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Picoradiant tiltmeter and direct ground tilt measurements at the Sos Enattos site

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Abstract We report the tilt sensitivity reached by the ARCHIMEDES tiltmeter in the 2–20 Hz frequency region, where seismic noise is expected to give an important limitation to the sensitivity in the next future Gravitational Waves detection, particularly through Newtonian noise. The tilt noise level $\tilde{\theta}(f)$ is about $10^{-12}\mathrm{rad}/\sqrt{\mathrm{Hz}}$ in most of the band, reaching the minimum of $\tilde{\theta} = 7 \cdot 10^{-13}\mathrm{rad}/\sqrt{\mathrm{Hz}}$ around 9 Hz. The tiltmeter is a beam balance with a 0.5 m suspended arm and interferometric optical readout, working in closed loop. The results have been obtained by a direct measurement of the ground tilt at the Sos Enattos site (Sardinia, Italy). This sensitivity is a requirement to use the tiltmeter as part of an effective Newtonian noise reduction system for present Gravitational Waves detectors, and also confirms that Sos Enattos is among the quietest sites in the world, suitable to host the third-generation Gravitational Waves detector Einstein Telescope.

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1 Introduction

Since the first discovery of Gravitational Waves (GW) announced in 2016 [1], the Advanced LIGO and Advanced Virgo experiments have detected gravitational radiation emitted by Binary Black Holes and Binary Neutron Star mergers [2,3]. These detections represented a breakthrough in astrophysics, as they widely improve the knowledge on Black Holes and Binary Neutron Stars population, on gravity in the strong field regime, and opened the way to the multi-messenger astronomy [4,5].

At present, existing GW detectors have been upgraded and are now under commissioning until the beginning of the Observing Run 4 (O4), which is planned to start in middle 2022. Meanwhile, the scientific GW community is proposing the realization of third-generation ground-based detectors, namely Einstein Telescope (ET) [6] and Cosmic Explorer (CE) [7]. In their design, a strong effort is devoted to improve the sensitivity and to extend the observation band toward lower frequencies. This will allow for the search of intermediate mass black holes and low-frequency spinning neutron stars, as well as a better estimation of coalescing binary parameters thanks to a longer lifetime in the detection window.

The low-frequency limit, which is around 10 Hz in the present detectors, will be extended to even lower frequencies in the next generation. In particular, the Einstein Telescope is designed to reach about 2 Hz [6,8]. Seism is the dominant noise in the 2–20 Hz frequency band. It can affect the sensitivity either through its direct transmission to the Test Masses (TM) or through the so-called Newtonian noise (NN), the coupling due to gravitational field variation produced on the TM by the displacements of surrounding masses [9–11]. Historically, the isolation of test masses from direct seismic shaking has been accomplished with complex isolation systems capable of reducing the coupling up to ten orders of magnitude [12,13]. Further improvements will require either an even better seismic isolation or the installation of the new detectors in suitable quieter sites, such as Sos Enattos, which is indeed a candidate site to host the ET underground detector [14,15].

While direct shaking can be reduced with suitable passive isolators, gravitational coupling must be subtracted by measuring the seismic field, inferring the gravitational field variation and finally by subtracting this effect from the detector signal.

NN has until now not limited the detectors' sensitivity, but it is expected that it will be the dominant noise if no reduction will be implemented. This procedure requires the measurement of the seismic field, with a signal-to-noise ratio (SNR) of about 100 in case of Virgo and LIGO detectors[16] .

One of the possible strategies that could simplify the reconstruction of the gravity field is the measurement of the seismic field with a tiltmeter [17].

A tiltmeter consists of an absolute rotational sensor, capable of measuring the inclination of the ground surface with respect to a suspended reference arm. Such a device is specifically designed to minimize the coupling with ground translations, so to be mainly sensitive to ground tilts [18,19]. In recent scientific runs, both in Advanced LIGO and Advanced Virgo, preliminary tests with tiltmeters have been conducted [20,21]. The measured tilt was of the order of $10^{-10}\text{rad}/\sqrt{\text{Hz}}$ (or slightly higher, depending on frequency). In the next runs, the sensitivity of the GW detectors might be limited by the NN and tiltmeters with sufficient SNR would help measuring this motion. In this paper, we show the results of an upgraded version of our tiltmeter, tested at the quiet site of Sos Enattos (Sardinia, Italy), whose sensitivity verifies the required characteristics. The paper is organized as follows: A first section is devoted to describe the experimental setup, and a second section will present and discuss the sensitivity and the noise budget. Implications for NN reduction and future developments will be discussed in the last, conclusive, section.

2 Experimental setup

Within the Archimedes experiment, devoted to measure the interaction of vacuum fluctuations and gravity [22–24], an high sensitivity prototype balance has been developed [21]. If no samples are suspended at the end of the arm, it can be used as a tiltmeter. It consists of a 0.5 m long arm, whose mechanical design is similar to LIGO tiltmeters [19]. The arm is suspended by its center through two thin wire-like suspensions (Cu-Be, 100µm × 500µm), as shown in Fig. 1.

The tiltmeter center of mass is positioned within 10µm of the bending point, which allows for a reduction of the translation-to-tilt coupling. Depending on the center of mass positioning, its resonance frequency is around 20–30 mHz. The free oscillations of the suspended arm are read with a Michelson interferometer, whose optical design is an improved version of the one described in [21]. In the old version, the interferometer had unequal optical paths and it was more affected by common noise coupling, such as laser frequency and amplitude noise.

In the present improved version, these two noise sources have been reduced by using an optical delay line to equalize the optical paths, and normalizing the output signal to the input laser power. The delay line is located after the beam splitter reflection and is made of 4 right-angle prisms, exploiting total internal reflection, as shown, in blue, in Fig. 1. In this way, the length difference between the optical paths has been reduced from 100 mm to 2 mm at worst, yielding to a frequency noise reduction by a factor 50.

The tiltmeter working point (interferometer output on half-fringe) is kept by controlling the arm position through electrostatic actuators. They consist of 4 metallic 2 cm × 10 cm plates located along the arm ends, as shown in Fig. 2. The control signal is given by a digital filter fed with the interferometer output. This control suppresses tiltmeter motion at low frequency (the unity gain frequency is 0.3 Hz), while leaving the arm free to oscillate at higher frequencies. In this way, the control loop has no effect in the NN frequency region and, together with the low resonance frequency, makes the tiltmeter arm an inertial reference for ground tilts in the frequency band of interest for Gravitational Wave detectors, particularly in

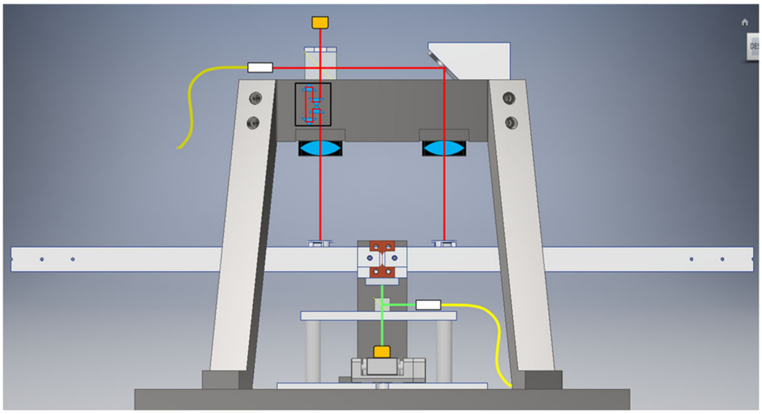

Fig. 1 Tiltmeter scheme. The red line identifies the path of the laser light in the interferometer. The light is injected with the fiber (in yellow at the top left) and split by the beam splitter. In the shorter interferometer arm, there is a delay line, consisting of prisms, which equalizes the pathlength. The two lenses, shown in blue, have focal lengths equal to their distance from the balance arm, so that the interferometer contrast is sensitive only to the second order to the tilts of the arm itself. Below the arm is the optical lever, which serves as an initial alignment reference

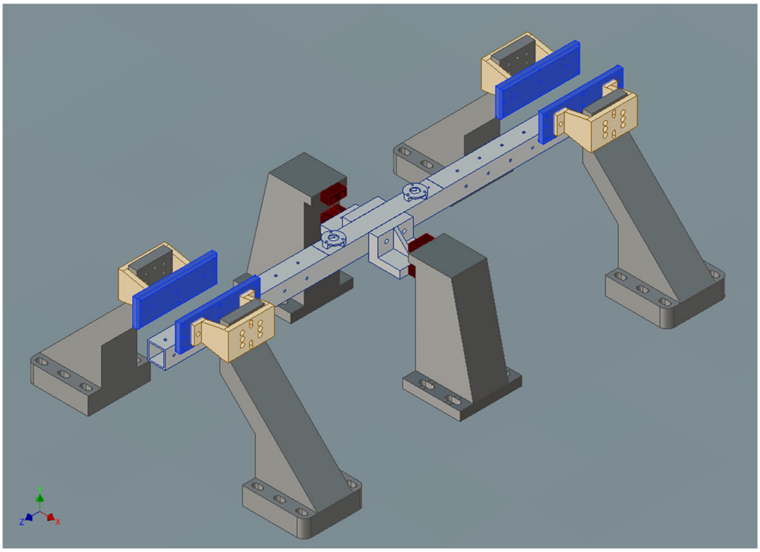

Fig. 2 Scheme of the electrostatic actuators, reported in blue in the picture

the band 2–20 Hz. Notice that the upper bound of the tiltmeter sensitivity is presently above 20 Hz, extending up to about 100 Hz where a low-pass filter is used as anti-aliasing.

3 Sensitivity and noise budget

The results obtained from these measurements are shown in Fig. 3. The figure shows the previous ground tilt measurement, performed at the Virgo site, and the current one, on the Sos Enattos site. The ground tilt measured at Sos Enattos remains around picoradiants/$\sqrt{\text{Hz}}$ in most of the frequency band, reaching the minimum value of $7 \cdot 10^{-13}\text{rad}/\sqrt{\text{Hz}}$ in the region of a few Hz and the maximum value of $6 \cdot 10^{-11}\text{rad}/\sqrt{\text{Hz}}$, at a resonance peak of the infrastructure, at 17.5 Hz. We also notice a peak at 7.5 Hz, with a tilt value of $10^{-11}\text{rad}/\sqrt{\text{Hz}}$, due to a resonance of the vacuum chamber, and a resonance at 4 Hz, still to be investigated. As can be seen from the figure, if we exclude the infrastructural resonance peaks, the value of the ground tilt measured at Sos Enattos is at least two orders of magnitude lower than at the Virgo site. It reaches almost three orders of magnitude in the region just above 10 Hz, where Virgo has a number of infrastructure resonances. If the value measured at Sos Enattos is taken conservatively as the sensitivity, we deduce that the tiltmeter is capable of measuring the Virgo site tilt with an SNR greater than 100, which is more than sufficient to be used for NN reduction. The sensitivity of the tiltmeter was also analyzed by evaluating the main fundamental noises. These included shot noise, laser radiation pressure noise, thermal noise and acquisition noise.

Main noise sources contributing:

- **Shot noise**

  The shot noise contribution to the tilt is evaluated as [25]:

$$\theta_{SN} = \frac{1}{2}\frac{\lambda}{\pi L}\sqrt{\left(\frac{h\nu}{\eta P}\right)}\frac{1}{C}; \tag{1}$$

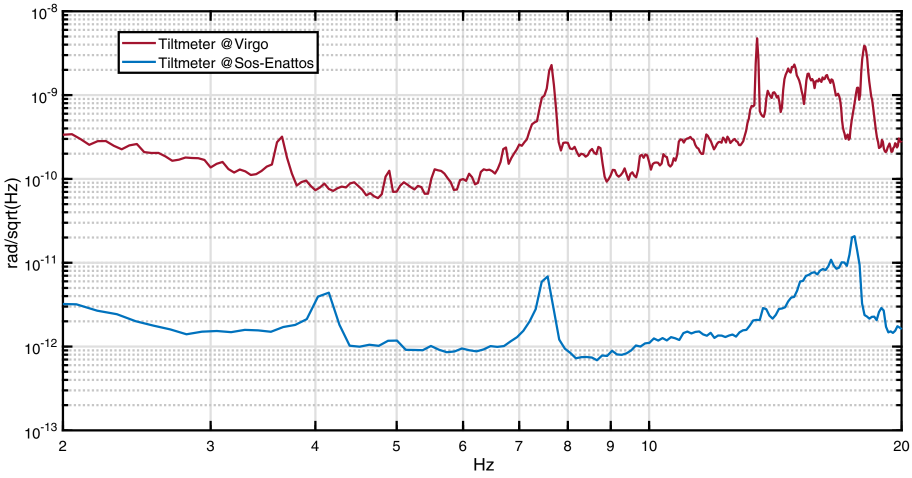

Fig. 3 Ground tilt in Virgo and Sos Enattos sites

where we have taken into account that the working point of the interferometer is the half fringe. In the above equation, h is the Planck constant, $\lambda = 532$nm is the laser wavelength, L=0.1 m is the interferometer arm length, $\nu = c/\lambda$, $\eta = 0.9$ is the photodiode quantum efficiency, $P = 3\,\mathrm{mW}$ is the input power, and $C = \frac{(V_{\max}-V_{\min})}{(V_{\max}+V_{\min})} \simeq 0.5$ is the contrast, computed by measuring the voltage at bright ($V_{\max}$) and dark ($V_{\min}$) fringe. The shot noise is independent of the frequency, and its level is $1.9 \times 10^{-14}\mathrm{rad}/\sqrt{\mathrm{Hz}}$.

- **Radiation pressure noise**
  Given the tiltmeter arm momentum of inertia as $I = 1.3 \times 10^{-2}\mathrm{kg}\cdot\mathrm{m}^2$, the radiation pressure noise can be written as:

$$\theta_{RP} = \frac{1}{2}\frac{L}{I\omega^2}\sqrt{\frac{Ph\nu}{c^2}} \tag{2}$$

  where $\omega = 2\pi f$. The radiation pressure noise contribution is absolutely negligible, as it corresponds to $10^{-22}\mathrm{rad}/\sqrt{\mathrm{Hz}}$ at 10 Hz.

- **Suspension thermal noise**
  To compute the suspension thermal noise contribution, we must define the *loss angle* as the inverse of the Q of the arm resonance: $\phi_{loss} = 1/Q = 0.01$. Given the resonance frequency $f_0 = 0.025\,Hz$, suspension thermal noise can be written as [26]:

$$\theta_{SThN} = \sqrt{\frac{1}{2}\frac{4k_B T(I\omega_0^2)\phi_{loss}}{\omega((I\omega_0^2 - I\omega^2)^2 + (I\omega_0^2)^2\phi_{loss}^2)}} \tag{3}$$

  where k_B is the Boltzmann constant and $T = 300\,\mathrm{K}$ is the temperature. The contribution remains well below $10^{-13}\mathrm{rad}/\sqrt{\mathrm{Hz}}$ over the entire frequency band.

- **Internal thermal noise**
  For this contribution, the resonance frequency of the arm has been considered as equal to $f_{0_i} = 950\,\mathrm{Hz}$, and the internal $Q_i = 1000$. The noise results to be [26]:

$$\theta_{I_{ThN}} = \sqrt{\frac{4k_B T(I\omega_{0_i}^2)\cdot\phi_{loss_i}}{\omega((I\omega_{0i}{}^2 - I\omega^2)^2 + (I\omega_{0i}{}^2)^2\phi_{loss_i}^2)}} \tag{4}$$

The contribution is almost flat and is about $10^{-15}\text{rad}/\sqrt{\text{Hz}}$ at 10 Hz.

- **ADC noise**
  The ADC noise has been measured by using a 50 Ω BNC termination at the ADC input. The noise level results to be 2.2×10^{-13}, almost flat over the 2–20 Hz frequency band. The value and the verified dependence from the square root of the sampling rate are consistent with the theoretical expectations. It is the main instrumental contribution to the noise budget.

The noise level shown in the figure is typically reached during the night or during the weekend. On working days, due to activities related to mine maintenance, the noise is significantly higher. From the noise budget and the above considerations, we can interpret the curve of Fig. 3 as an upper limit of the site seismic noise when not disturbed by anthropogenic noise. Further commissioning activities are planned to ensure that there are no other noises that are limiting the sensitivity. These include, in particular, laser frequency noise due to the residual asymmetry of the arms or scattered light.

4 Discussion and future developments

The tiltmeter has reached the required sensitivity to be used in Newtonian noise reduction in the next scientific runs of the Virgo gravitational wave detectors. In this case, in fact, to obtain an effective Newtonian noise reduction it is necessary that the ground tilt is measured with a good SNR. The ground tilt $\tilde{\theta}$ at the Virgo site (similarly at the LIGO site [17]) is of the order of $\tilde{\theta} \approx 10^{-10}\text{rad}/\sqrt{\text{Hz}}$; the sensitivity achieved ensures an SNR of around 100, which is more than sufficient to meet the specifications. For future-generation detectors, in particular the Einstein Telescope, the study of Newtonian noise subtraction is still at a preliminary stage and moreover the detectors' sites have not yet been chosen. At this preliminary stage, it is particularly important to measure the characteristics of the candidate sites in order to make an appropriate choice, keeping in mind that the band of interest of future detectors will extend down to frequencies of around 2 Hz. The sensitivity achieved, which to our knowledge is, in this region of frequencies, at the best in the world for ground tilt measuring devices [17,27,28], makes it available for the characterization of the various candidate sites for third-generation gravitational wave observatories. For Sos Enattos, the measurements show that at low frequency, the site is about 100 times quieter than the sites where Virgo and LIGO are installed. This result is expected, because it is compatible with similar results obtained with seismometers [14,29] and confirms that Sos Enattos is one of the quietest sites in the world where to install the future ET observatory.

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