can be improved by long data taking

Conclusions and future perspectives

- The **new large-band tiltmeter** has been installed in Virgo will be taking data during O4 close to the North End tower

- **Actuation noise** is currently limiting sensitivity at low frequency, and a solution will be soon implemented to improve this aspect

- Will try to **further minimize the seism-to-tilt coupling**

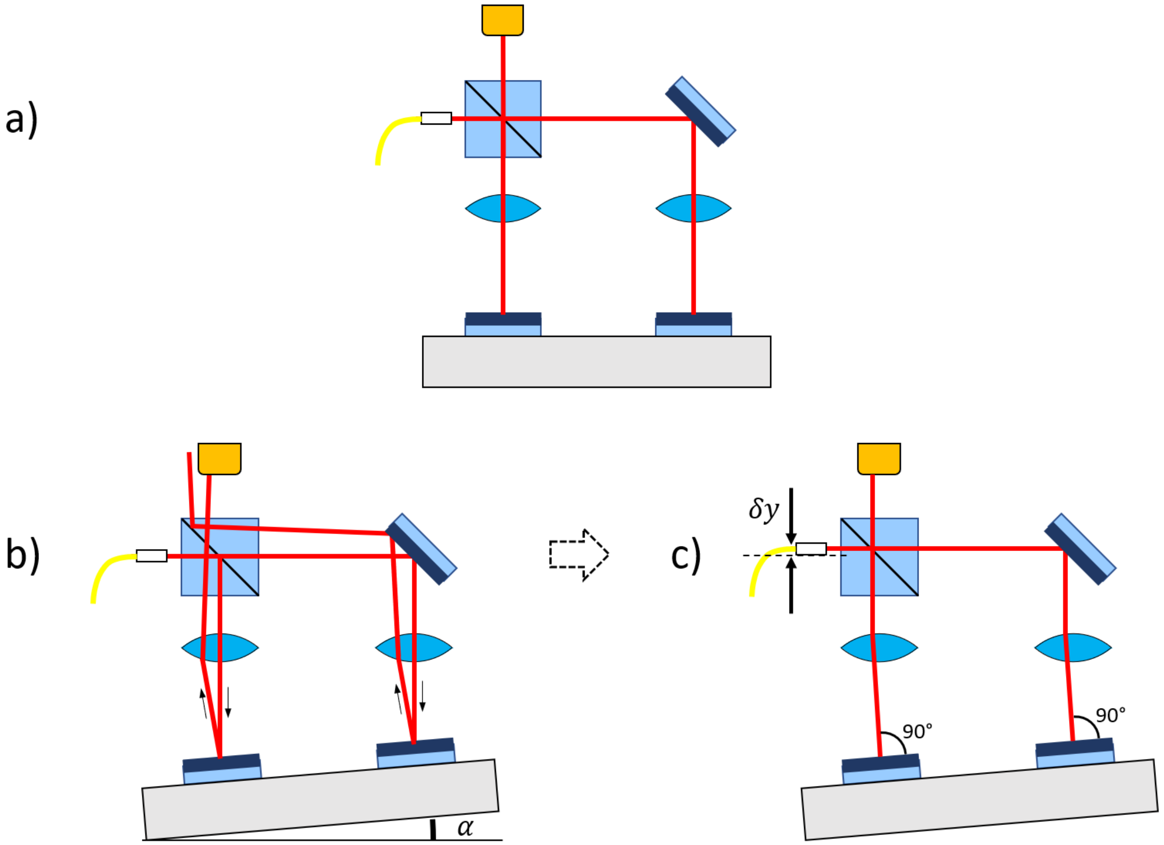
- **OCTOPUS** simulations will be used to improve the tiltmeter performances

- Besides NNC, could the tiltmeter already be possibly used to improve Virgo SA performances? Analysis ongoing

A **new version of this tiltmeter is being built to be installed in Sos-Enattos**. Many improvments have been foreseen to further reduce power and frequency noise coupling.
We expect a much lower noise level than Virgo at the Sos-Enattos site

Extra slides

ITF robustness against tilts

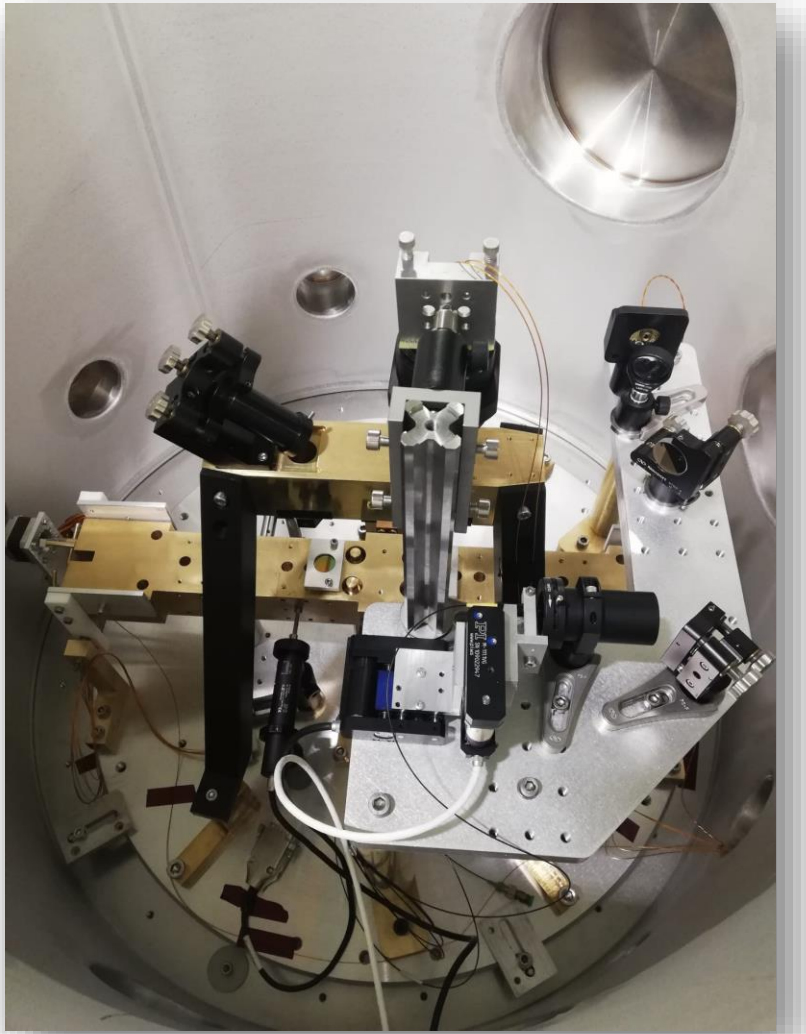


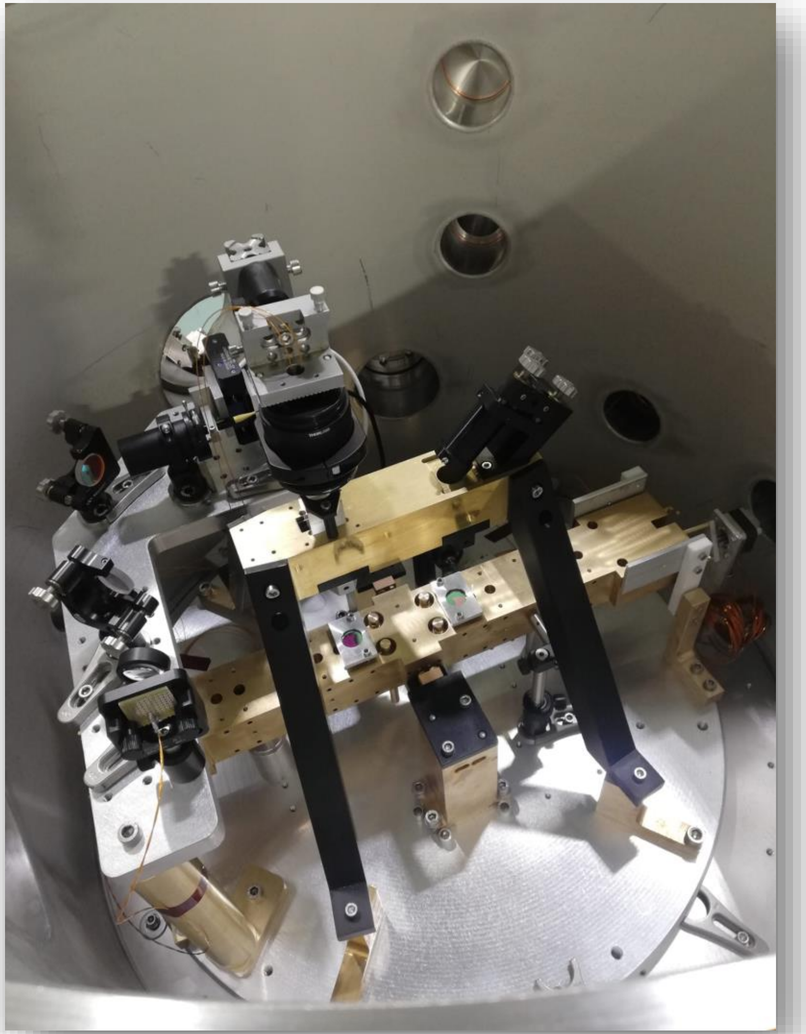
(a) The interferometer is aligned while the balance arm is horizontal

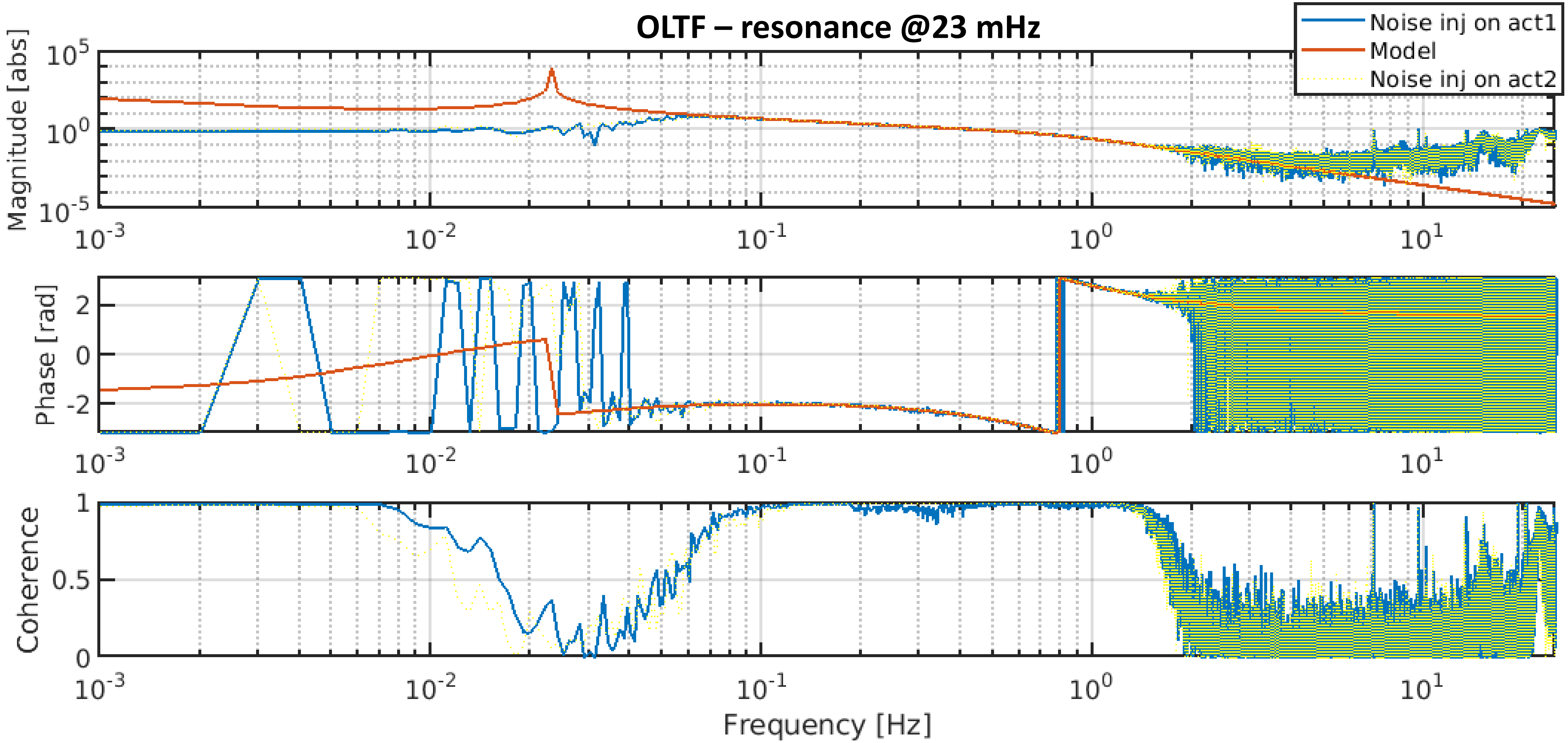
(b) An arm tilt α would misalign the interferometer

(c) The presence of lenses in both arms permits the realignment by moving vertically by an amount $\delta y = L_f \alpha$ the input laser beam, where L_f is the lens focal length

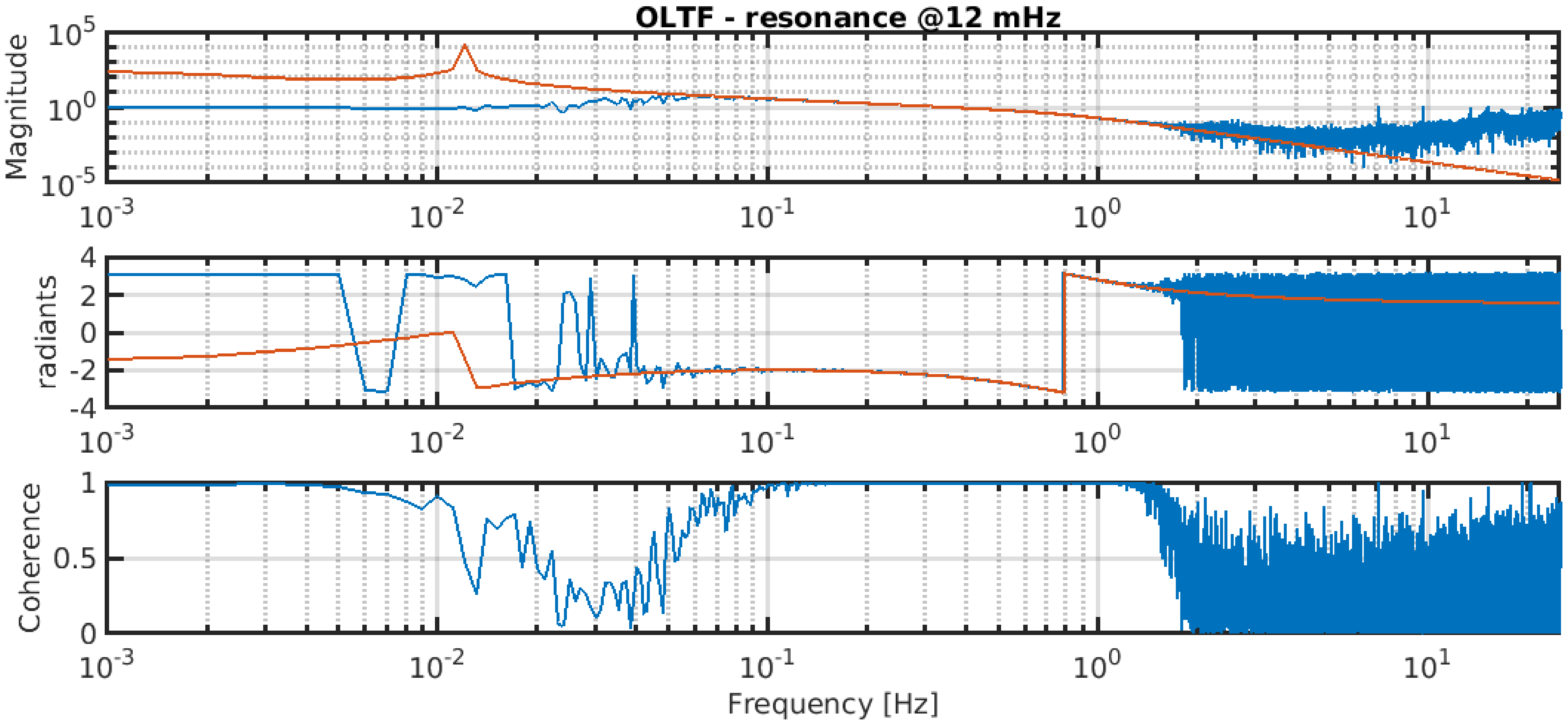
ʾΑκίνητος: the large-band tiltmeter







OLTF – resonance @23 mHz
Noise inj on act1
Model
Noise inj on act2
Magnitude [abs]
Phase [rad]
Coherence
Frequency [Hz]


OLTF - resonance @12 mHz
Magnitude
radiants
Coherence
Frequency [Hz]