Recent developments on beam-balance tiltmeter

A. ALLOCCA FOR ARCHIMEDES AND VIRGO COLLABORATIONS

VIR-0957A-20

Outline

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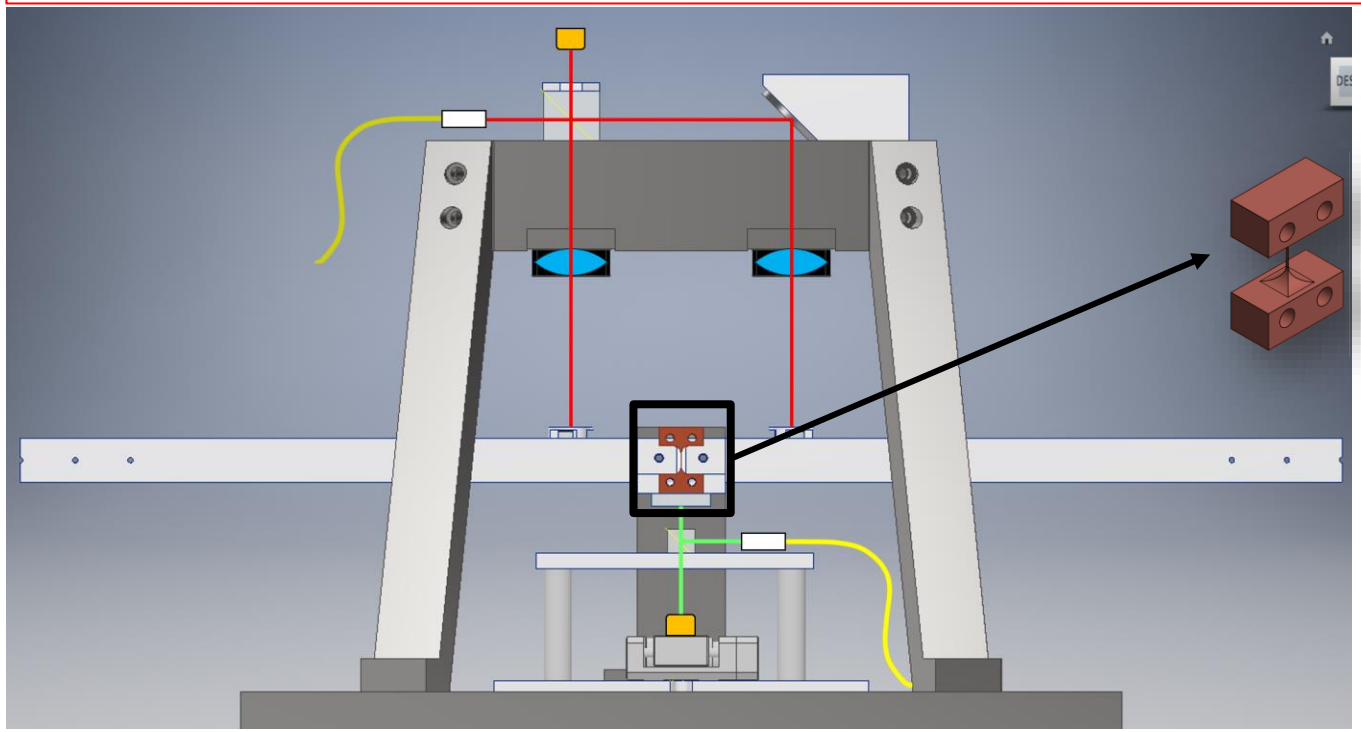
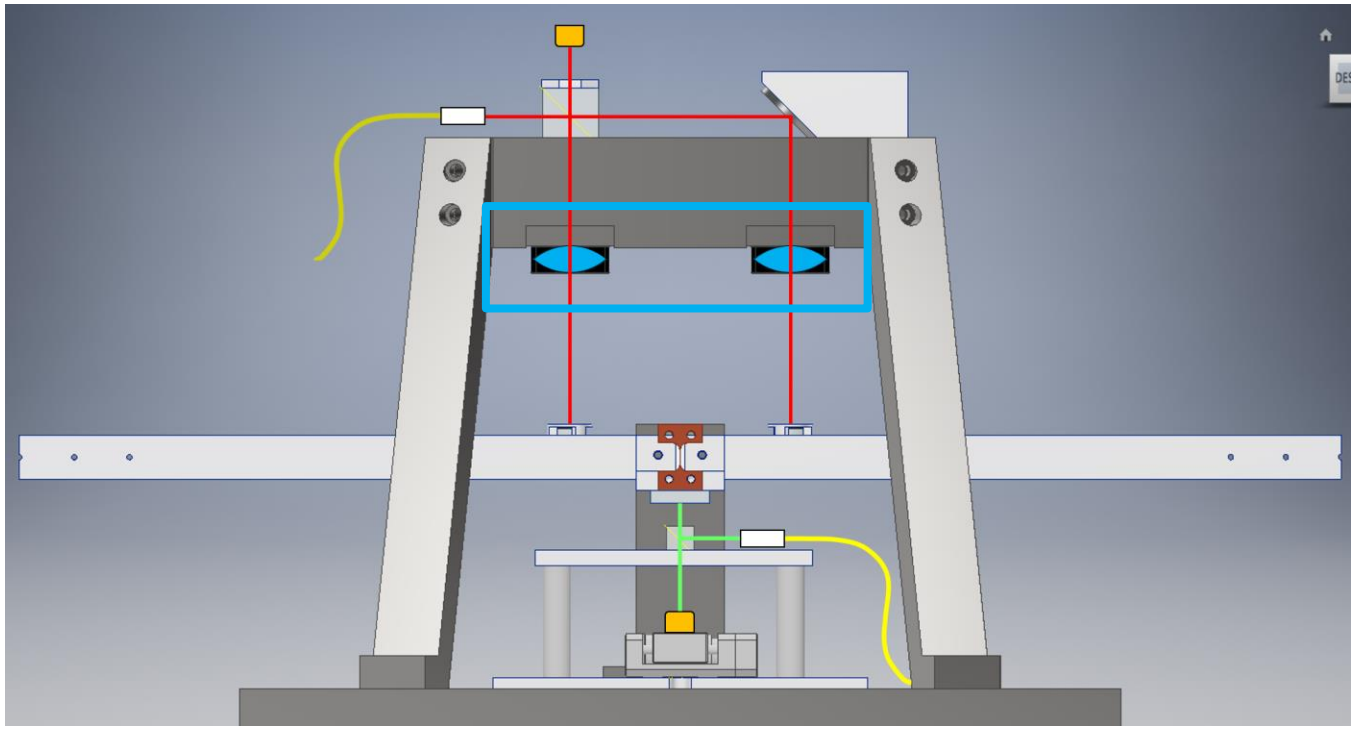
The tiltmeter

The tiltmeter is a prototype of the **Archimedes** experiment, aiming to the measure of the interaction between quantum vacuum energy and gravity



- **Beam balance** with 50 cm long arm suspended through **thin flexible joints**, very similar in design to LIGO tiltmeters (Venkateswara et al., 2014)
- The **Cu-Be joints (100µm x 500µm section),** allow to keep **the resonance frequency below 50 mHz**, with a low momentum of inertia arm
- The balance **center of mass** is positioned **as close as possible to the bending point** ($\approx 10\ \mu m$)
- Depending on the center of mass positioning, its **resonance frequency** is around **20-30 mHz**

The tiltmeter



The tiltmeter is equipped with two different optical readout, 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 tilts**

Performance in Virgo

- Installed by the Virgo-Napoli group in Feb 2019.
  The first data taking started about two months later and lasted until mid July

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

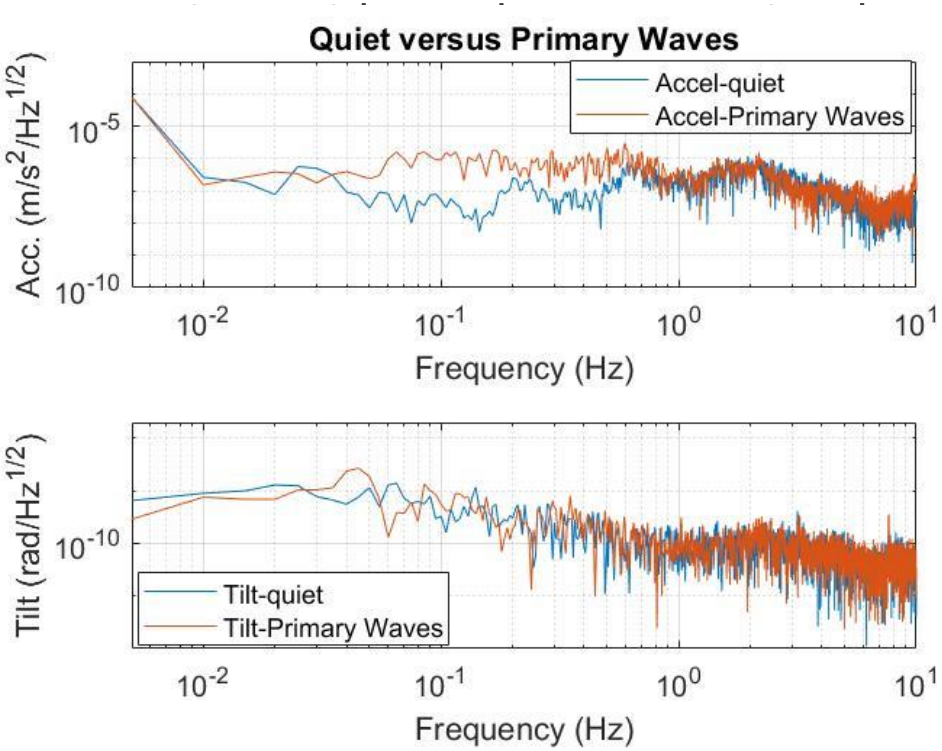
- **Digital acquisition and control system is completely Virgo-like** (same modules used to control the superattenuators – developed by **Virgo-Pisa group**)

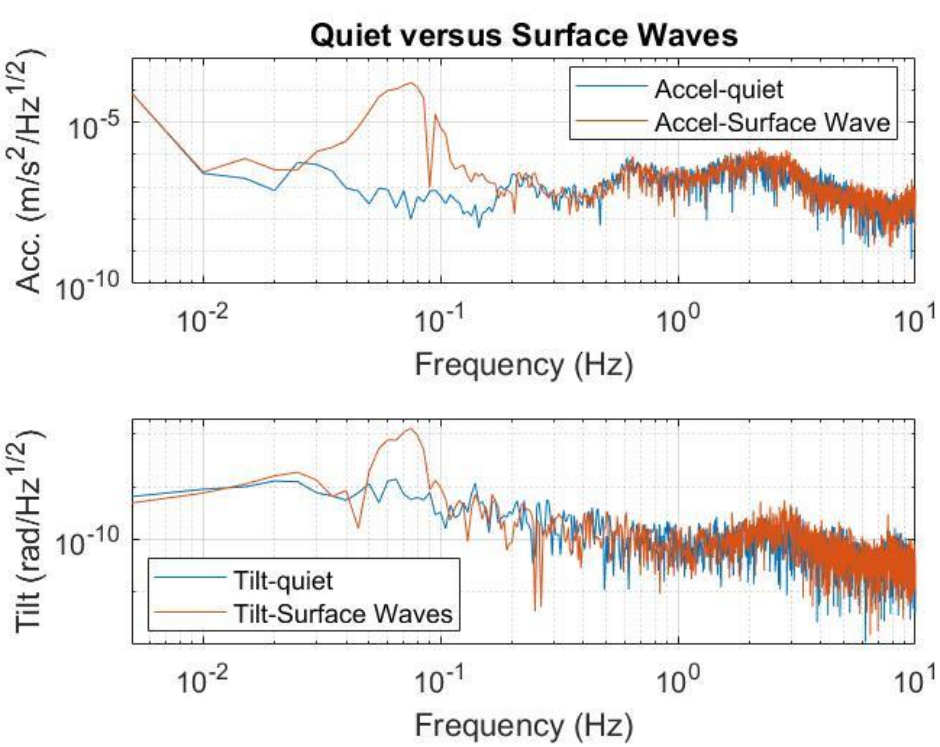
- All the signals were part of the **Virgo channel list** (V1:ENV_NE_tilt*)

- **Vacuum pumps** provided by the **EGO vacuum group**

Performance in Virgo – earthquake response

As expected, the tiltmeter is sensitive to Surface Waves and not to P-waves (which are essentially translational).

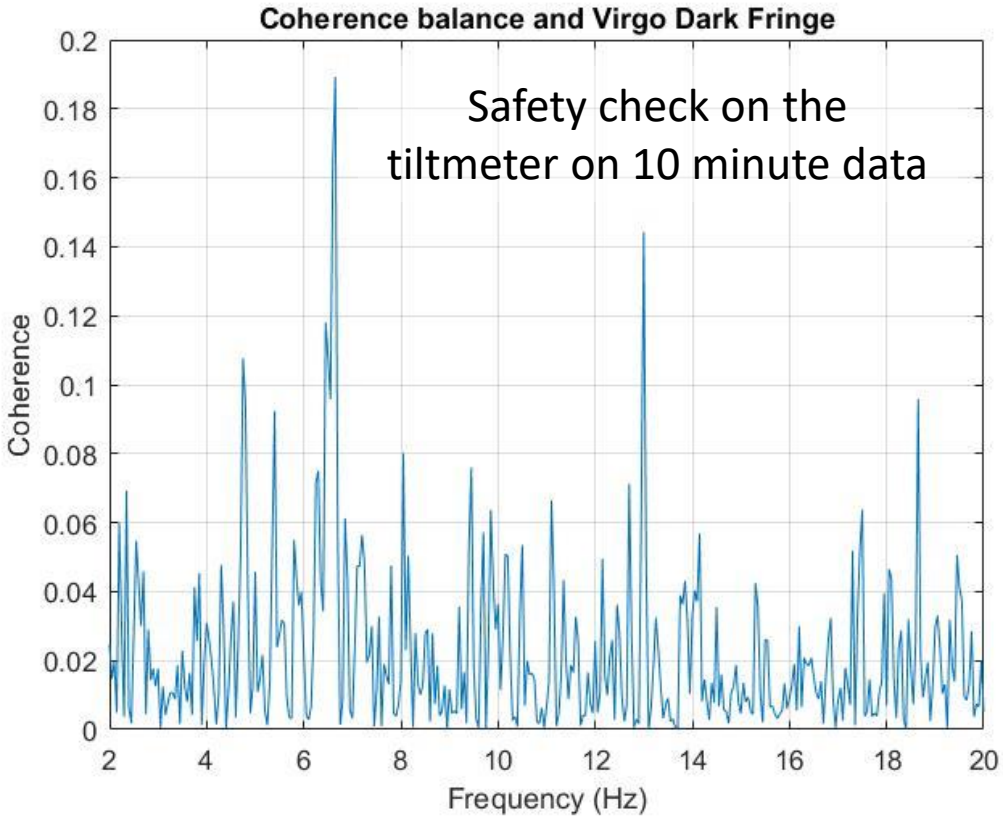




Performance in Virgo – coherence with B1

In most cases, there is coherence between tiltmeter and seismometer signals

At several frequencies, the tiltmeter is partially coherent also with B1, besides with seismometers placed in the building.
This coherence highlights a possible coupling mechanism through diffused light.



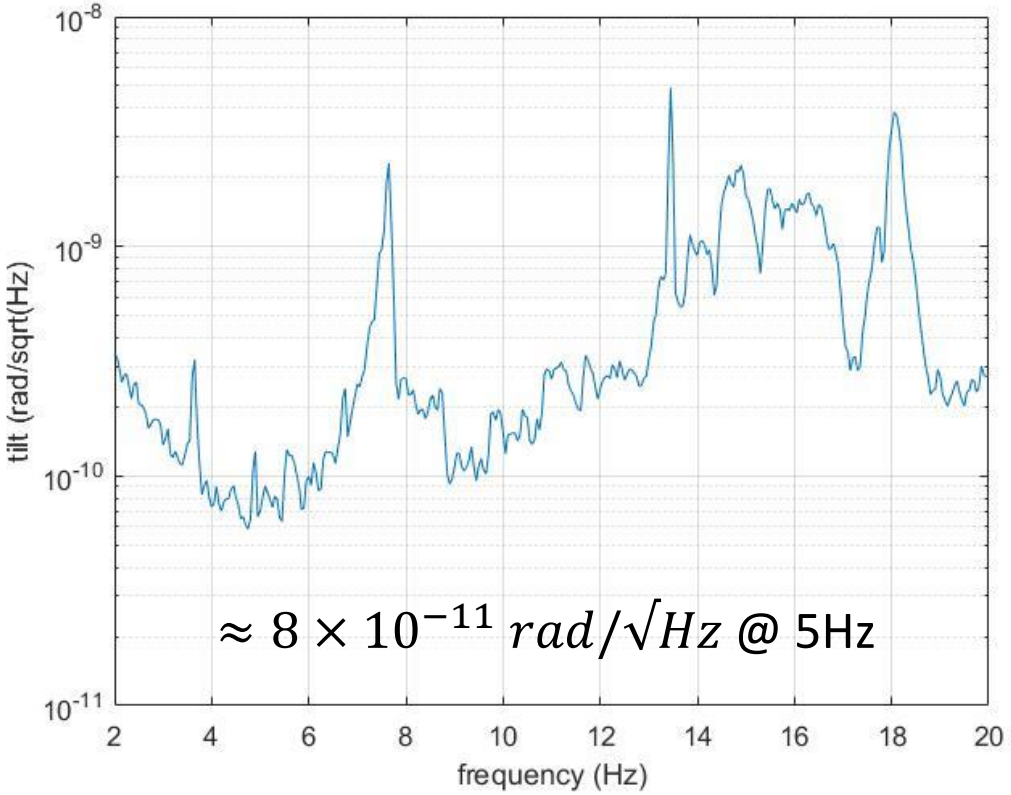
Performance in Virgo – tilt measurement

In the **10-20 Hz** range, the measured tilt shows results similar to LIGO site:

- in the extreme range (10-13 Hz and 18-20 Hz) the floor is comparable
- in the middle range (between 13 and 18 Hz) the noise is higher.

Seismic noise level in Virgo is comparable with the LIGO site

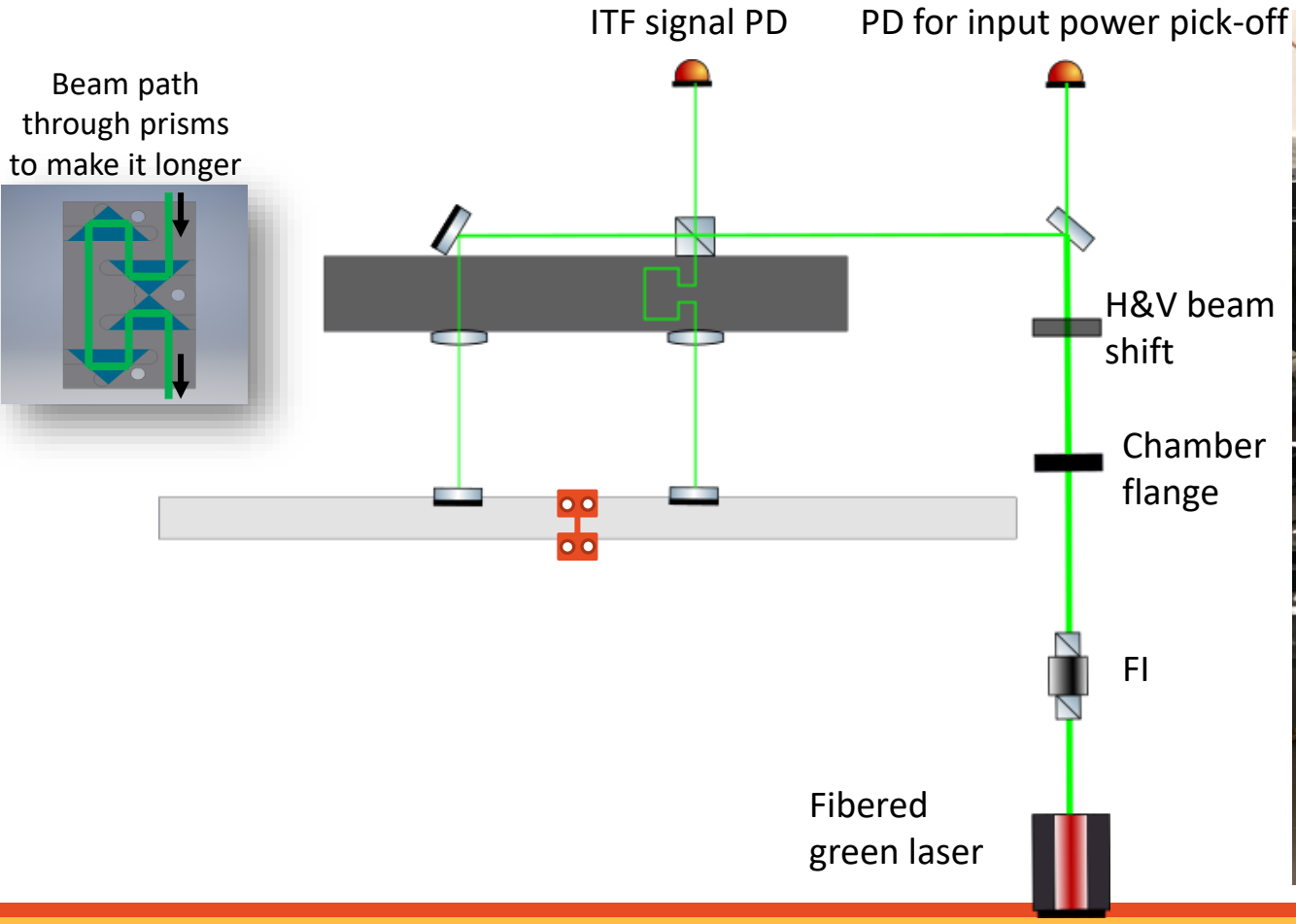
Tilt measurement in the NN frequency band

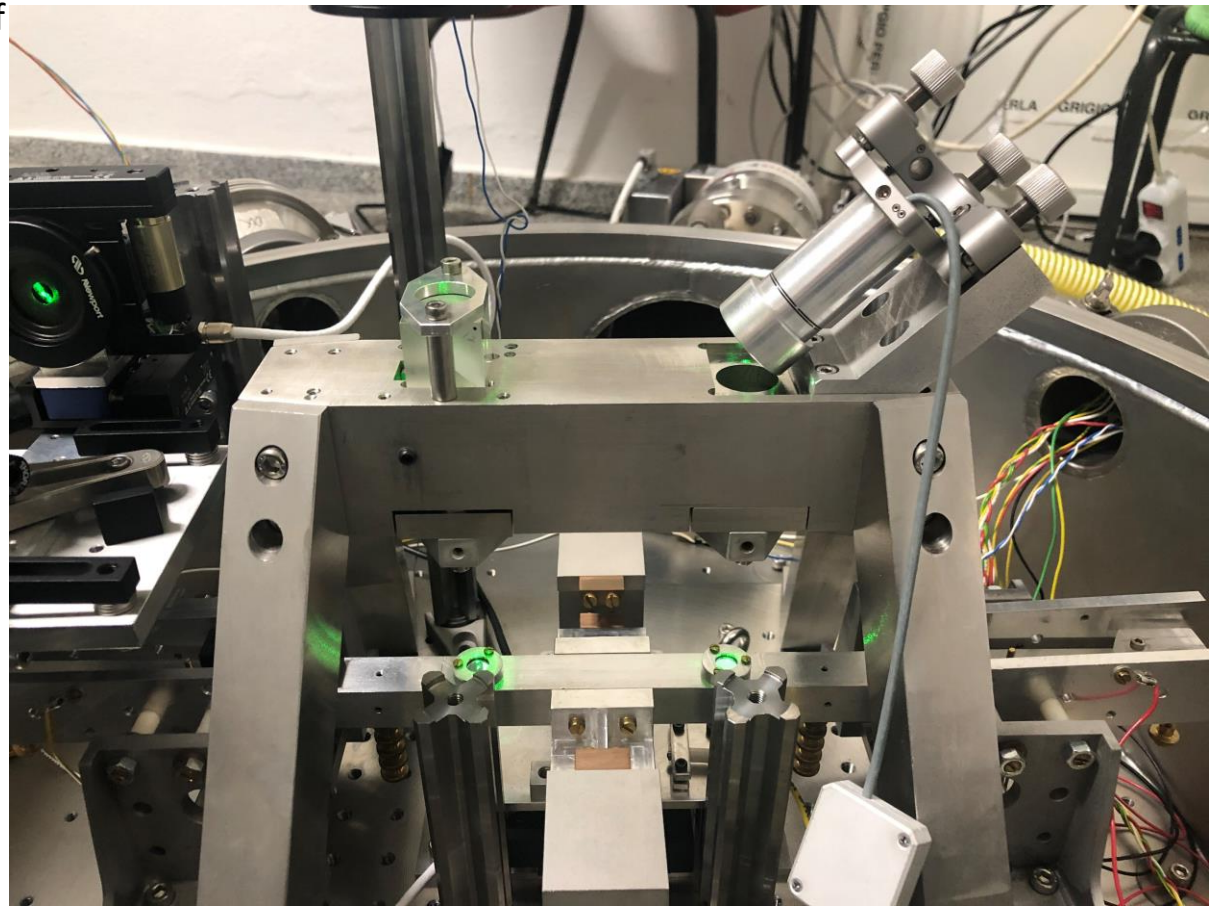


Tiltmeter improvements

- Reduced frequency noise coupling by equalizing interferometer arms (from $\Delta L = 10\ cm$ to $\Delta L \approx 2\ mm$)
- 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
- Increased robustness of ITF signal by using a larger beam (waist from 0.5 mm to 2 mm) and by installing a tip-tilt to better align the beam and improve the contrast

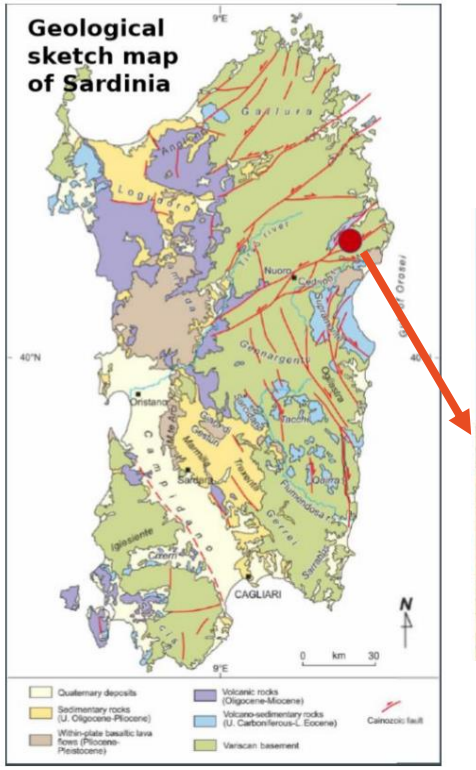
Tiltmeter – the balance optical scheme





Tiltmeter in Sos-Enattos

The tiltmeter has been installed in a quiter site



Sos-Enattos mine in Lula (NU)

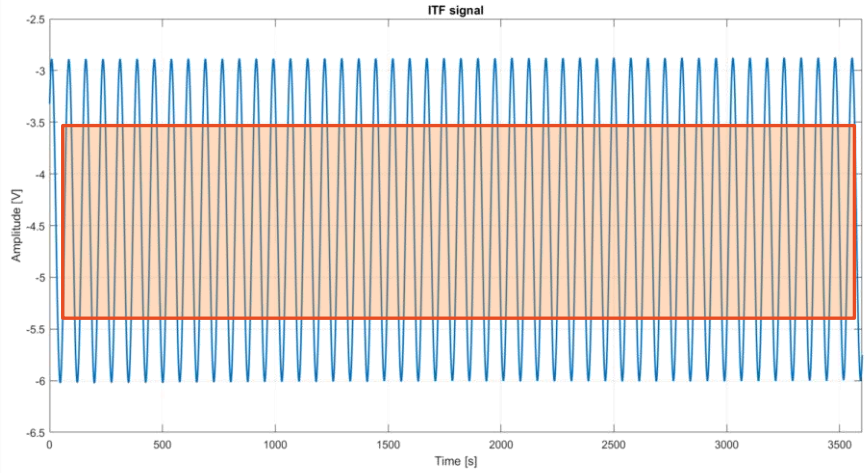
Surface lab

Archimedes in Sos-Enattos

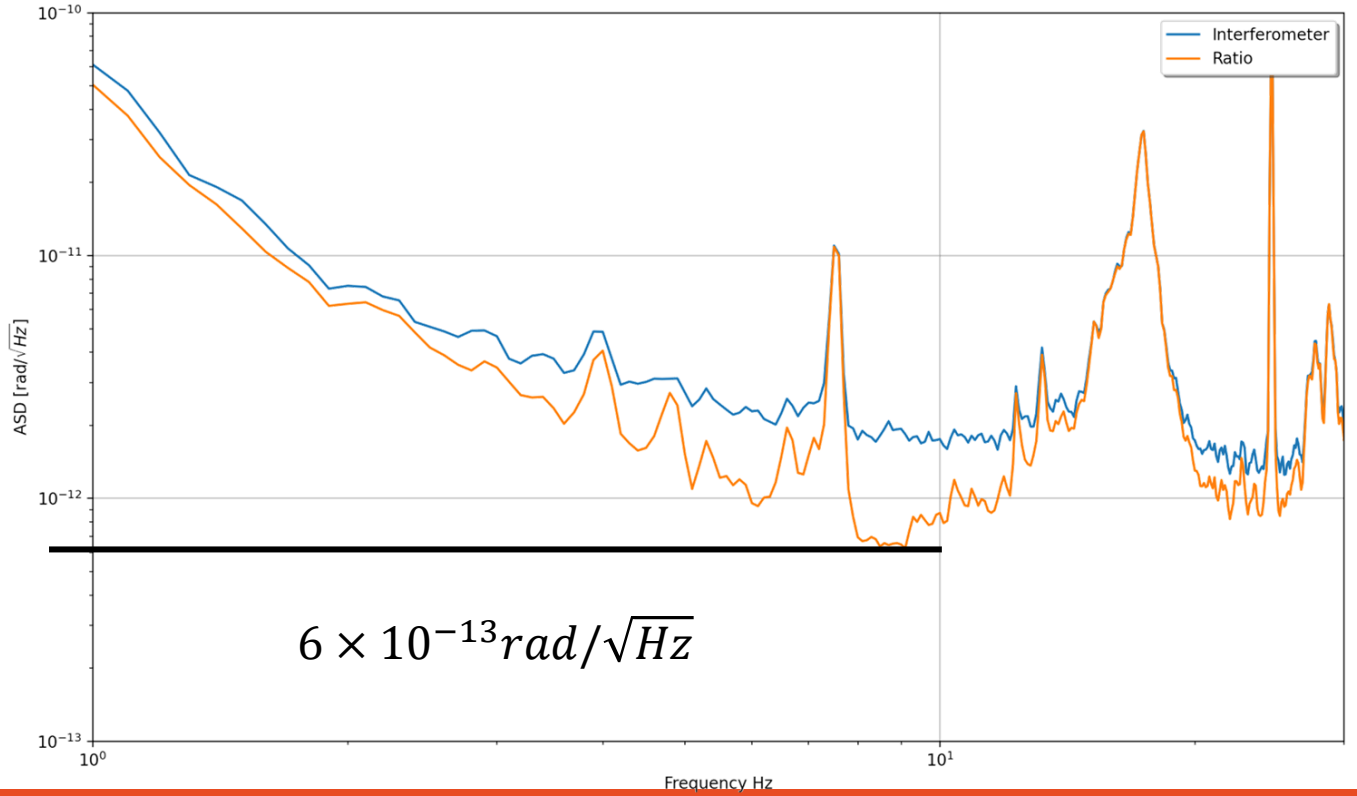
In Sos-Enattos works are ongoing towards the installation of the Archimedes experiment, in the SAR-GRAV laboratories, promoted by the **Sassari University, INFN, INGV and Regione Sardegna**

Tiltmeter in Sos-Enattos – preliminary sensitivity

The balance is <u>not yet controlled</u> with electrostatic actuators, but **<u>drifting</u>**. The sensitivity is computed over 1 hour of data, averaging the linear part of the signal, around half fringe



- Blue trace: ITF signal
- Orange trace: ITF signal divided by the normalized pick-off signal

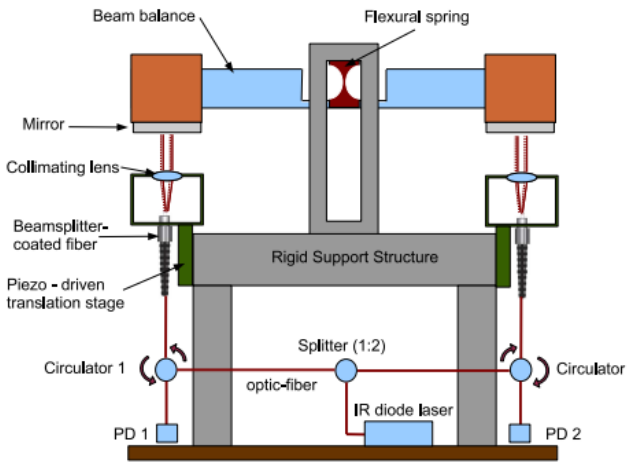


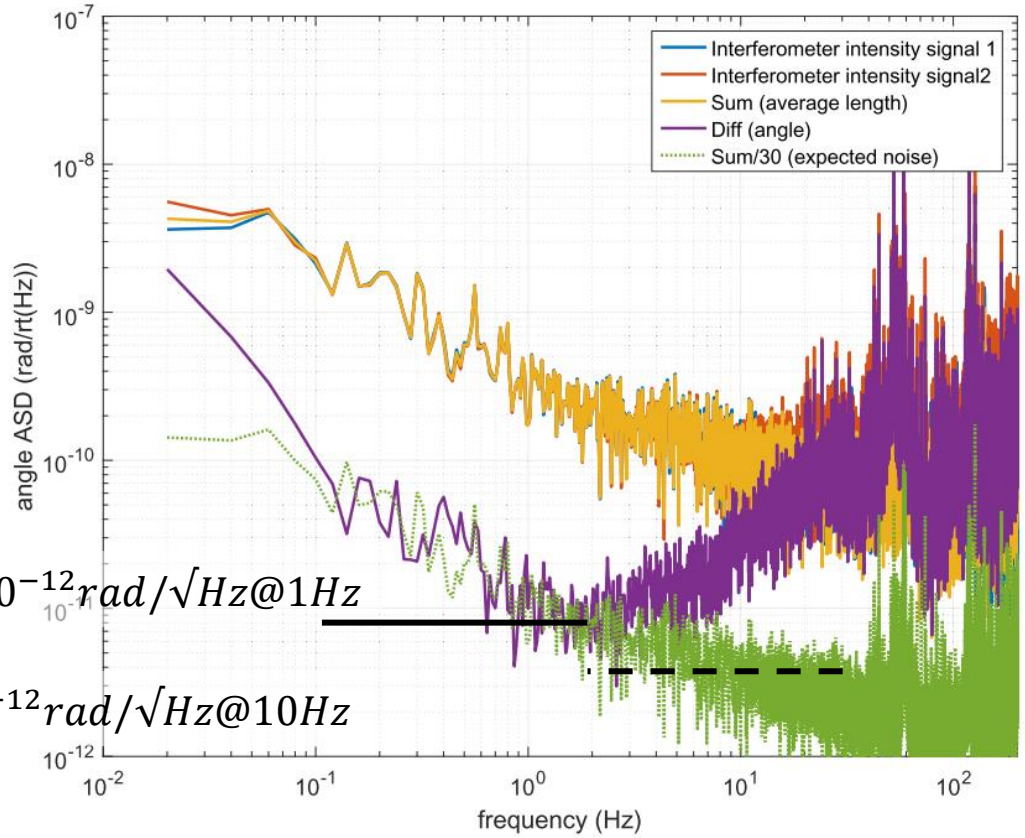
Panoramic view

Measurement performed with beam-balance held fixed

LIGO tiltmeter – Beam balance with dual-interferometer for the read-out

- Sum: measure of the average cavity length (limited by freq. noise, which can be subtracted)
- **Difference**: measure of the arm length difference





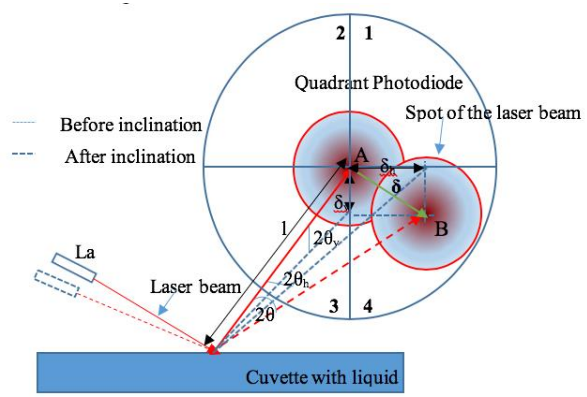
Measured sensitivity $\approx 8 \times 10^{-12} rad/\sqrt{Hz}@1Hz$

Inferred sensitivity$\approx 4 \times 10^{-12} rad/\sqrt{Hz}@10Hz$

Jan Harms and Krishna Venkateswara 2016 Class. Quantum Grav. 33 234001

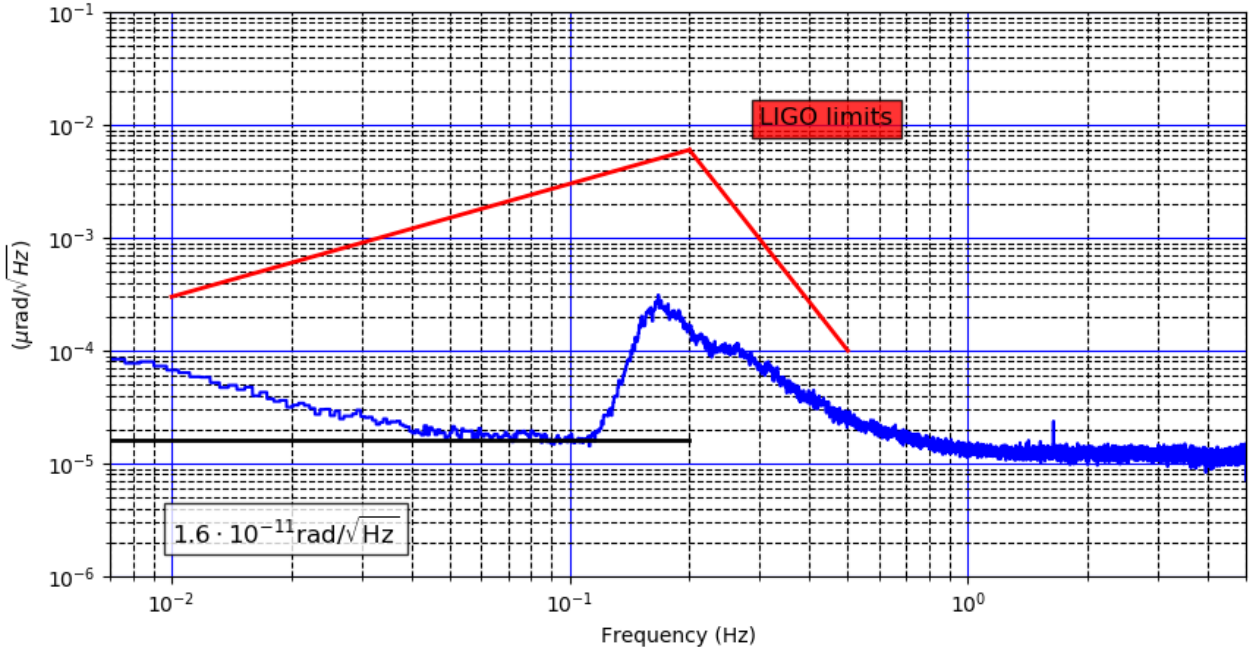
Panoramic view

CERN-JINR Precision Laser Inclinometer (**PLI**)



The PLI uses the displacement of the laser ray reflected from a liquid surface when the base support is tilted by ground oscillations

Result on sensitivity: over 24 hours at CERN

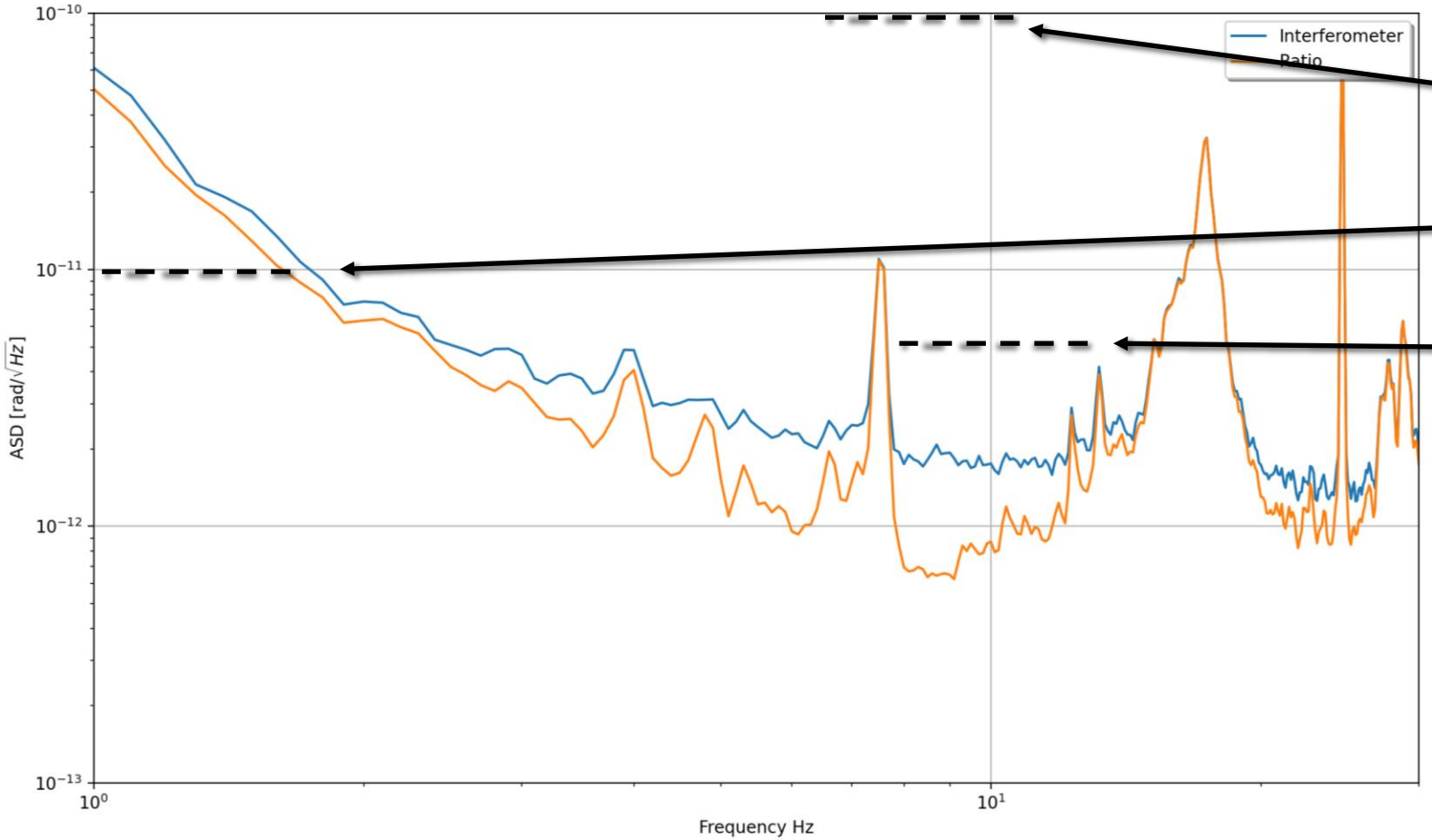


B. Di Girolamo *et al.*

https://indico-test.jinr.ru/event/410/contributions/3014

In the next upgrades, it is foreseen to extend the sensitivity band up to 25-30 Hz

Sensitivity comparison - **preliminary**



Tilt measurement in Virgo/LIGO

PLI sensitivity at CERN

LIGO tiltmeter (inferred) sensitivity

To be understood the structures at 7Hz and the around 20 Hz, possibly resonances of the vacuum tank coupling through stray light mechanisms

Conclusions

- The tiltmeter prototype has shown good results during the operation time in Virgo
- In Sos-Enattos (after improvements and in a much quiter site), the sensitivity reaches $6 \times 10^{-13} rad/\sqrt{\mathrm{Hz}}$ around 10 Hz

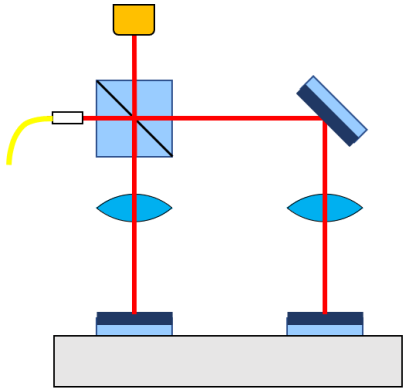
Next steps

- Further actions are foreseen to improve the sensitivity of the beam balance installed in Sos-Enattos.
  The arm will be controlled with electrostatic actuators to prevent the drift.
  Stray light mitigation actions will be also perform to improve the sensitivity above 10 Hz.

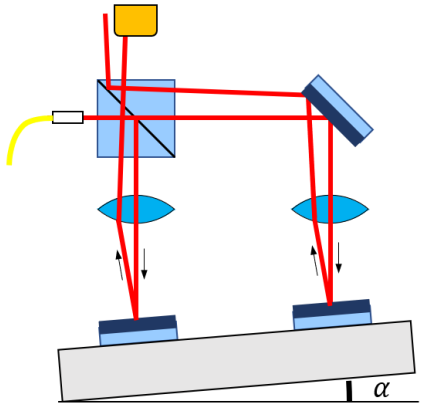
Extra slides

ITF robustness against tilts

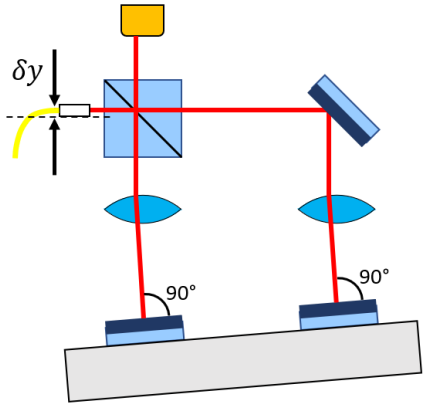
a)



b)



c)

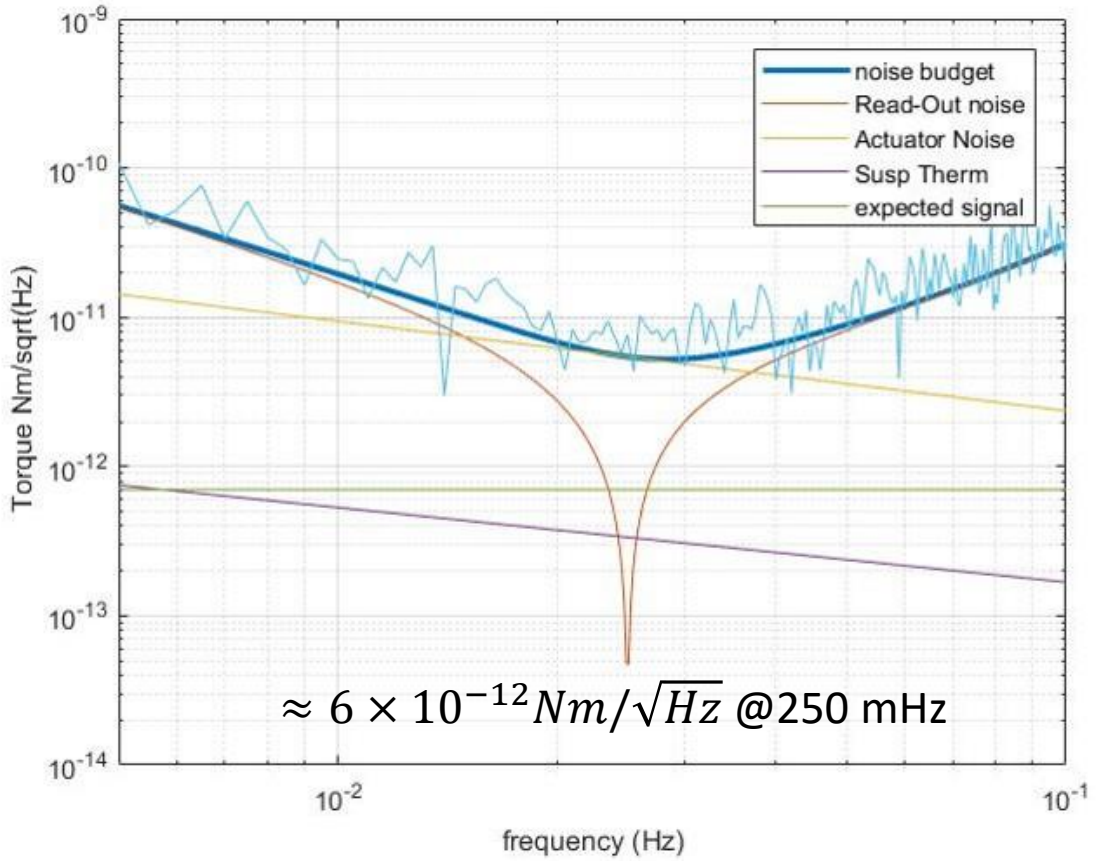


(a) The interferometer is aligned while the balance arm is horizontal

(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

Torque sensitivity at low frequency



ASD of ITF, pick-off and ratio