

UNIVERSITÀ DEGLI
STUDI DI NAPOLI
FEDERICO II



EGO

Ἀκίνητος Large-band tiltmeter

A. ALLOCCA, E. CALLONI, R. DE ROSA, L. ERRICO, M. ESPOSITO, G. PONTORIERE, P. RUGGI,
G. BALLARDIN, L. FRANCESCON, R. MACCHIA, F. NOCERA, A. PASQUALETTI, F. PAOLETTI

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

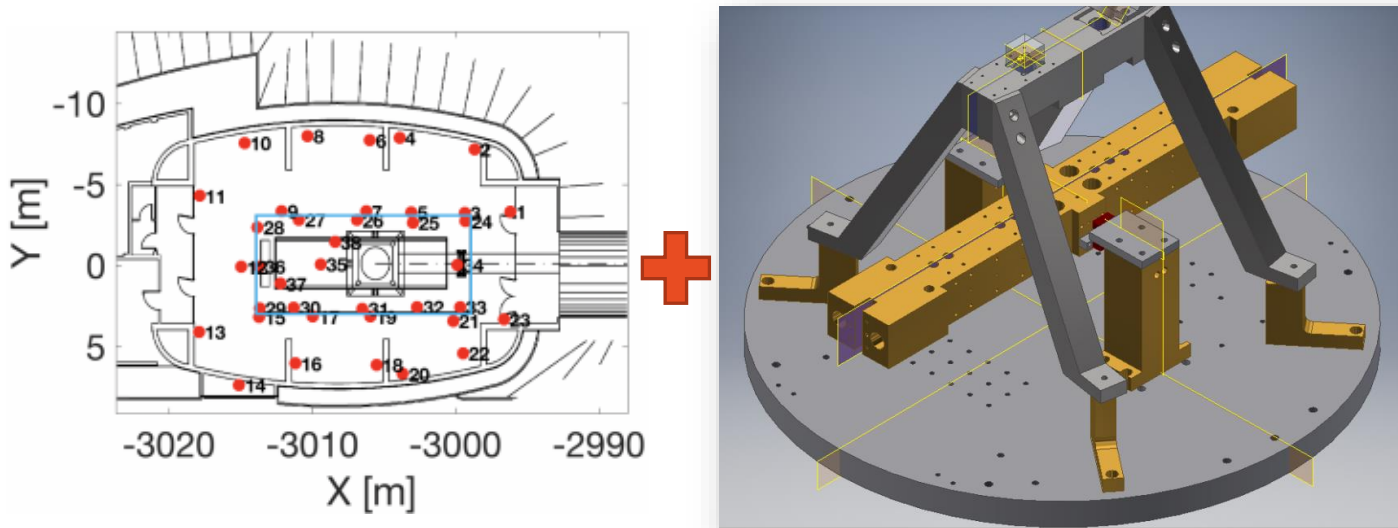
Outline

- **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

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**



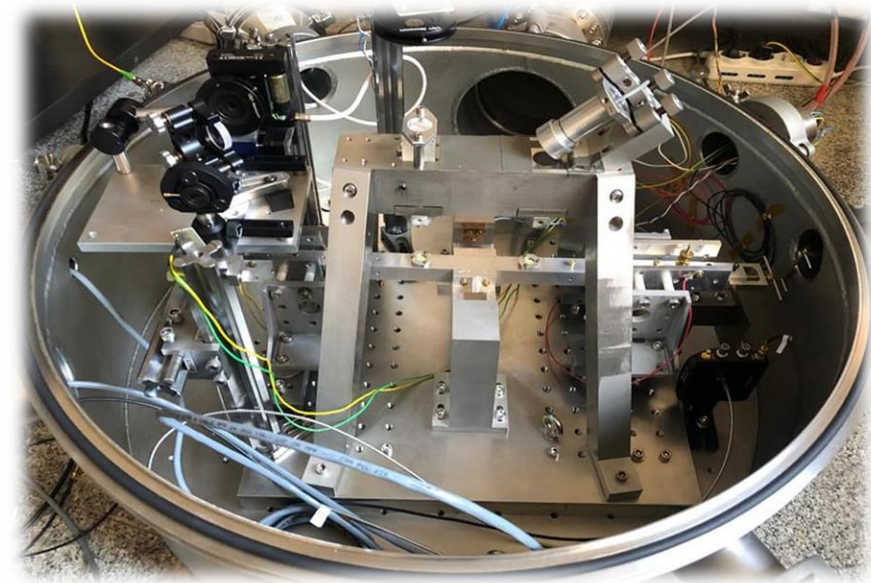
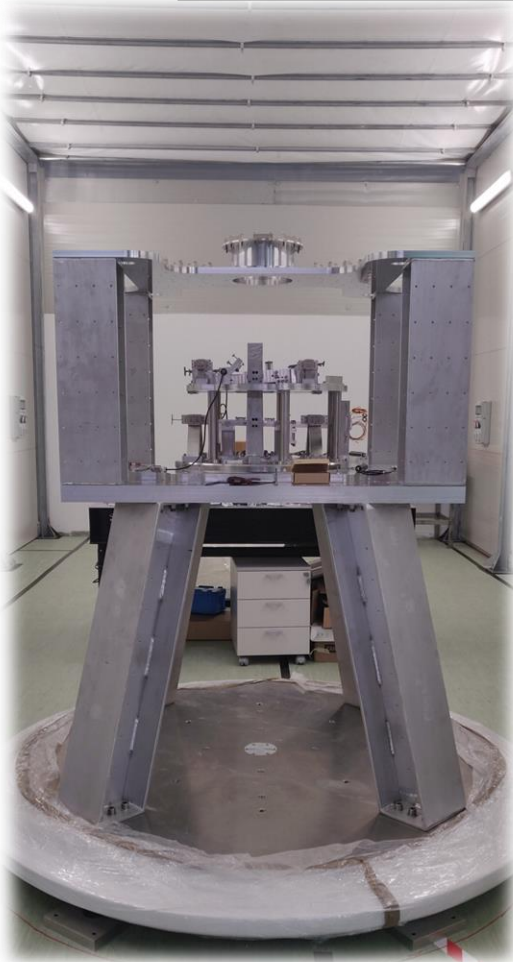
Tiltmeter

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



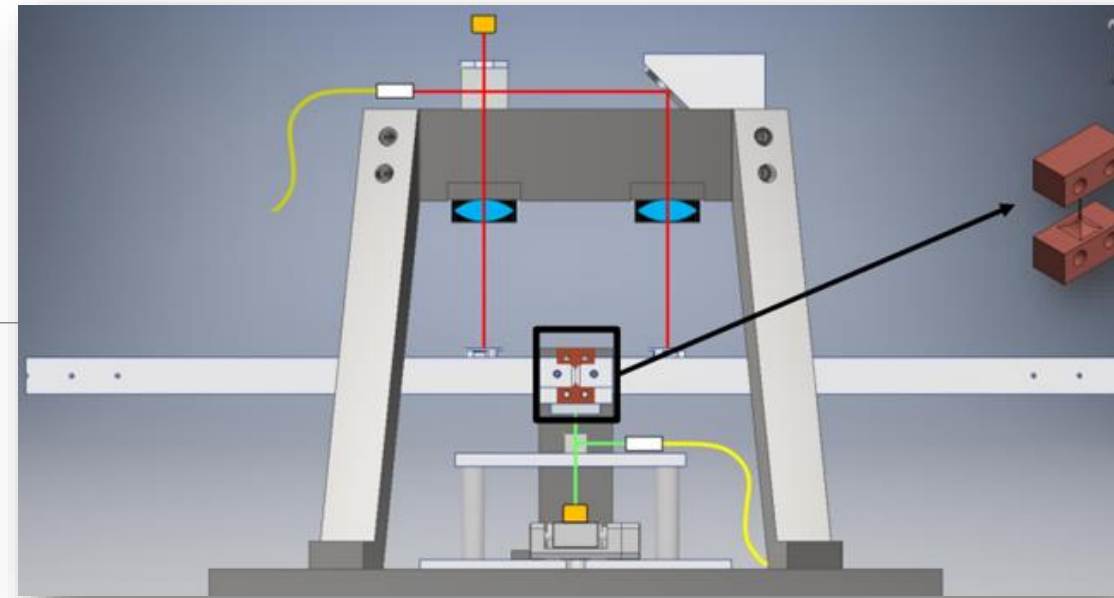
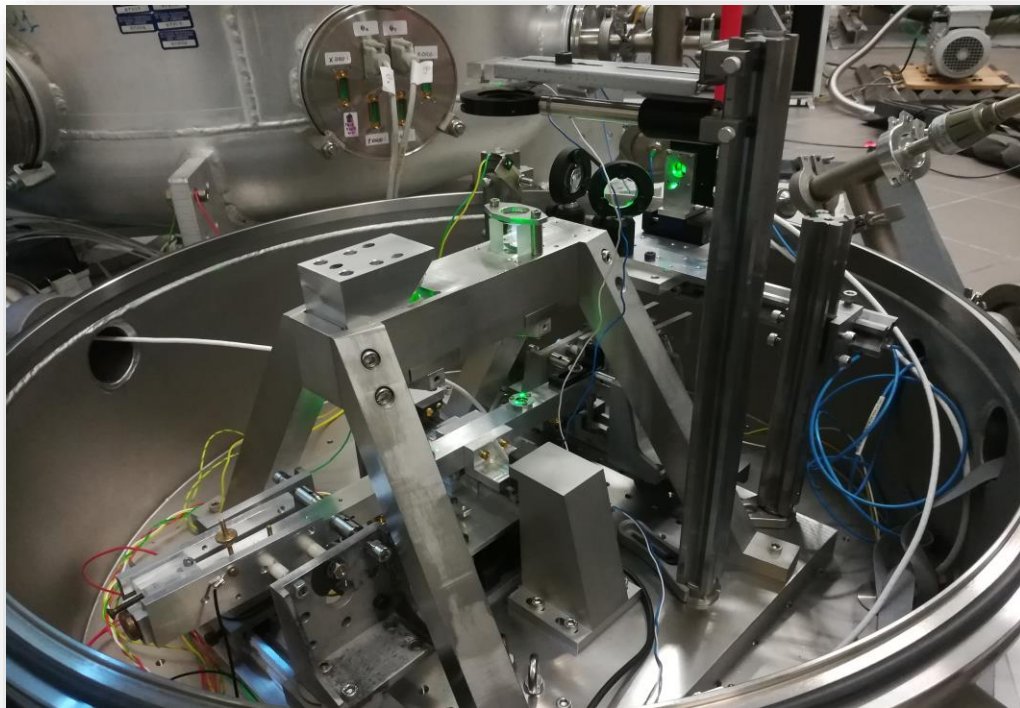
Tiltmeter prototype

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.

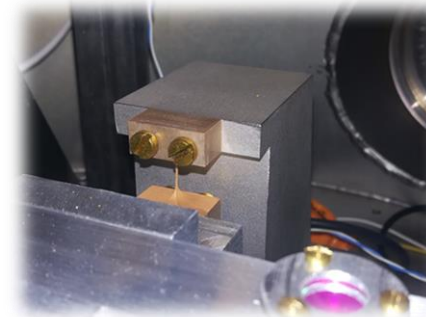


Tiltmeter prototype - mechanics

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

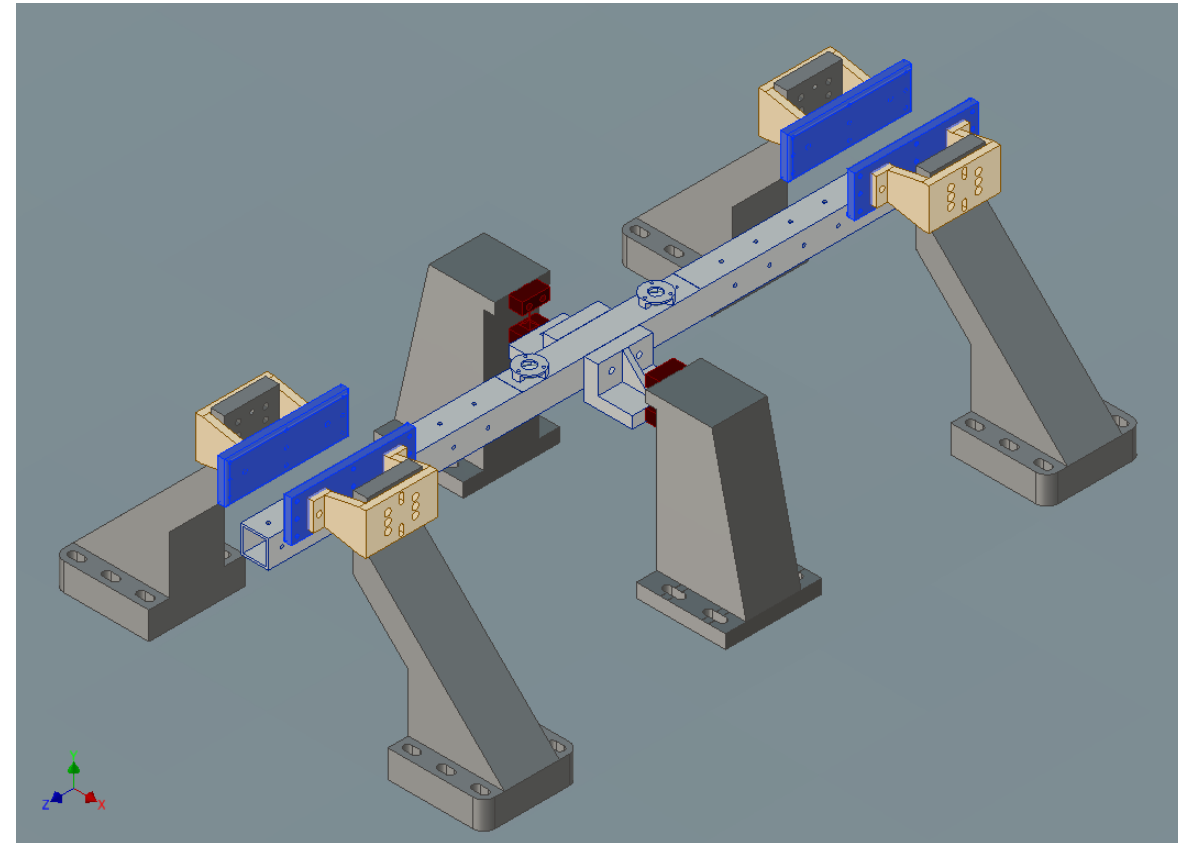
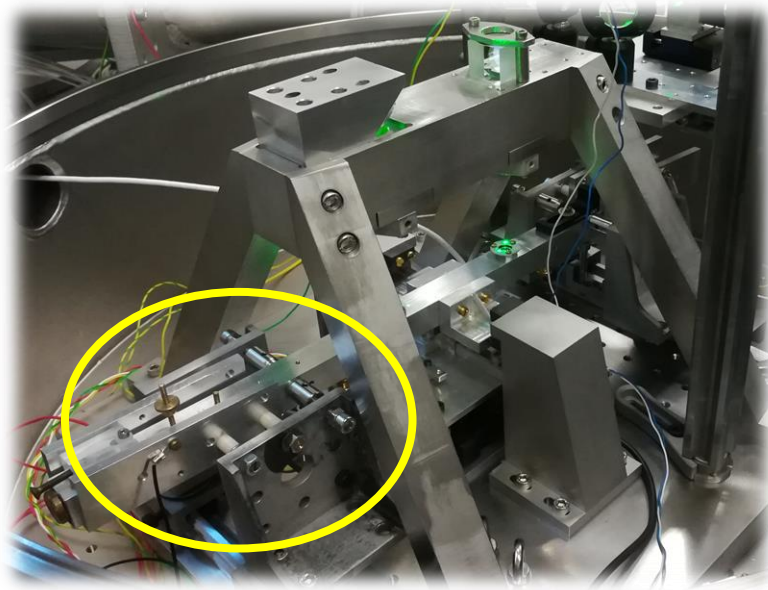


- Tiltmeter arm is suspended through **Cu-Be flexible joints**, $100\mu\text{m} \times 500\mu\text{m}$ in section, very similar in design to LIGO tiltmeters (Venkateswara *et al.*, 2014) which allow to keep the resonance frequency below 20 mHz



Tiltmeter prototype – controls

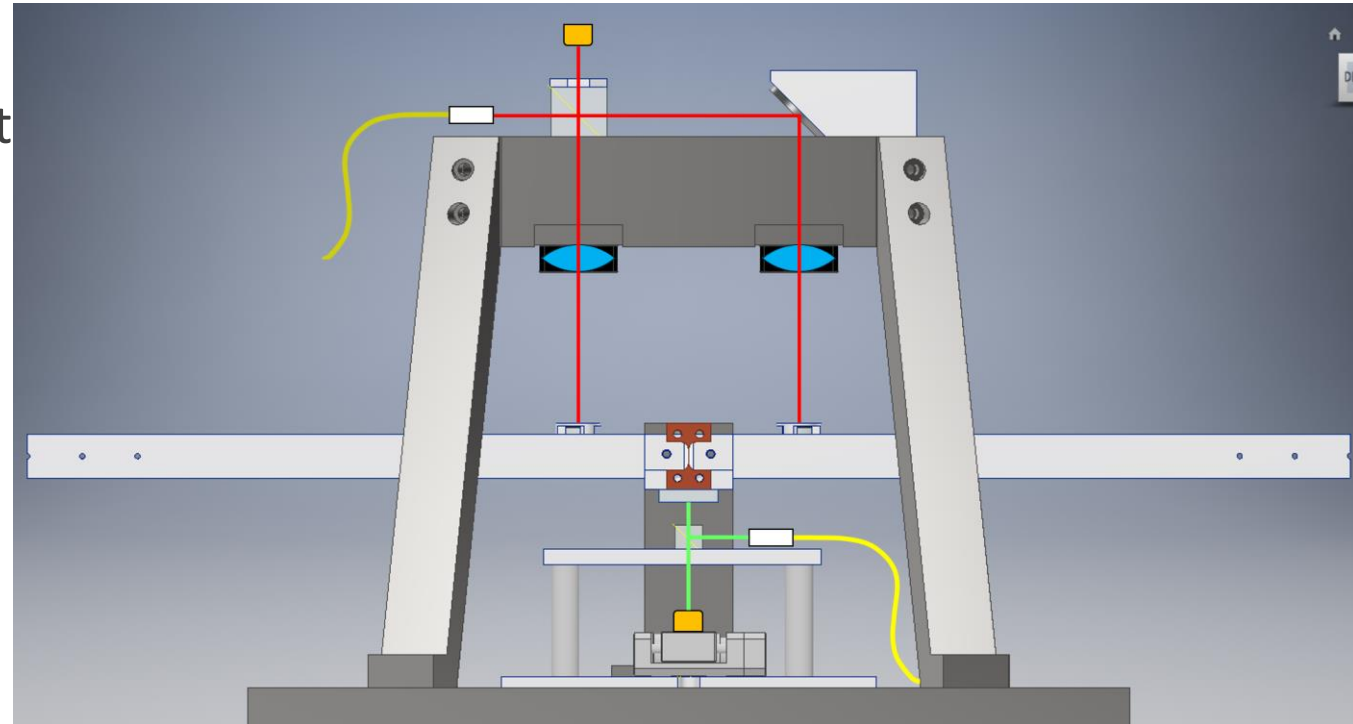
- Control in feedback performed with **electrostatic actuators** (a couple at the end of each side of the arm – blue in figure)



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):

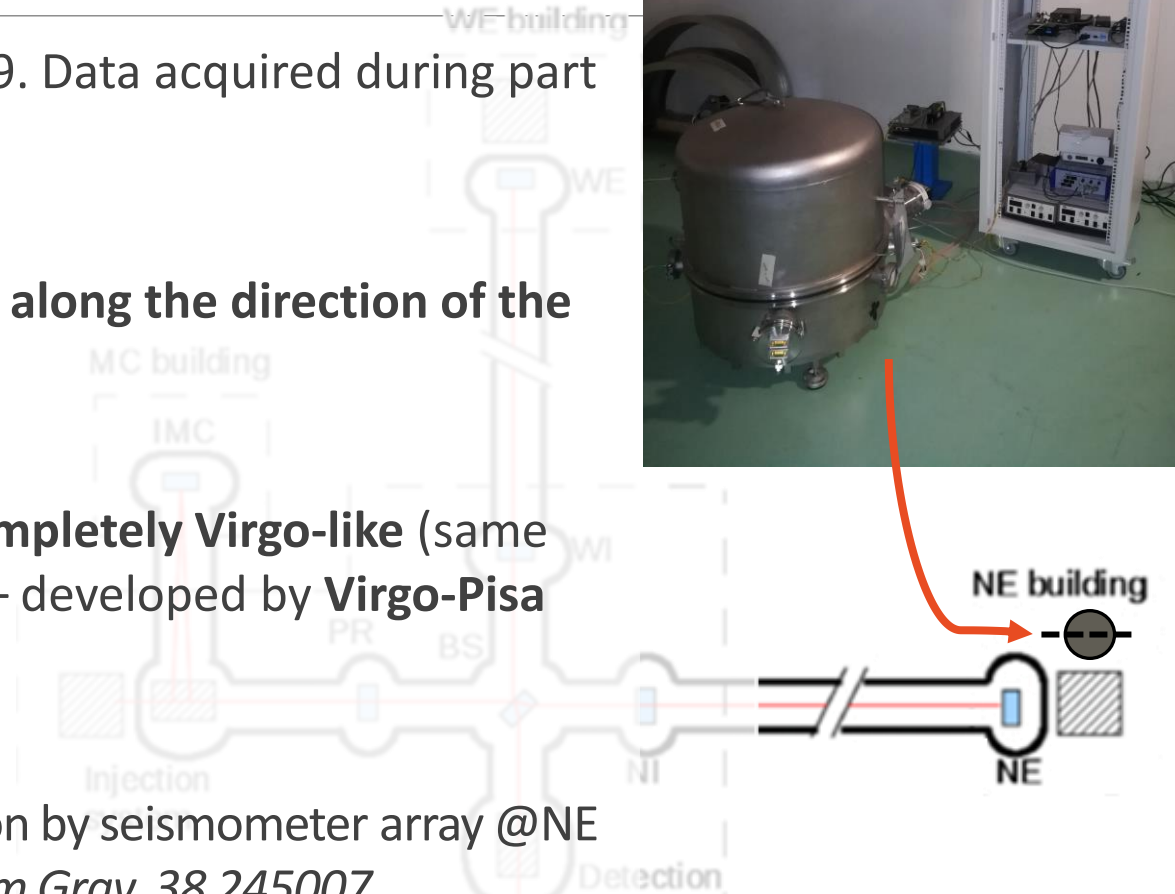
- **Optical lever** (wider dynamic range)
- **Interferometer** (higher sensitivity)



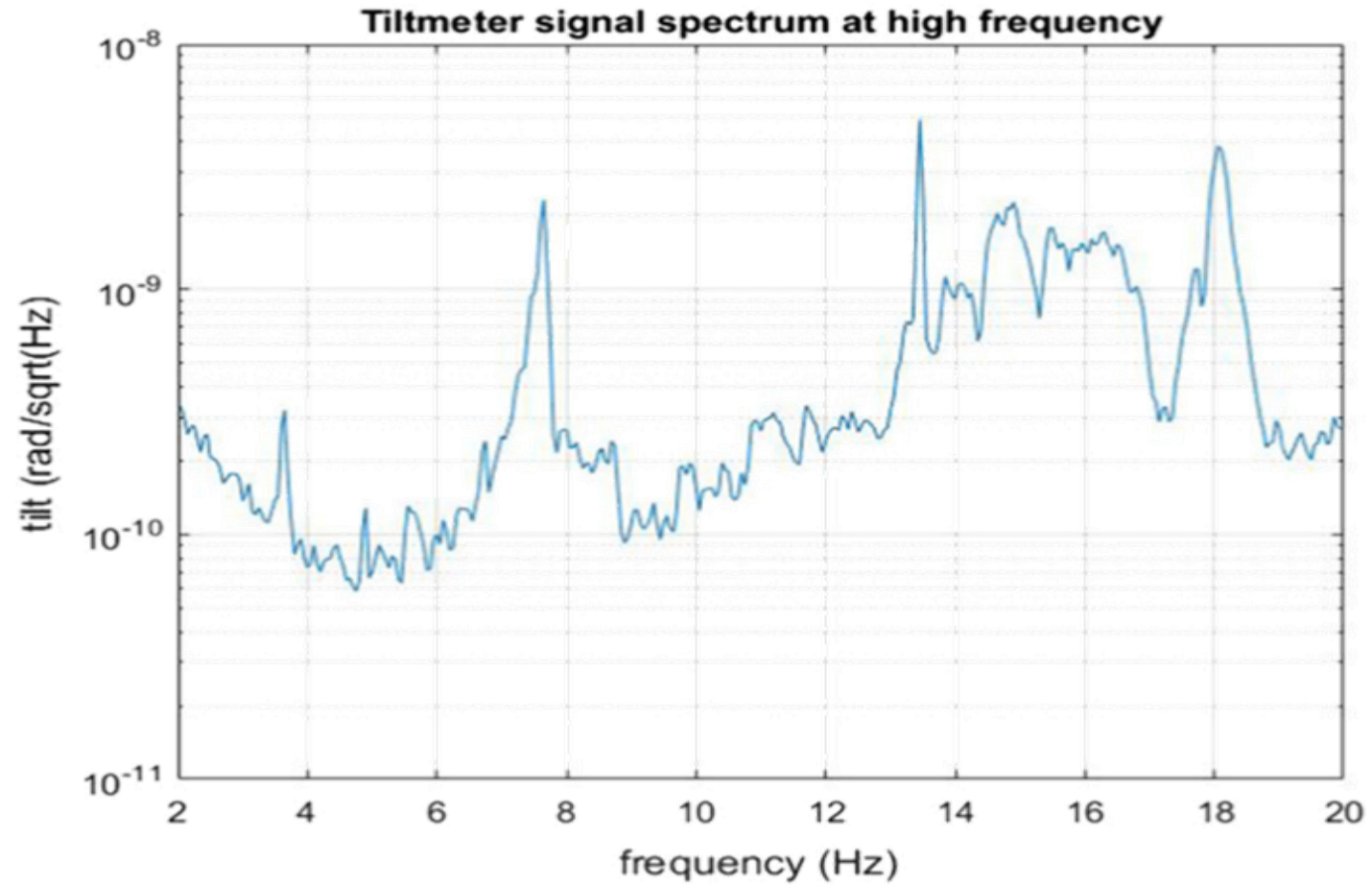
Lenses in the ITF read-out are added to give **robustness against static arm tilts**

First installation in Virgo

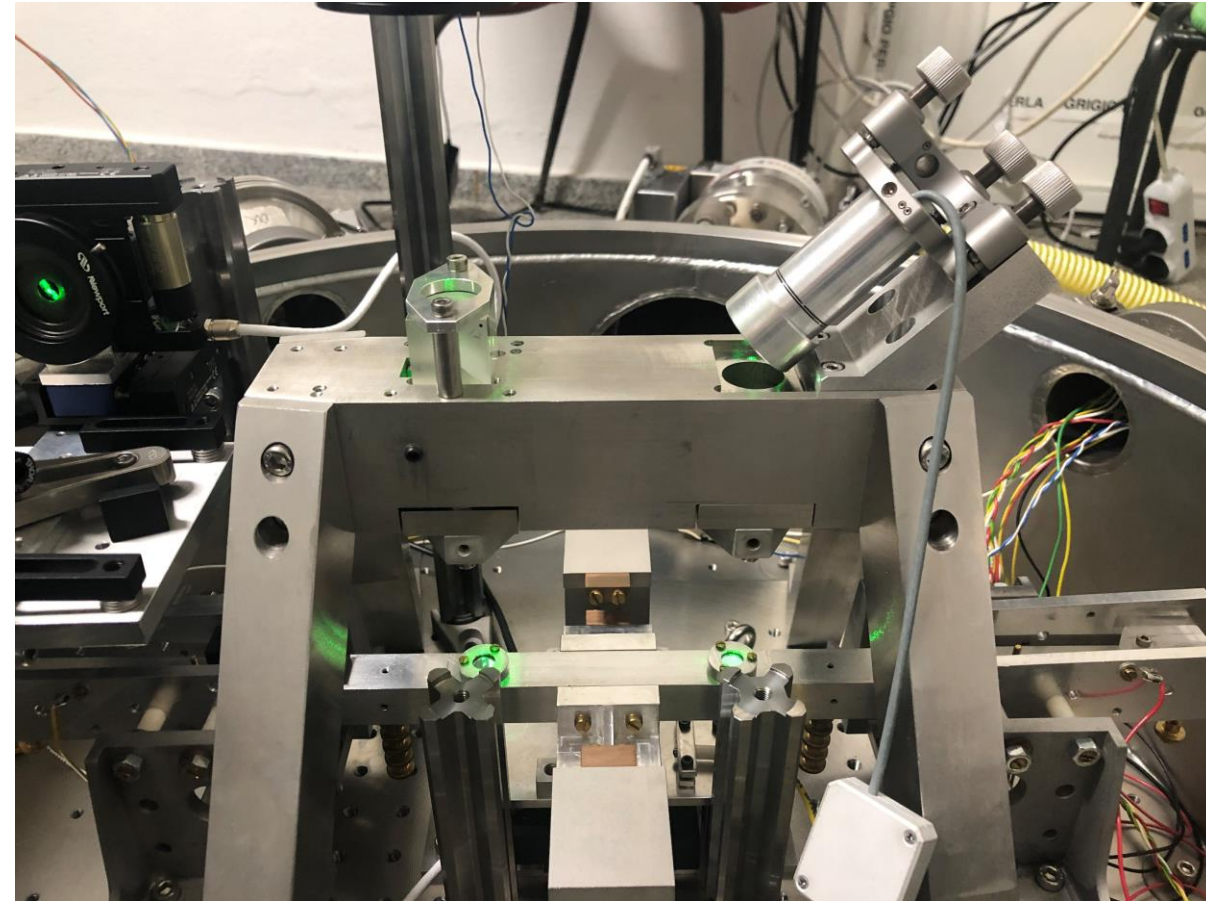
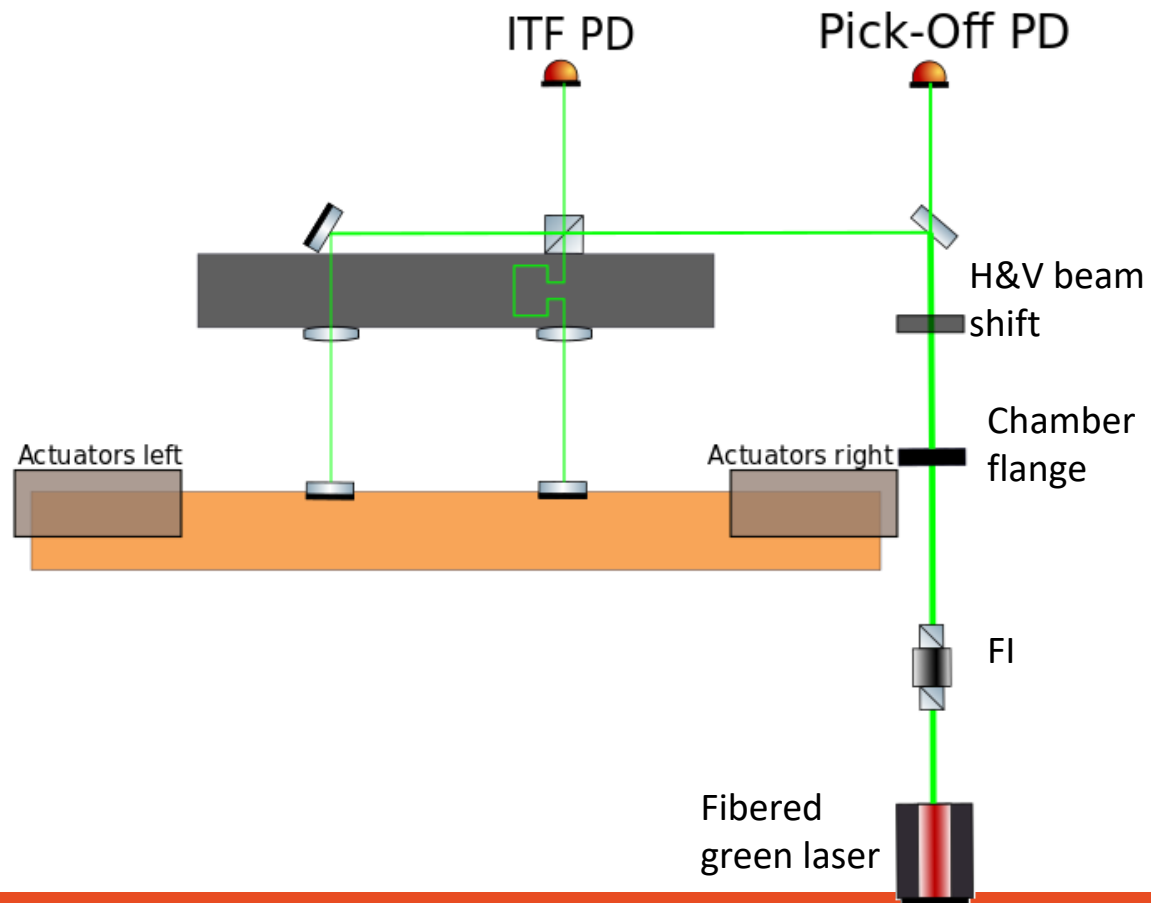
- Installed by the Virgo-Napoli group in Feb 2019. Data acquired during part of O3
- Oriented to be mainly sensitive to **ground tilts along the direction of the North Arm**
- **Digital acquisition and control system was completely Virgo-like** (same modules used to control the superattenuators – developed 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*



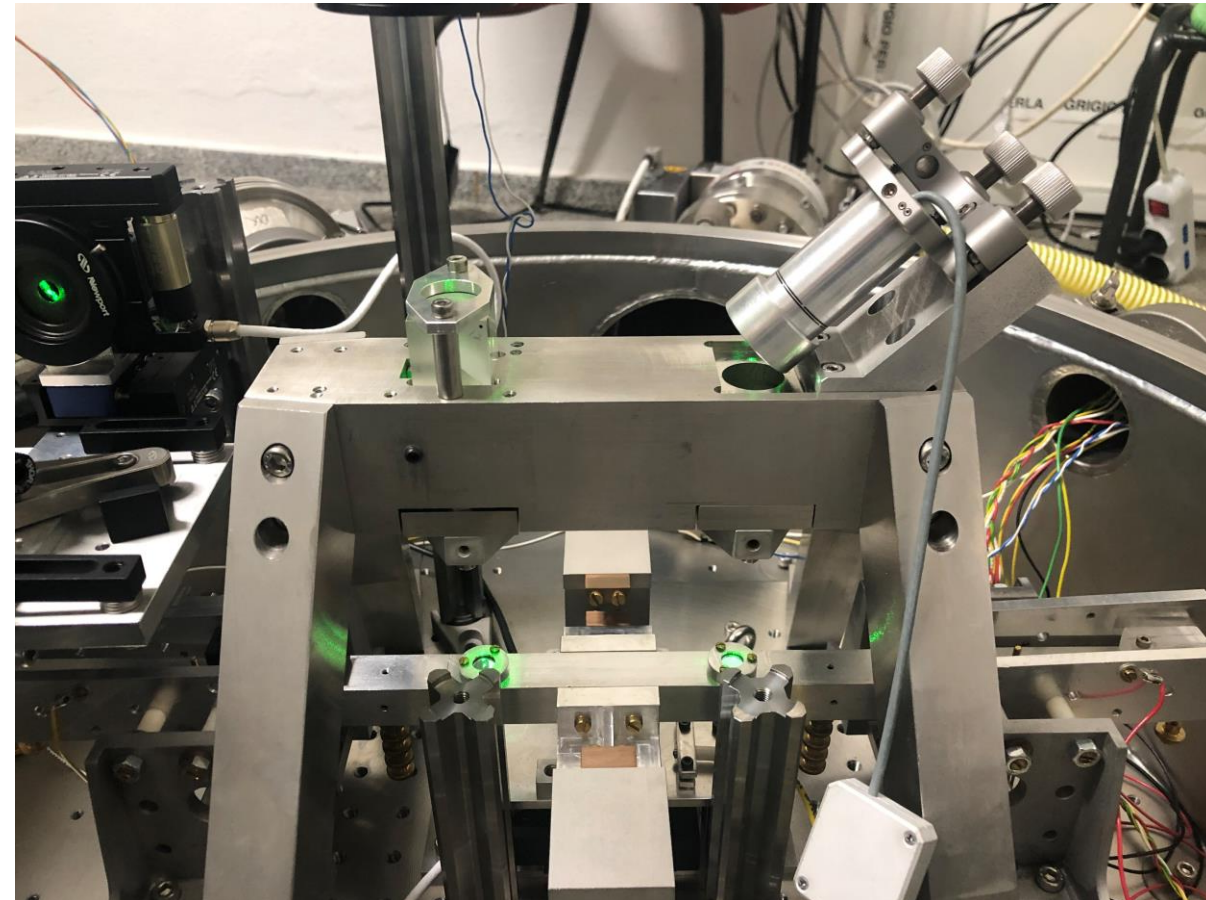
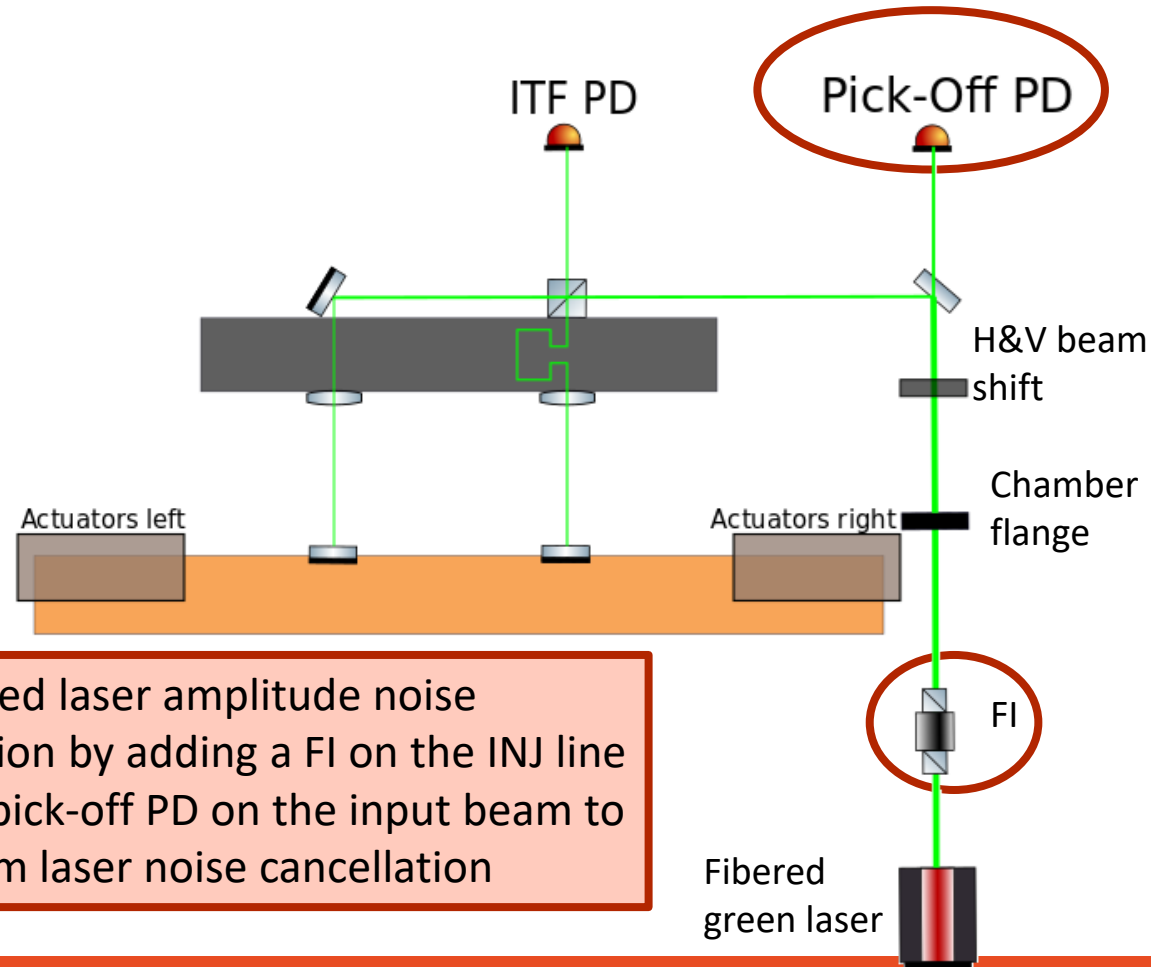
Tiltmeter sensitivity in Virgo 2019



Tiltmeter – first improvements

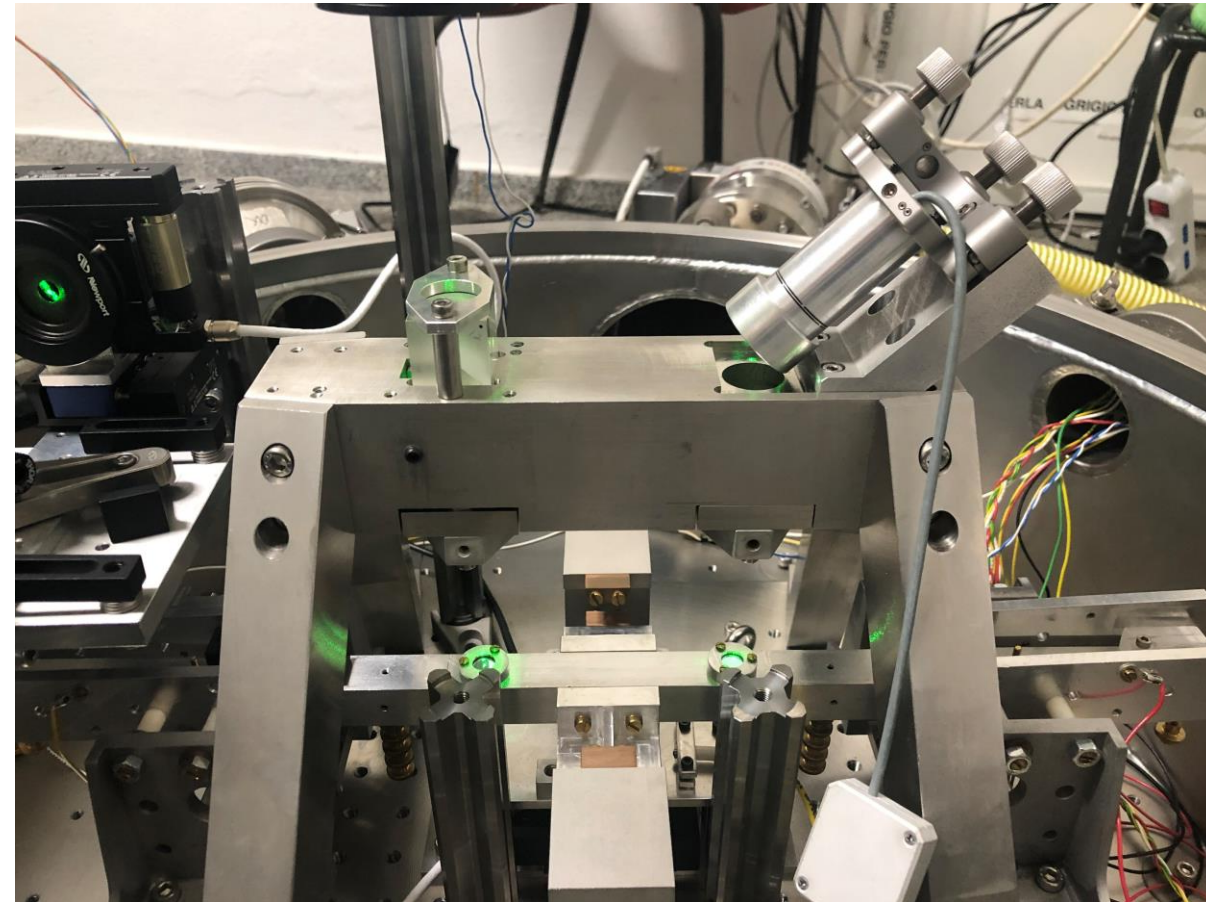
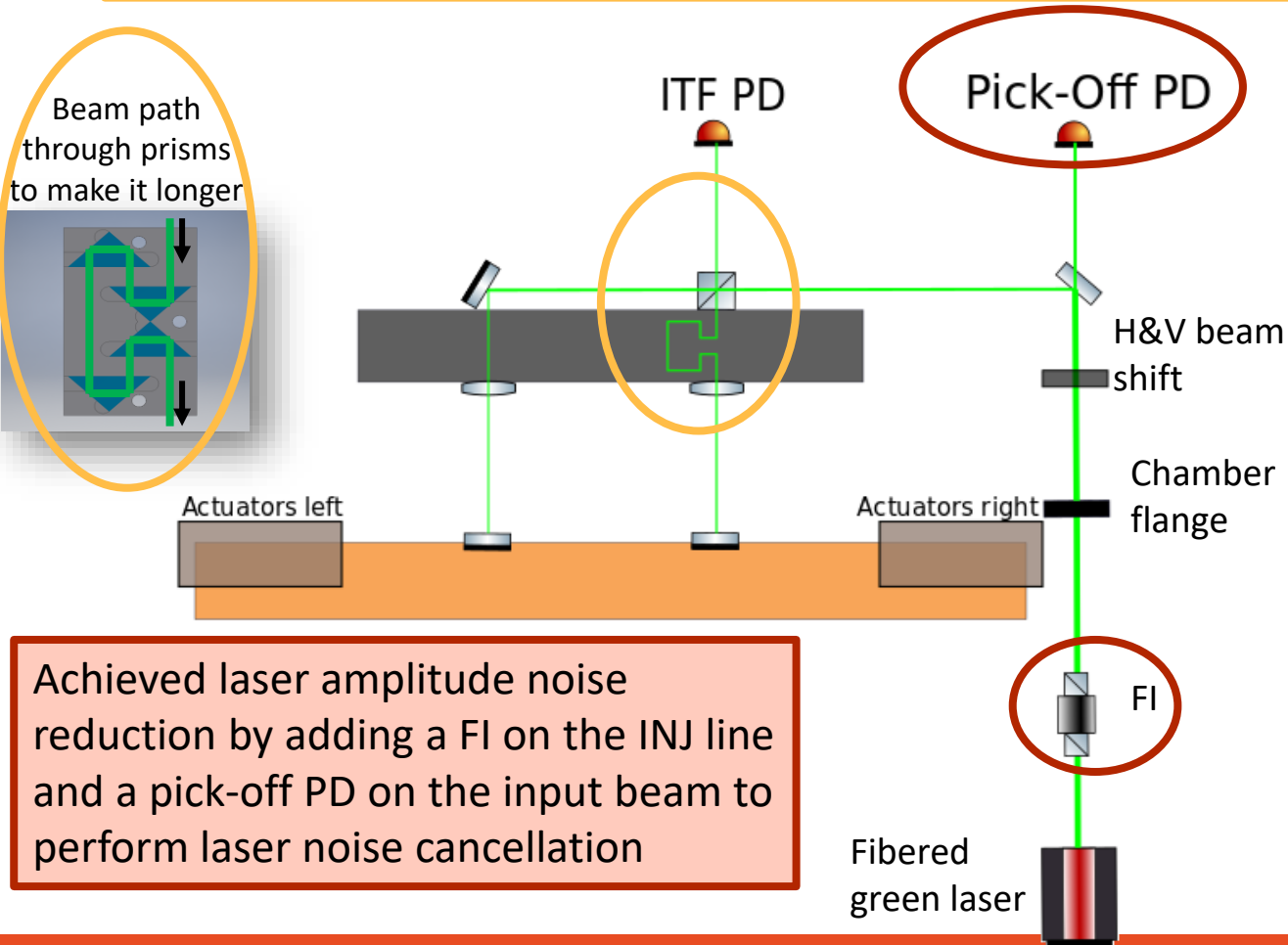


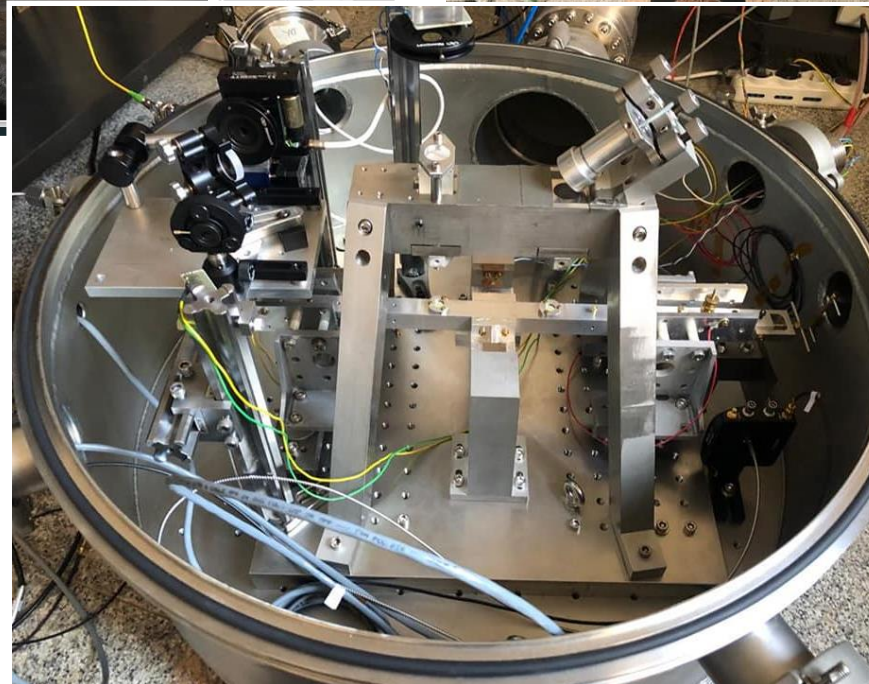
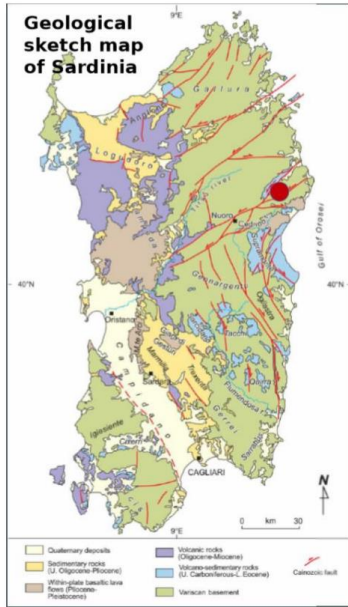
Tiltmeter – first improvements



Tiltmeter – first improvements

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

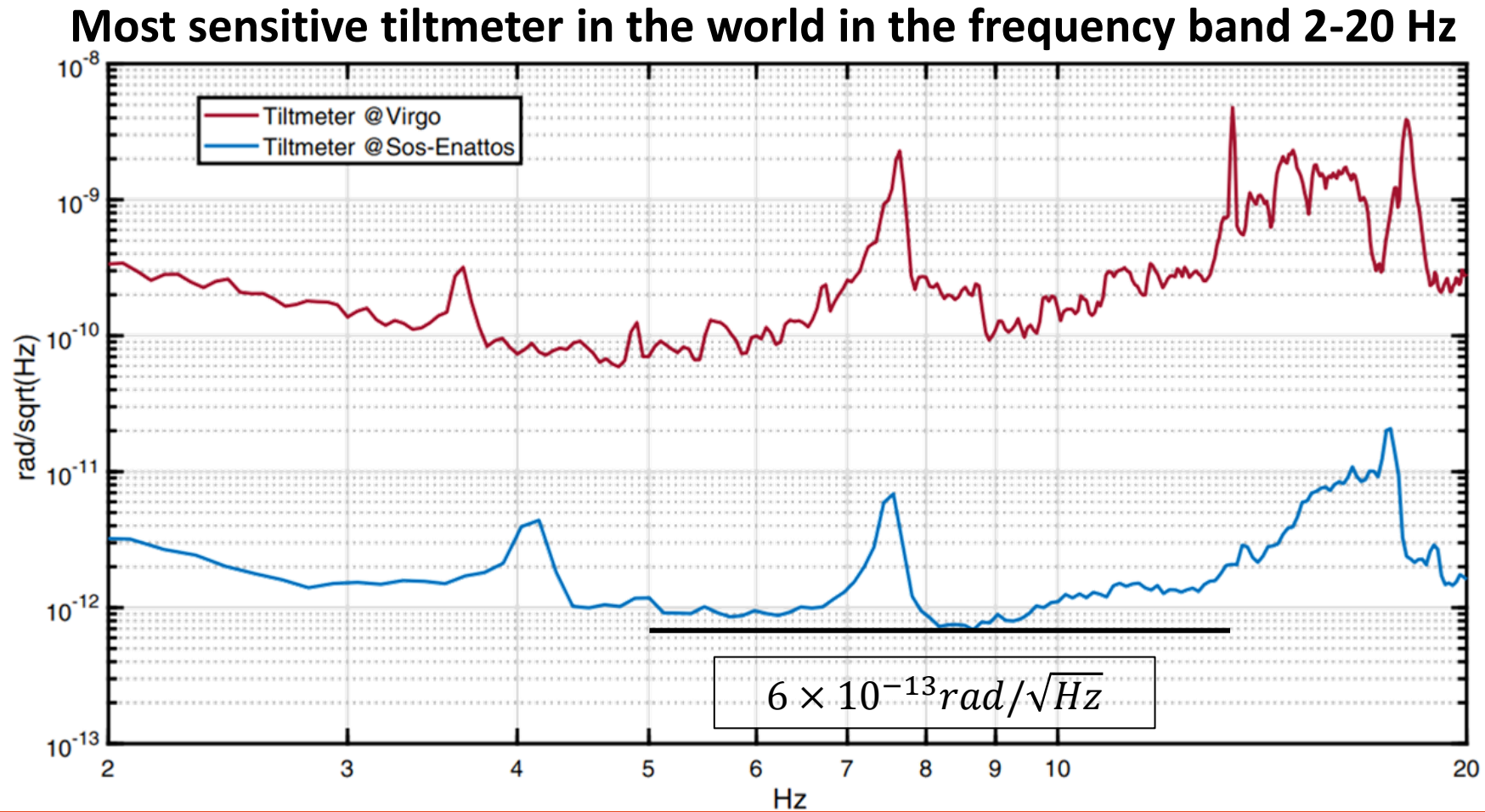




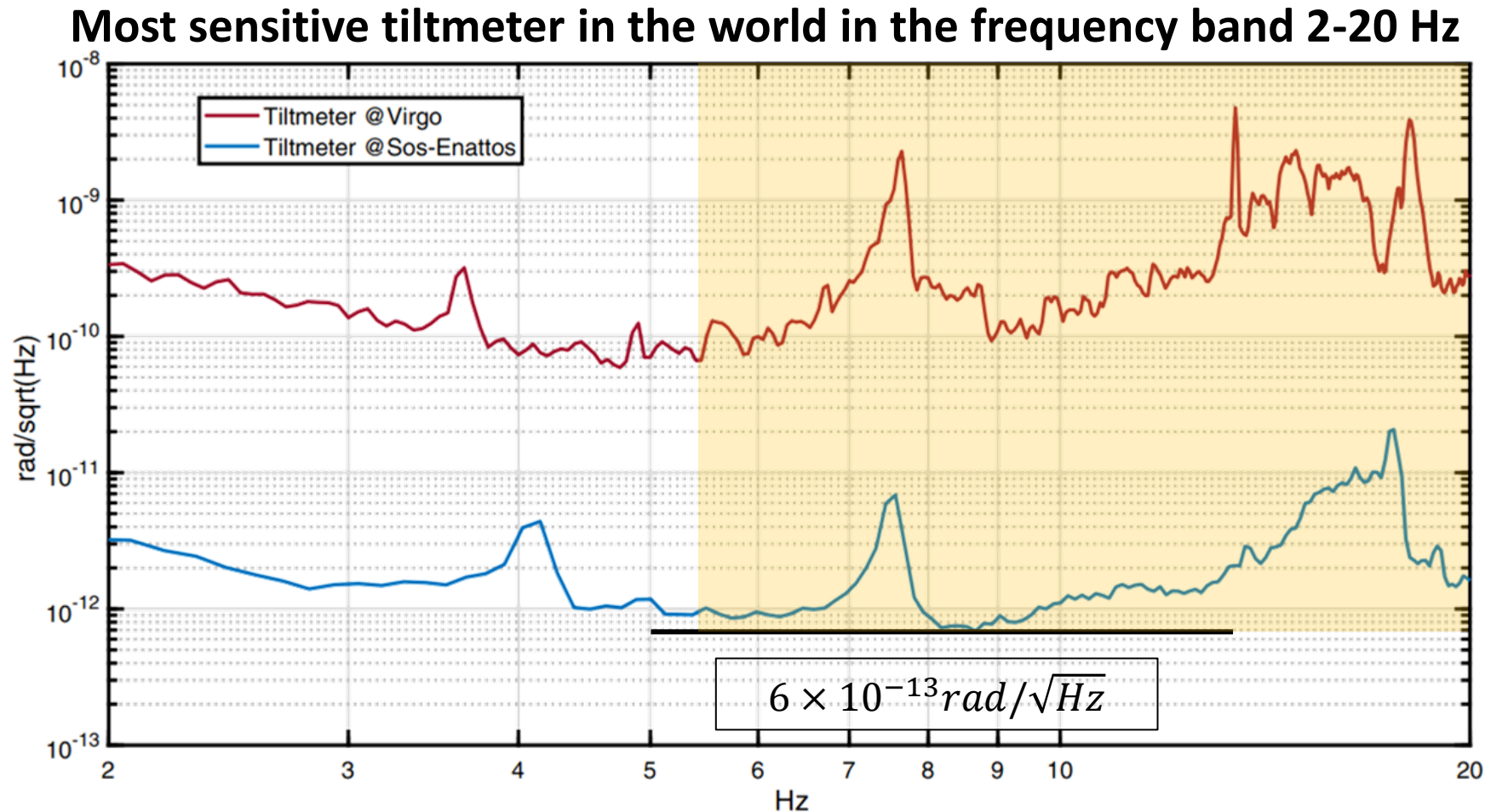
Tiltmeter in Sos-Enattos

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

Tilt measurement comparison between Virgo and Sos-Enattos



Tilt measurement comparison between Virgo and Sos-Enattos



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

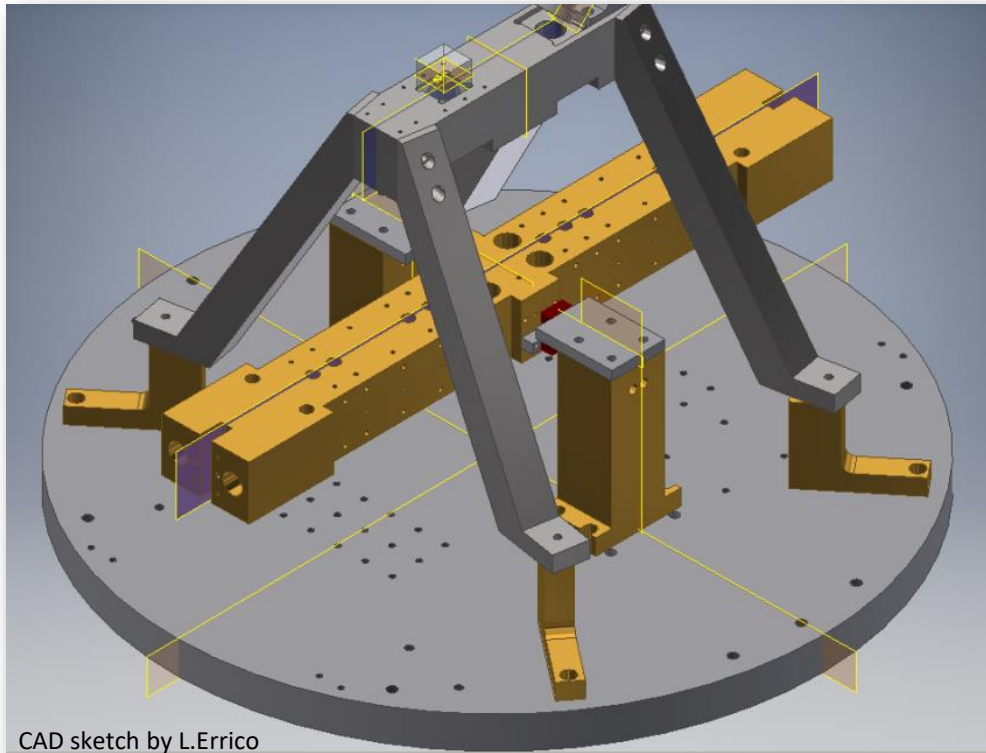
Outline

- 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

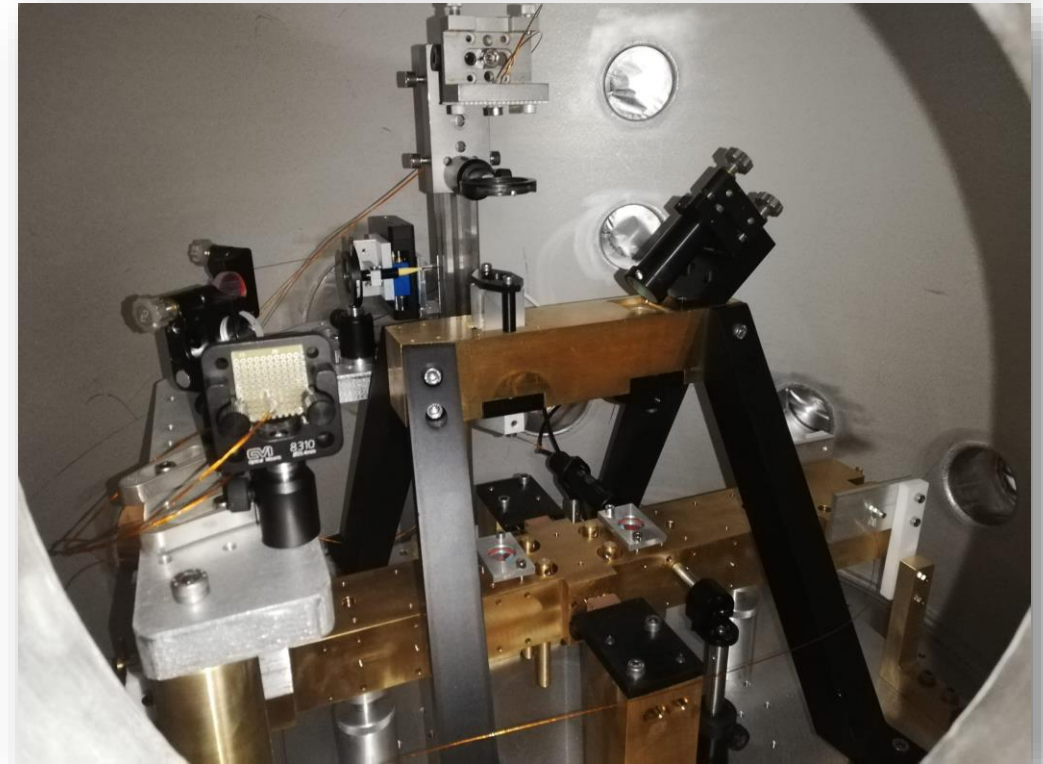
Ἀκίνητος: the new tiltmeter

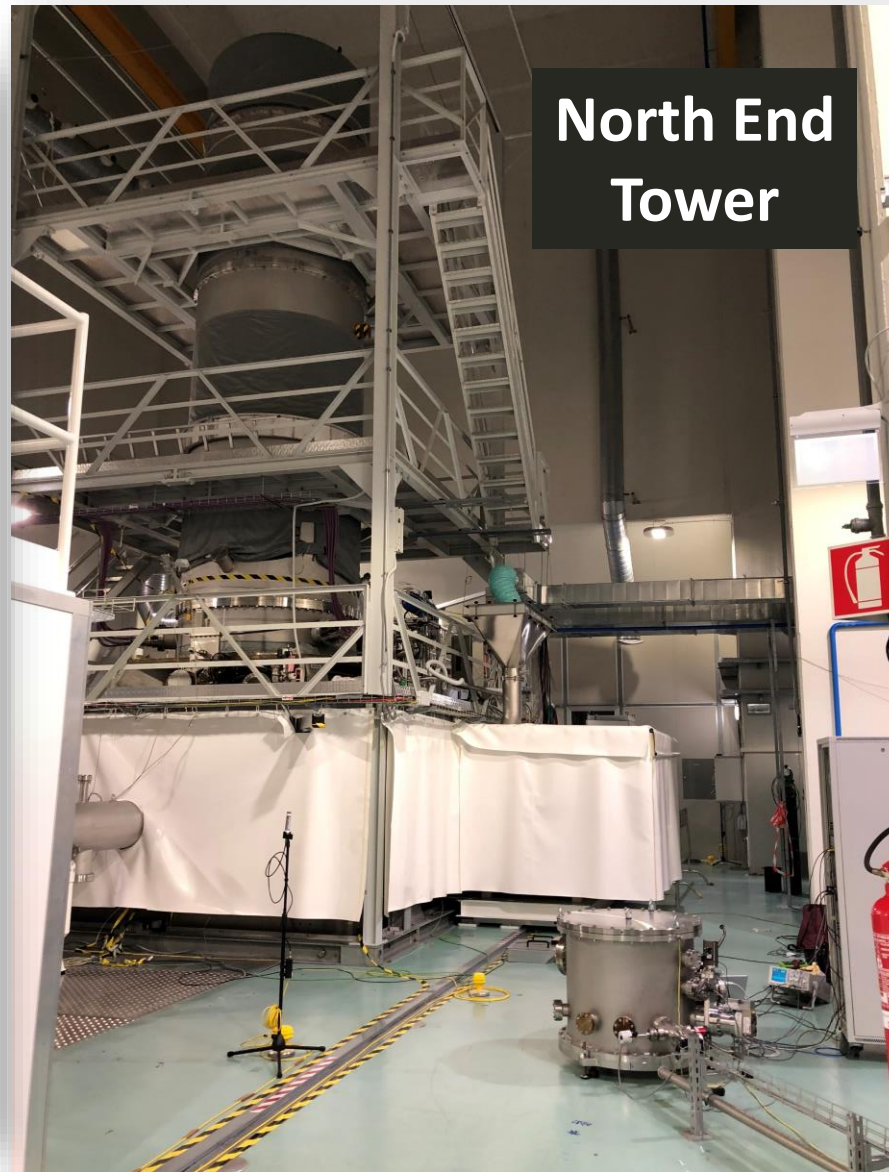
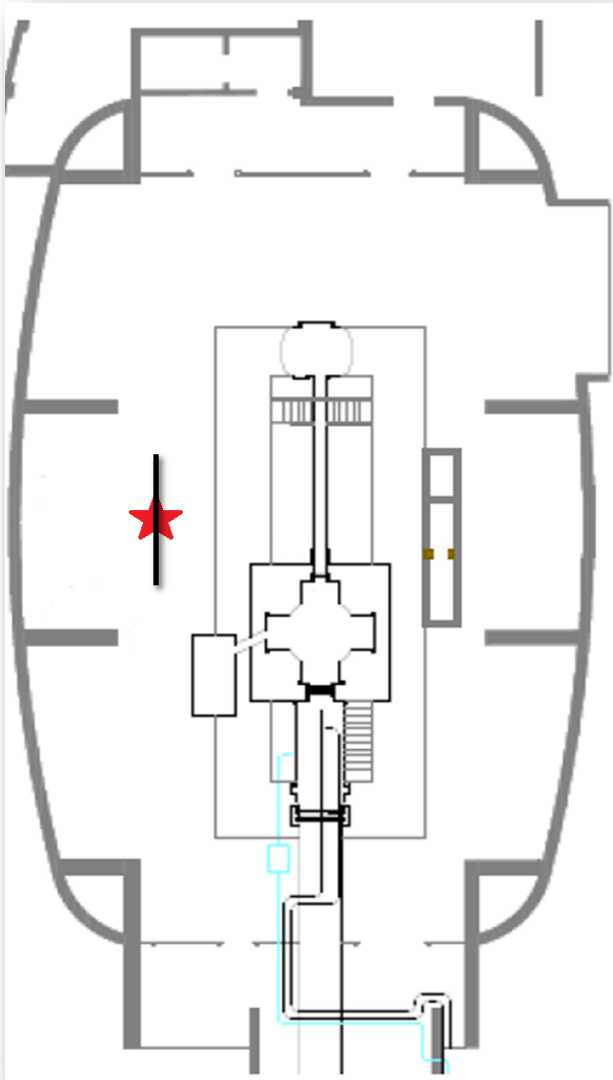
The new tiltmeter exploits the same working principles as the prototype.

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



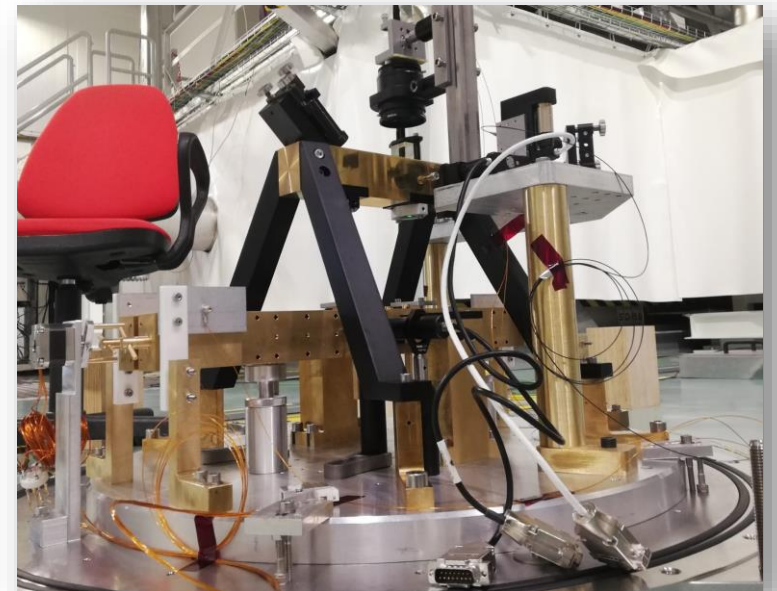
CAD sketch by L.Errico





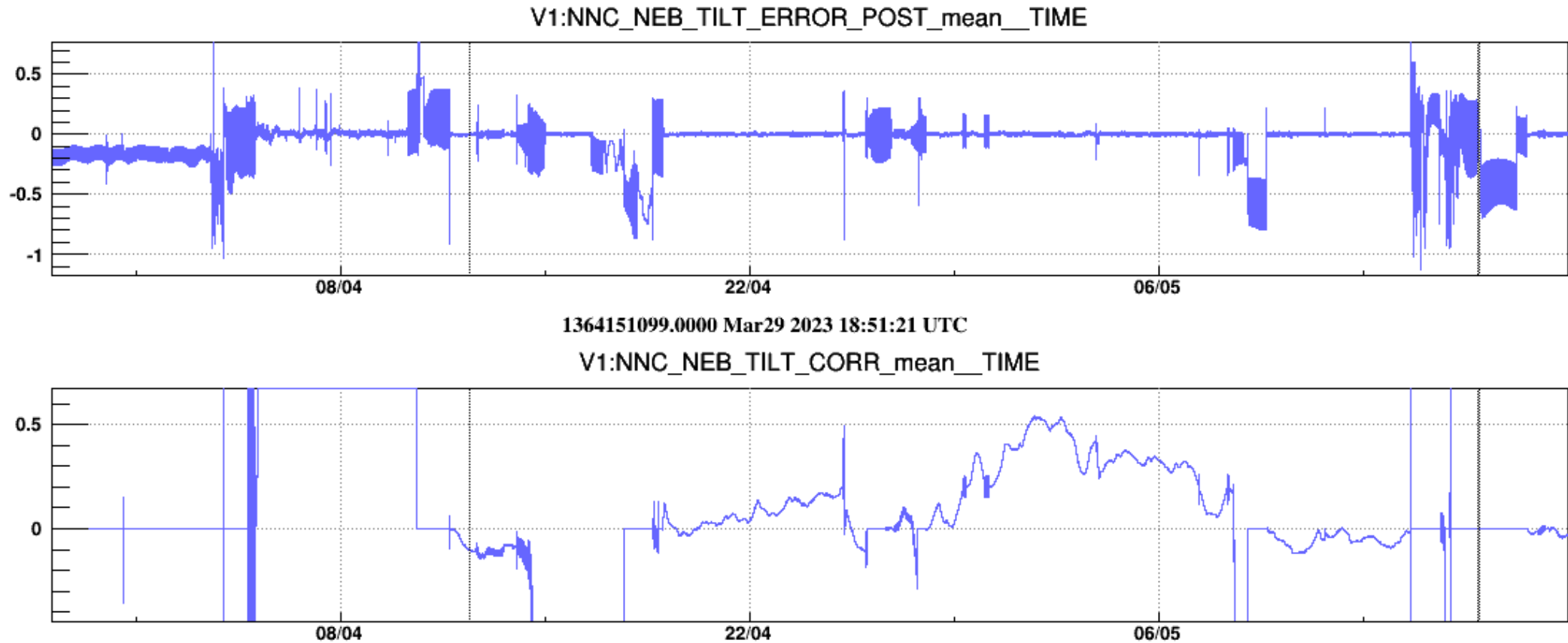
Ἀκίνητος: the new tiltmeter

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



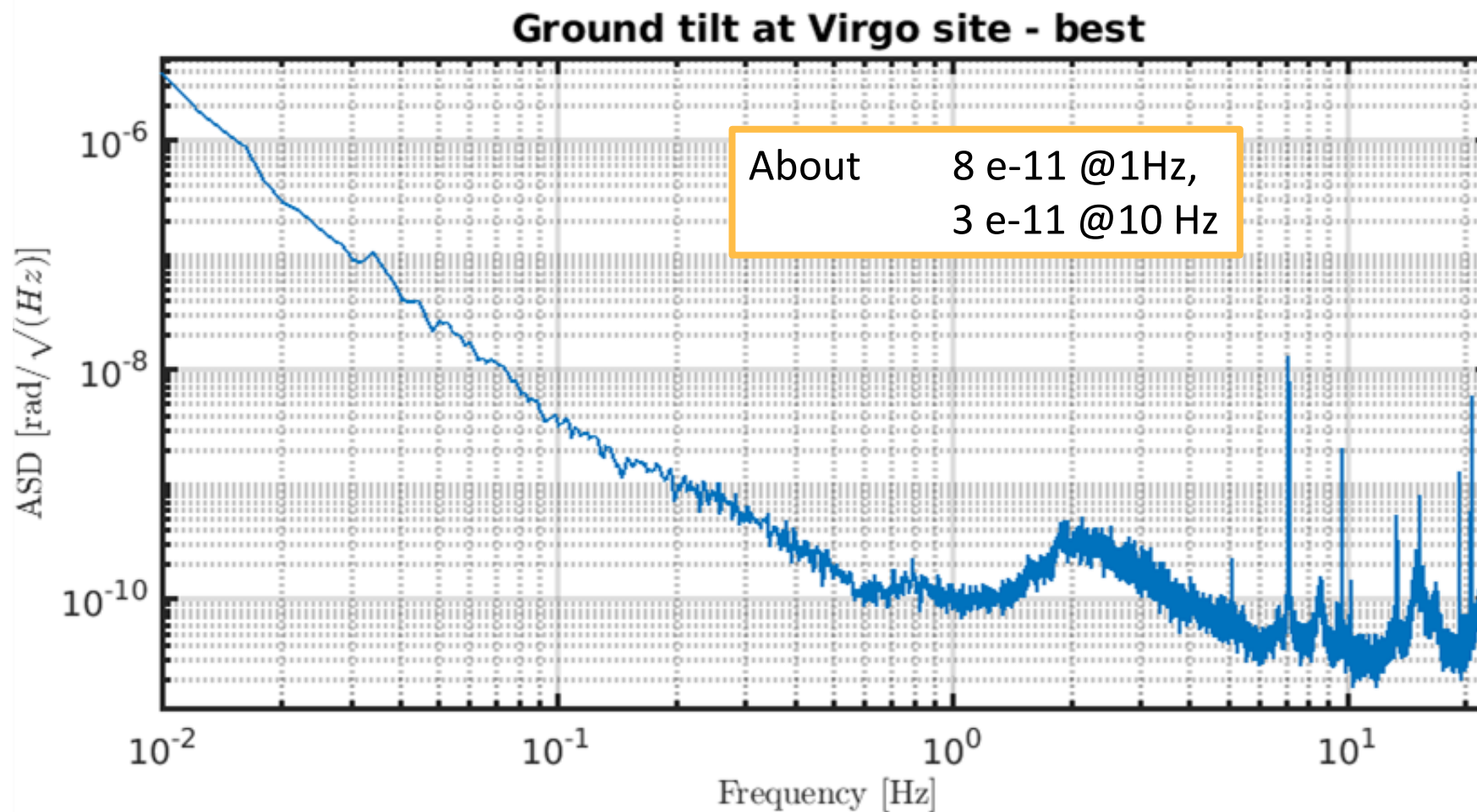
First 2 months of data

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

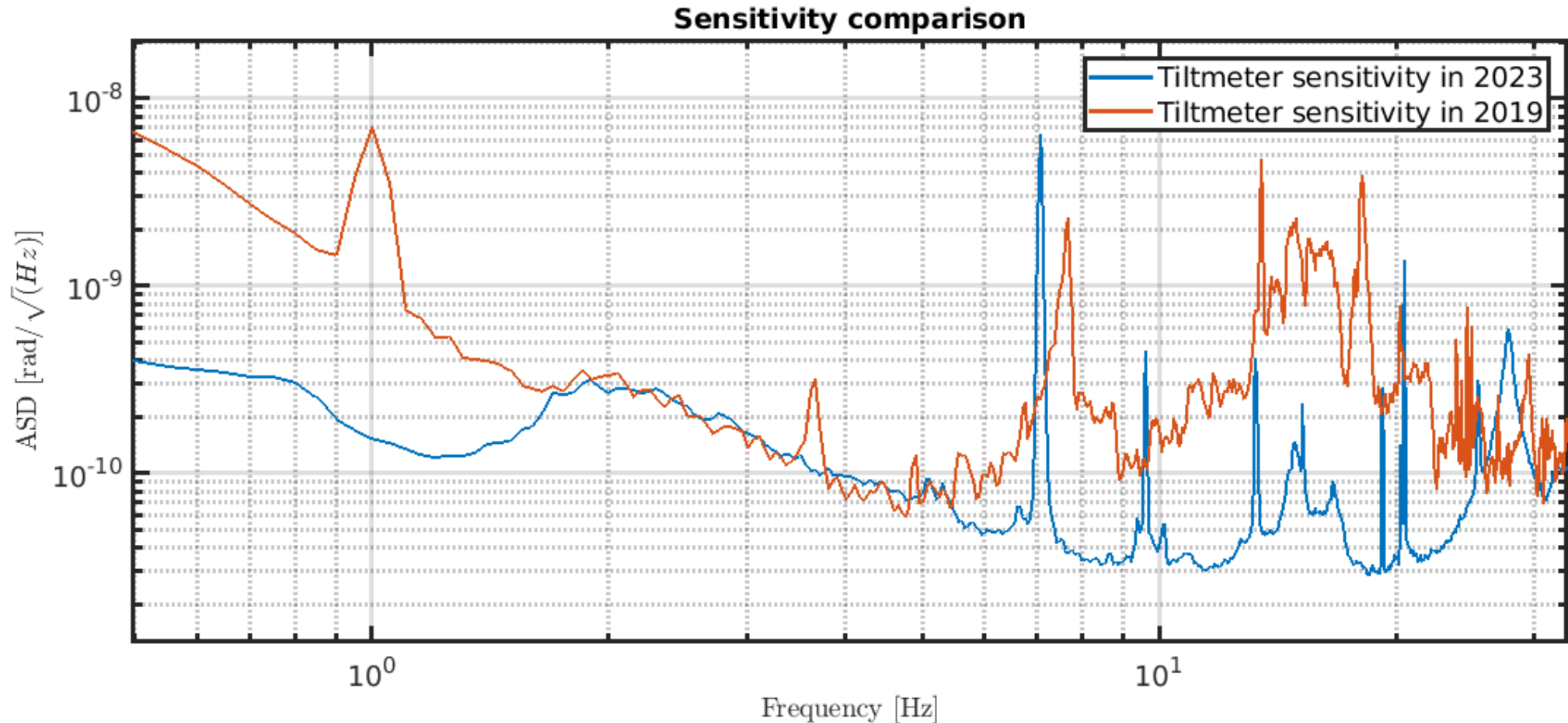


- Good duty cycle (more than 70%)
- Low correction to hold the beam in position using ITF readout

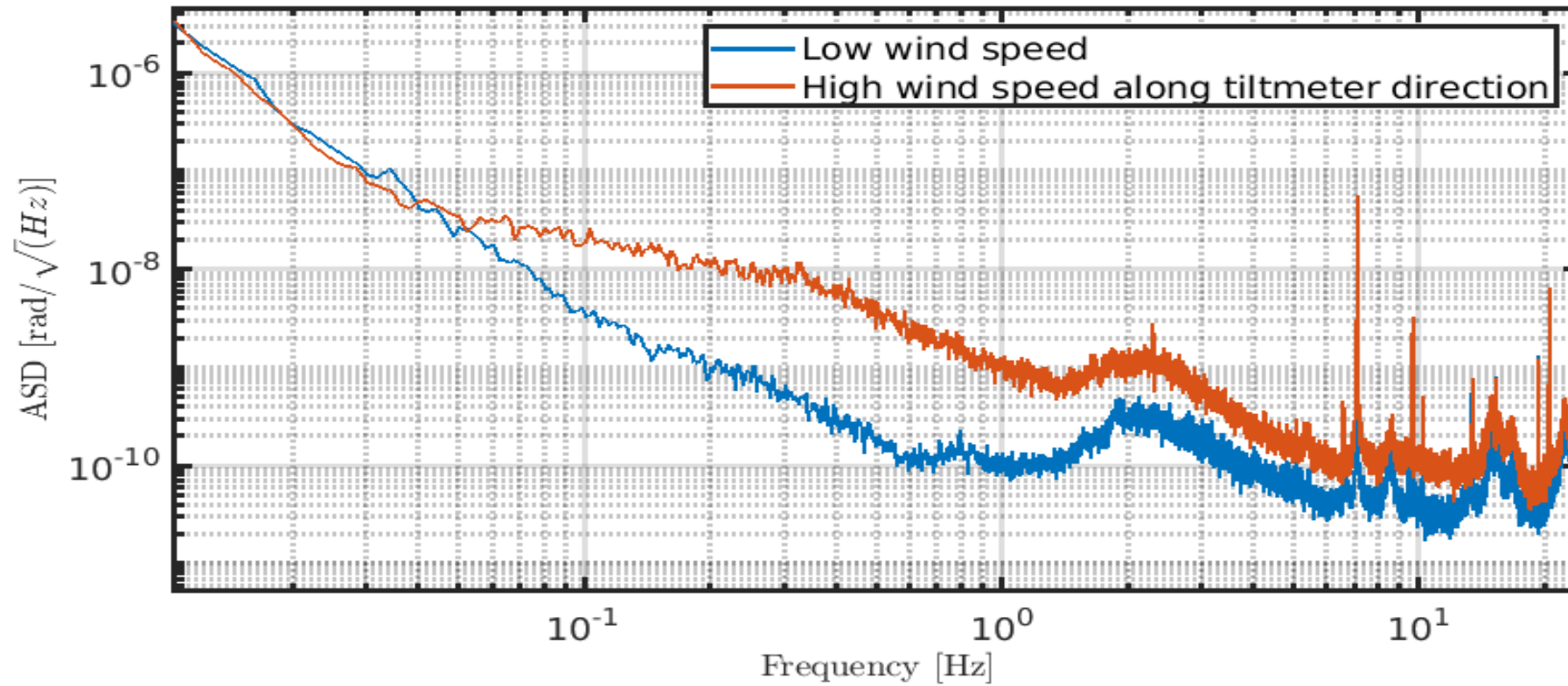
Best sensitivity curve in the first month of operation



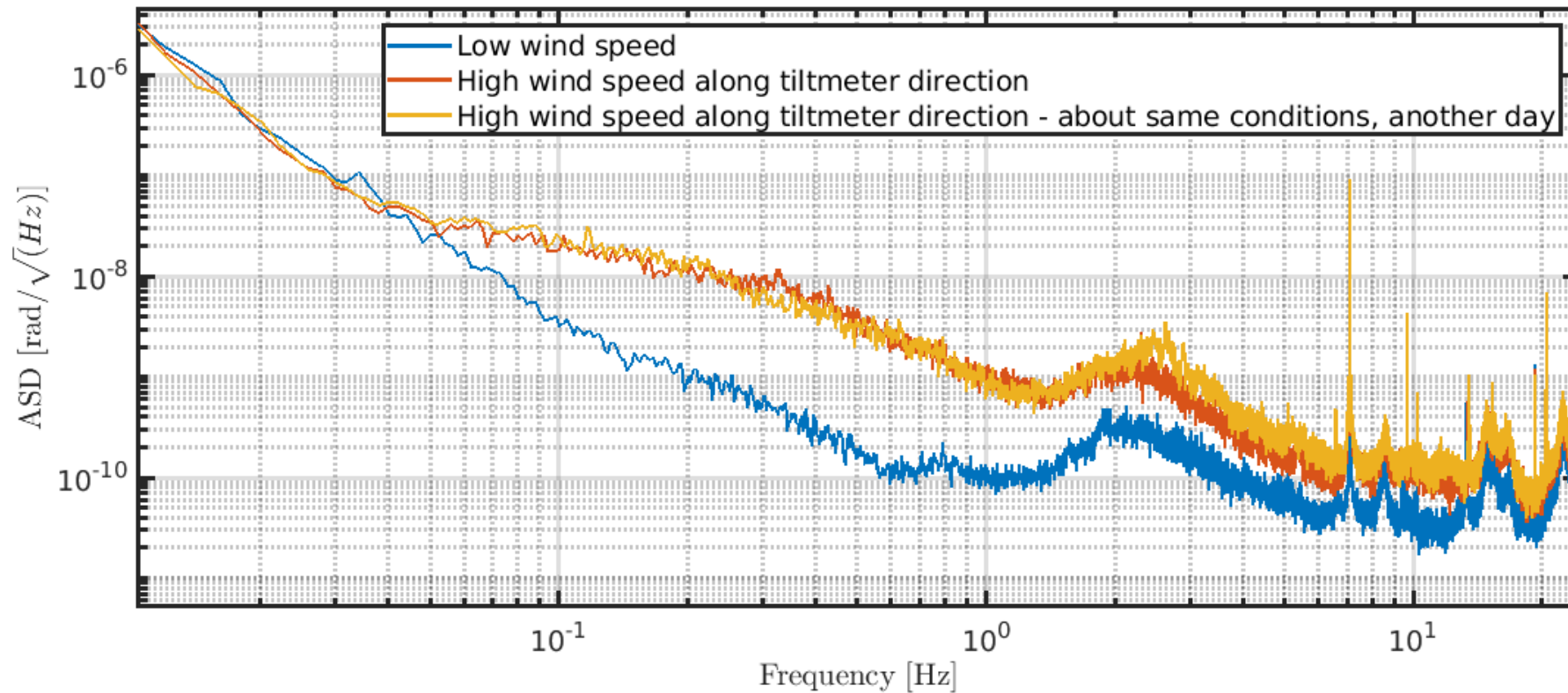
Comparison between tiltmeters sensitivity in 2019 vs 2023



Ground tilt measurement in different wind conditions

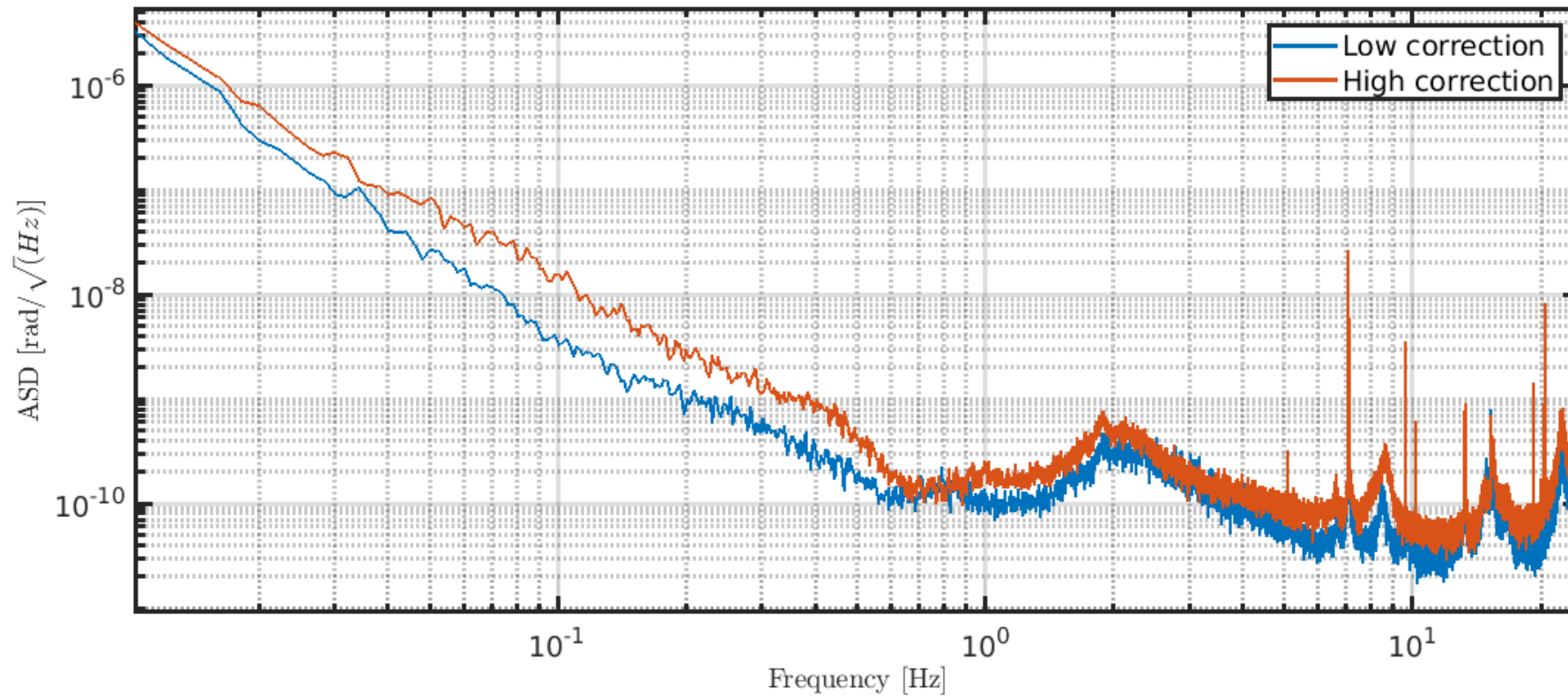


Ground tilt measurement in different wind conditions - repeatability

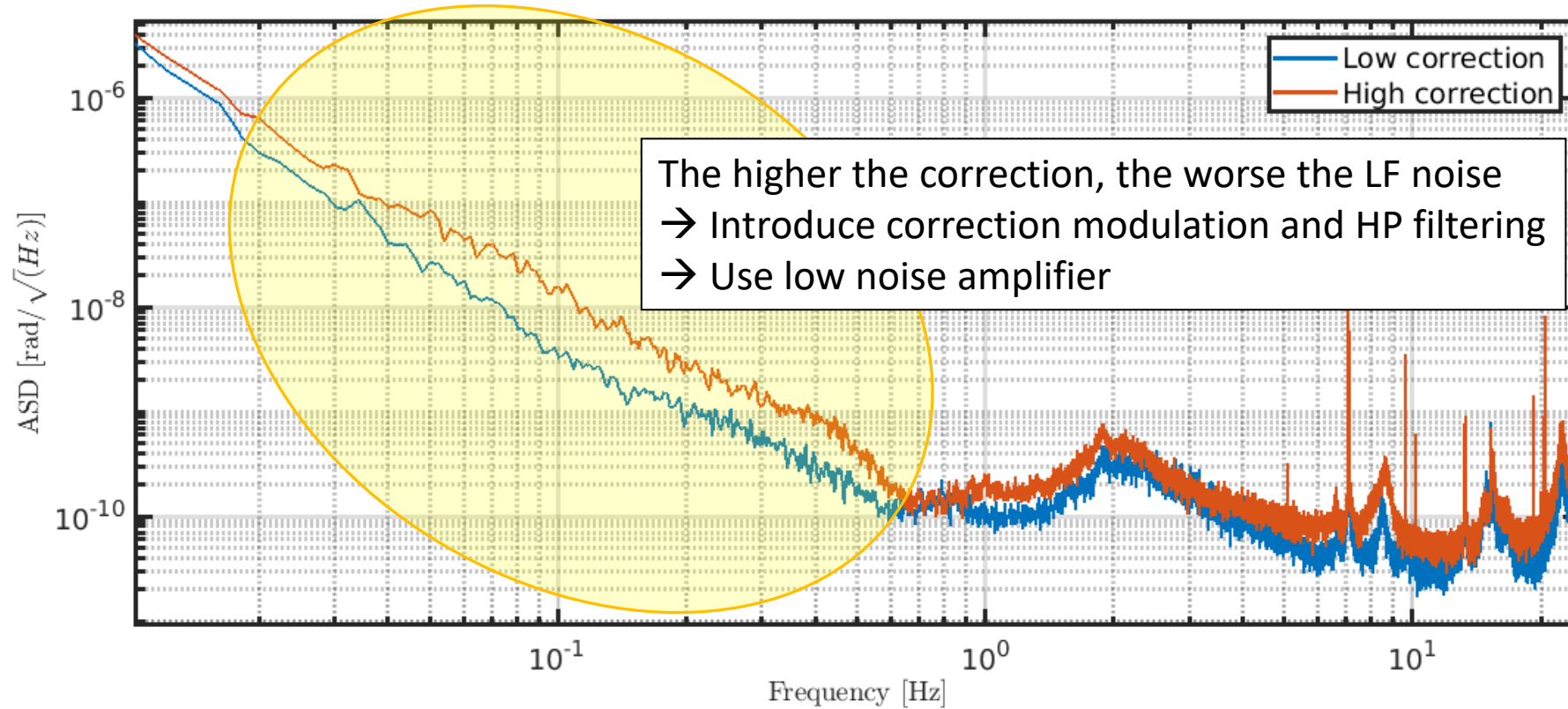


Same spectrum in similar conditions: further confirmation that tilt is actually measured

Effect of actuation noise @low frequency



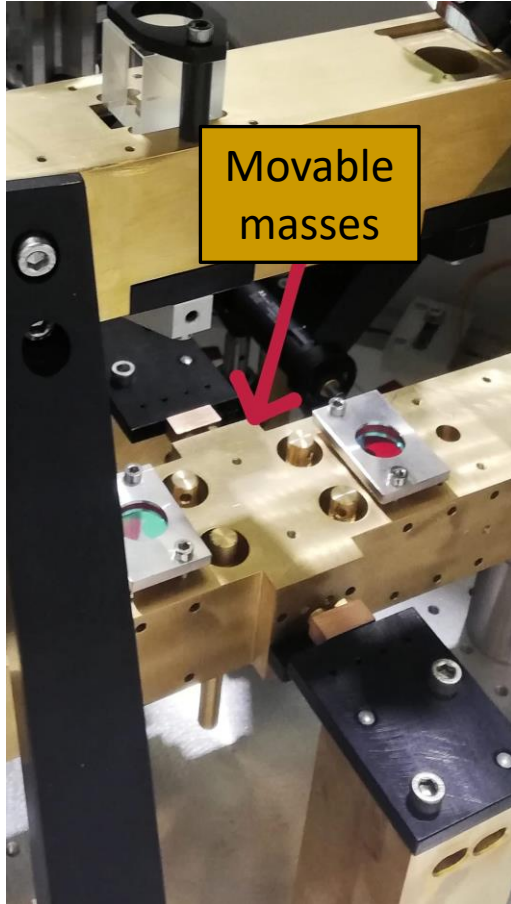
Effect of actuation noise @low frequency



Outline

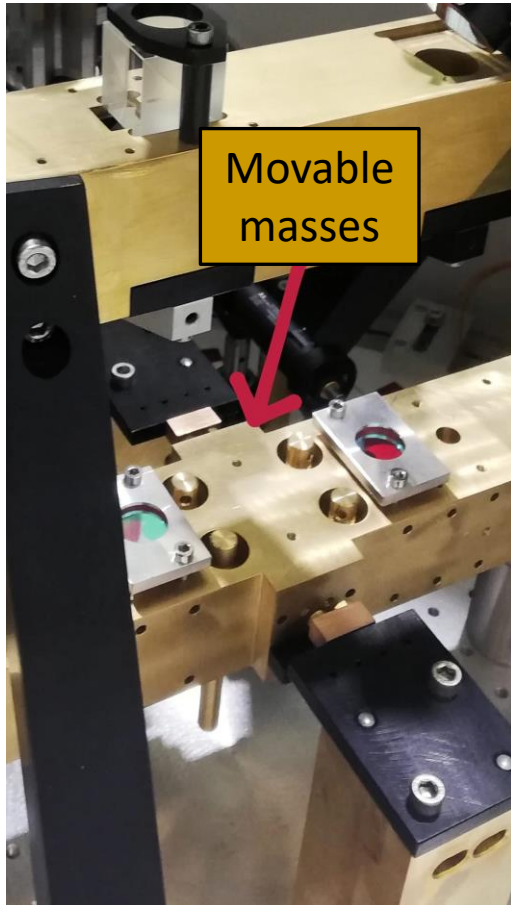
- The tiltmeter: from the prototype to the first upgrade
- Akìnetos: two months of data taking and first experimental results
- **Towards the optimal seism-to-tilt decoupling: center of mass raising**

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

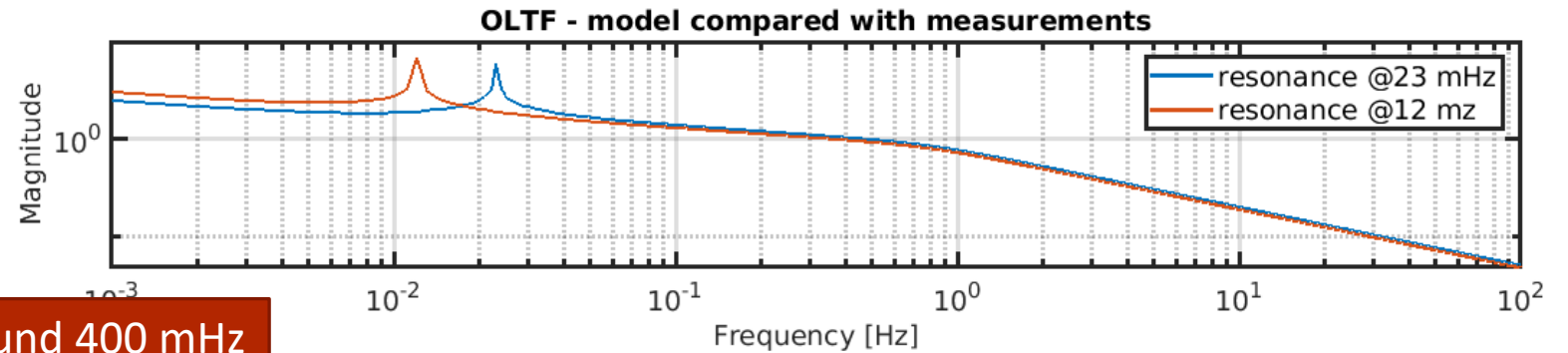


- The tiltmeter behavior was simulated with OCTOPUS, a Matlab simulation tool developed by P Ruggi based on impedance matrices approach (see L. Trozzo talk) and tuned in order to match the measured transverse resonance frequencies – pretty reliable model
- A residual seism-to-tilt coupling along the 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 $50\text{ }\mu\text{m}$.
- This distance has also been estimated looking at the coherence between the seismometers and tiltmeter signal

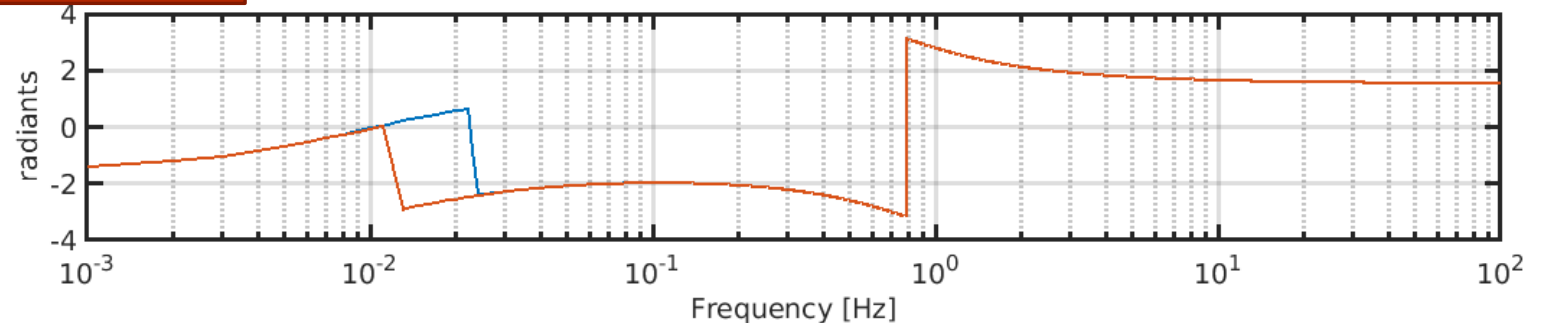
Center of mass raising to reduce the seism-to-tilt coupling



The center of mass was raised by about $35\text{ }\mu\text{m}$ 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

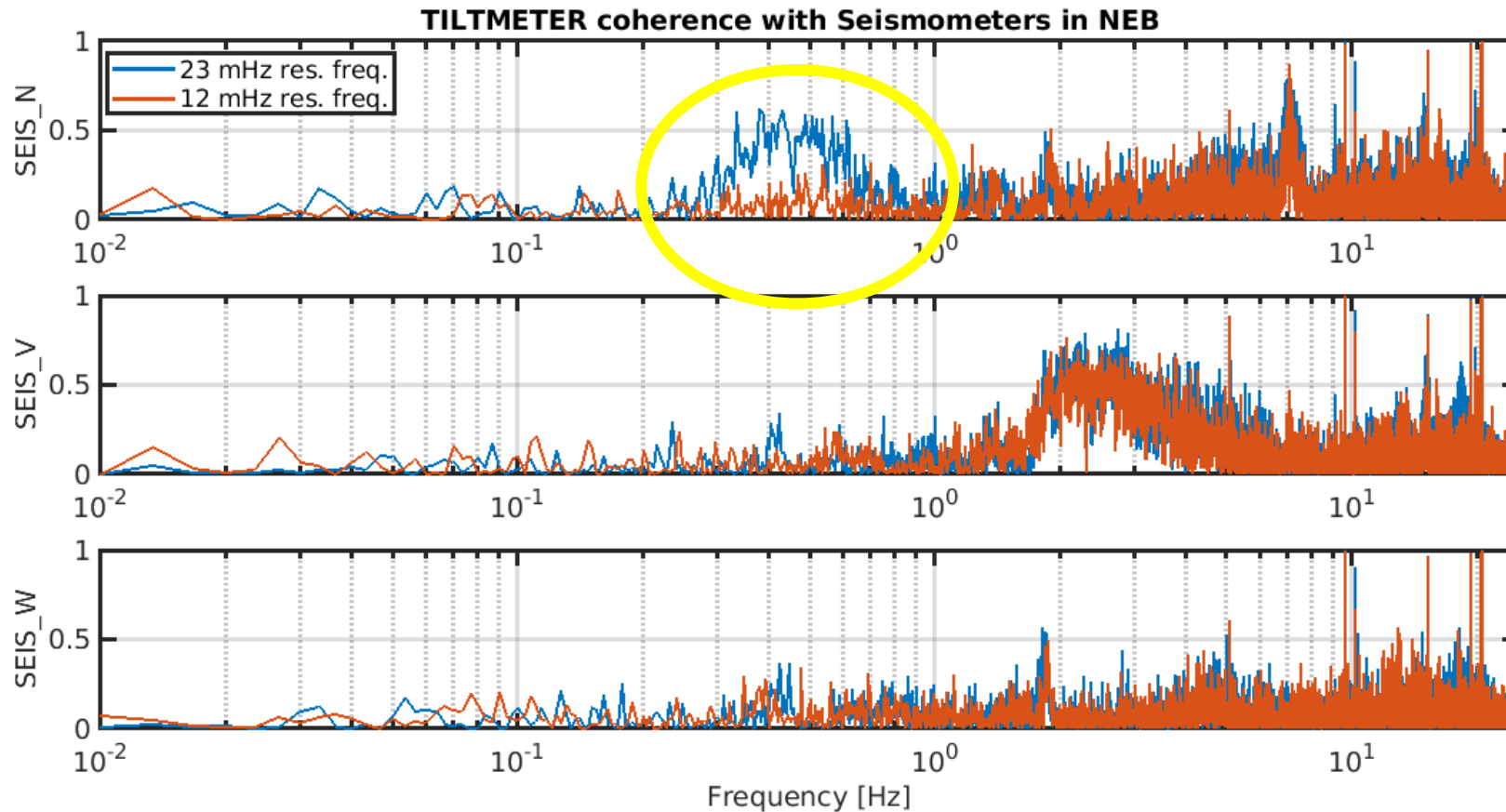


UGF around 400 mHz



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

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**

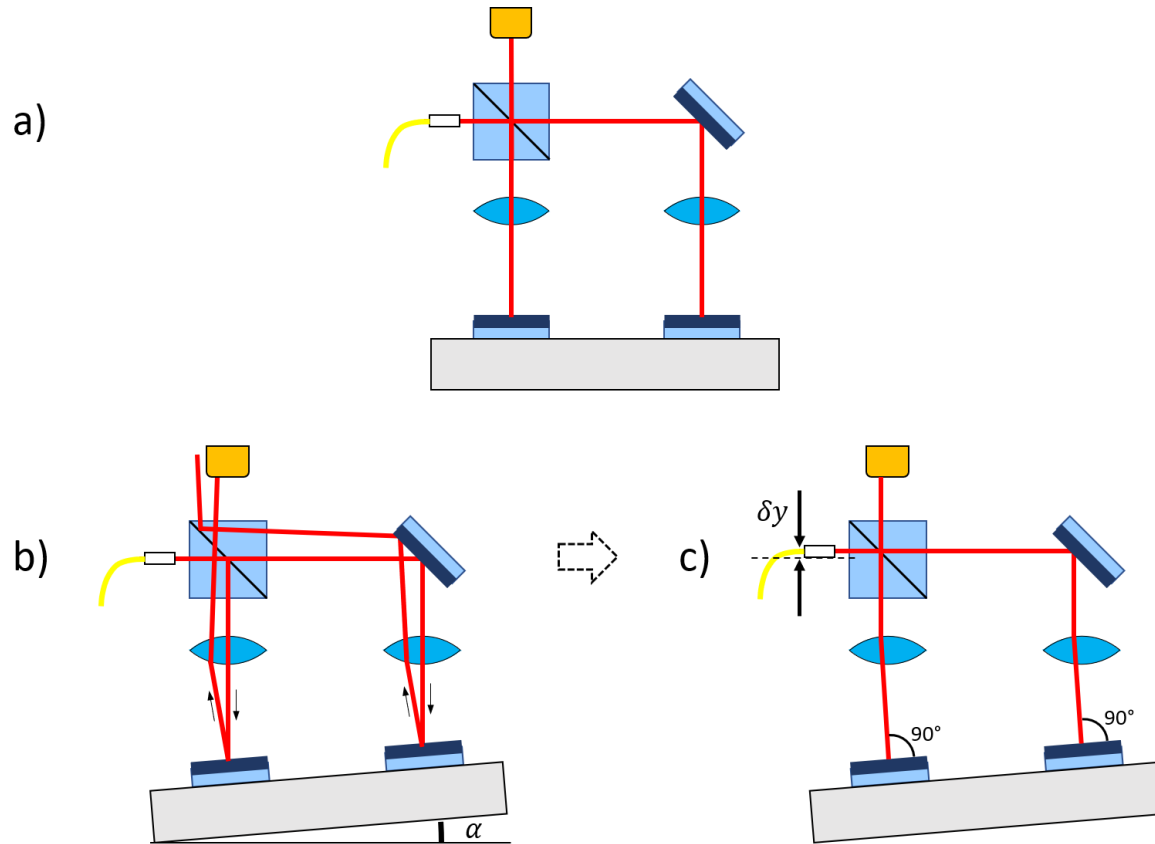
Conclusions and future perspectives

- 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 improvements 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

Ἀκίνητος: the large-band tiltmeter

