IL NUOVO CIMENTO **45 C** (2022) 150
DOI 10.1393/ncc/i2022-22150-4

COMMUNICATIONS: SIF Congress 2021

Test of the Archimedes prototype balance at SAR-GRAV laboratory

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received 20 January 2022

Summary. — In the framework of the Archimedes experiment, which aims to measure the interaction between vacuum fluctuations and gravity, a high sensitivity prototype balance has been developed, which can be used as a tiltmeter when no weights are suspended to its ends. The tiltmeter has been first installed at the Virgo site, and then moved to the Sos Enattos site, at the SAR-GRAV laboratory in Sardinia. This site, characterized by low seismic noise, allows sub-picoradian sensitivity to be achieved in the frequency region between 2 and 20 Hz, which is the best in the world at the moment.

1. – Introduction

The goal of the Archimedes experiment is to measure the interaction between General Relativity (GR) and Quantum Field Theory (QFT). To accomplish this task we will use an interferometric balance from which two YBCO or BSCCO superconductive crystals are suspended. These crystals are multi-layered Casimir cavities and a change in their reflectivity will affect the internal vacuum state energy. If GR interacts with QFT, the energy variation will correspond to a weight variation that can be measured.

Presently, the balance is under construction at the SAR-GRAV laboratory located in Sardinia. Specifically, the lab is near the former mine of Sos Enattos (Nuoro, Italy).

It was chosen to place the balance at the SAR-GRAV laboratory essentially for four reasons: first, Sardinia is a low seismic noise region; second, since the North-East part of this region is one of the less populated in Europe, there is low Anthropogenic Noise; moreover, the site already hosts several sensors monitoring environmental noise, both on the surface and underground. Finally, the site is easily accessible to different types of machinery used for the transport and construction of the experiment.

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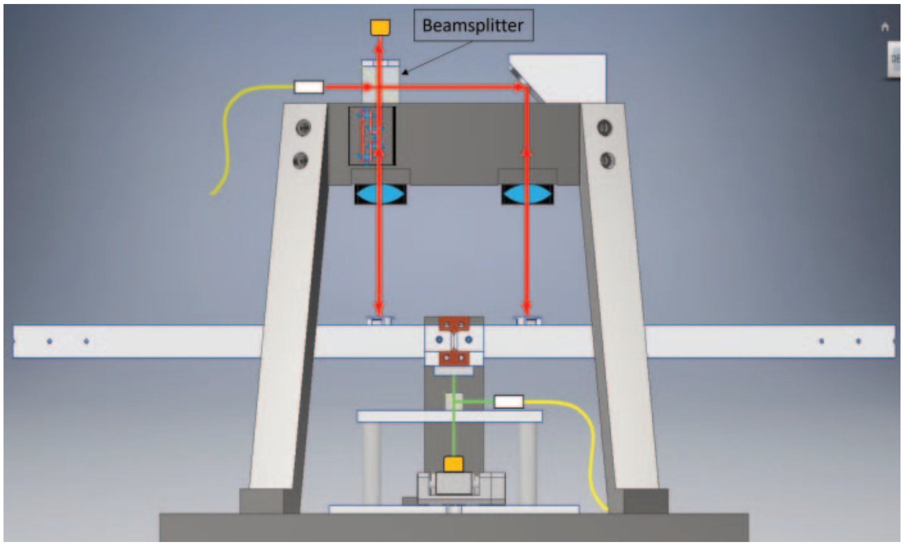

Fig. 1. – Scheme of the Archimedes prototype where it is possible to see the path of the laser beam shown in a red line. The laser beam is split by the beamsplitter into two paths that hit a mirror mounted on the arm. Through a photodiode placed above the beamsplitter, it is possible to read the interference.

All these reasons make it possible to achieve the high sensitivity required by the experiment. Note that the balance should measure a torque $\tau_s \approx 3.5 \times 10^{-13}\,\mathrm{Nm}/\sqrt{\mathrm{Hz}}$ to detect the interaction between GR and QFT [1]. The main problem arises from the seismic noise. It couples with the arm generating a moment of force

$$\tau_{seis} = M \cdot d \cdot a_n, \tag{1}$$

where M is the total arm mass, d is the distance between the center of mass of the arm and the pivot point, and a_n is the transverse acceleration. Recalling the required torque sensitivity of the experiment

$$a_n \leq \frac{\tau_s}{M \cdot d} \approx 10^{-9}\,\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}, \tag{2}$$

where a safety factor of about one order of magnitude has been considered.

In this framework, a prototype has been built. In particular, Archimedes' prototype consists of a smaller interferometric balance which, initially, has been used as a tiltmeter. Originally, it was installed at the Virgo site (Cascina, Italy) then moved to the SAR-GRAV laboratory where it was used to characterize the environmental noise.

2. – Archimedes' prototype

Archimedes' prototype uses a Michelson interferometer technique. As shown in fig. 1, a laser beam passing through a beamsplitter, suspended over the arm, is split into two different paths. Each of them passes through a lens before reaching the mirrors placed on the arm itself. In the first laser path, four prisms are inserted to equalize the optical path length. This provides high suppression of the frequency noise.

The tiltmeter consists of a 50 cm long arm made of aluminum. This specification leads to a low momentum of inertia of about 0.013 kg m^2 that is necessary to have a high torque-to-tilt transfer function [2]. The arm is suspended through two thin flexible joints made from a copper-beryllium alloy with dimensions of 0.5 mm $\times$ 0.1 mm and 6 mm height.

The arm is held by two pillars through the flexible joints. At the ends of the arm, two pairs of actuators are placed. These are used to keep the arm in equilibrium by sending a correction signal to contrast the motion using a feedback control system as used for torsion pendulums [3, 4].

3. – Results

As said before, the prototype was initially placed at the North End building of the Virgo site from April to July 2019. Then, in 2020, it was finally moved to the SAR-GRAV laboratory. In both cases, no samples were suspended and so the arm was used as a tiltmeter.

Figure 2 shows the comparison between the previous ground tilt measurement θ_g, on the Virgo site, and the current one, on the Sos Enattos site. As can be seen, between 2 Hz and 20 Hz the ground tilt measured at the SAR-GRAV laboratory remains around $10^{-12}\,\mathrm{rad}/\sqrt{\mathrm{Hz}}$, reaching the minimum value $\theta_g^{min} \approx 7 \times 10^{-13}\,\mathrm{rad}/\sqrt{\mathrm{Hz}}$ in the region around 8–9 Hz. At 17.5 Hz a resonance peak due to the infrastructure results in a maximum value of $\theta_g^{max} \approx 2 \times 10^{-11}\,\mathrm{rad}/\sqrt{\mathrm{Hz}}$. We also noticed two more peaks, one at 4 Hz, and the other at 7.5 Hz. While the former is under investigation, the latter, resulting in $\theta_g \approx 7 \times 10^{-12}\,\mathrm{rad}/\sqrt{\mathrm{Hz}}$, is due to a resonance of the vacuum chamber.

As can be seen from fig. 2, in most of the frequency bands, the sensitivity achieved

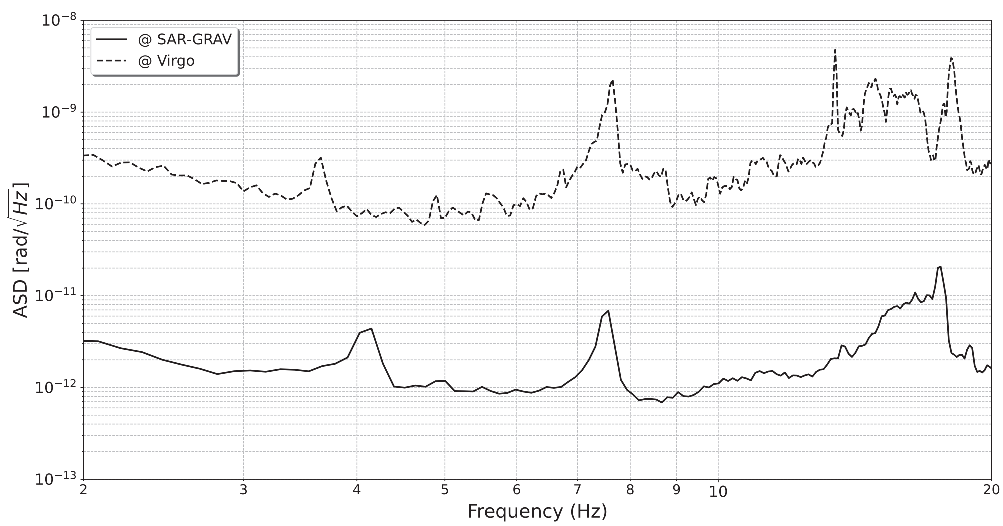

Fig. 2. – Ground tilt measurement in Virgo and Sos Enattos sites [5]. The dashed line represents the results obtained while the prototype was installed at the Virgo site, while the solid line represents the ground tilt measured at the SAR-GRAV laboratory.

by Archimedes' prototype at Sos Enattos is at least two orders of magnitude better than at the Virgo site. In particular, in the region above 10 Hz, the ground tilt measured at Sos Enattos is almost three orders of magnitude lower than the Virgo site.

4. – Conclusions

The sensitivity achieved in the frequency band between 2 Hz and 20 Hz by Archimedes' prototype is, to our knowledge, the best in the world [6-8] for ground tilt measuring devices. The quietness of the Sos Enattos site in comparison with the one of Virgo, is compatible with similar results obtained with seismometers [9, 10].

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The author acknowledges all the Archimedes Collaboration, particularly Prof. E. Calloni, Prof. D. D'Urso, and PhD D. Rozza who gave me the possibility to take part in this project.

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