PROCEEDINGS OF SCIENCE

Archimedes experiment: weighing the vacuum

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Archimedes is an experiment devoted to measure the weight of zero point energy by weighing a cascade of rigid Casimir cavities constituted by a layered type II superconductor, when the reflectivity of the cavities is modulated and thus the energy inside. In this paper the working principle of the experiment is presented and the results of the existing prototype are presented, showing the torque sensitivity of about 10^{-11} $Nm/\sqrt{Hz}$ in the region of frequency from about 50 mHz up two 150 mHz. Moreover the major upgrades needed to reach the desired final sensitivity are discussed.

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1. Introduction

Does the vacuum fluctuations gravitate or not? This is one of the oldest, unsolved question raised since the dawn of quantum mechanics [1]. Despite of the many theoretical investigations to explore the motivations and consequences of assuming of discarding such hypothesis [2, 3], never a direct experimental measurement has been carried out to investigate the weight of the vacuum. Few years ago we proposed an experiment to test the interaction of vacuum fluctuations with gravity by weighing a suitable rigid Casimir cavity, being nowadays the Casimir effects recognized by the scientific community as a macroscopic manifestation of vacuum fluctuations [4, 5].
The name of the experiment, Archimedes, derives from the partial analogy that we found with the Archimedes force in the fluid when we studied the interaction of such type of cavity with the gravitational field on the earth under the hypothesis that the vacuum fluctuations interact with this field and follows the strong equivalence principle: in fact it is found that the gravitational field exerts a force on the cavity equal to the weight of the vacuum modes expelled by the cavity. The analogy is partial because the cavity follows the equivalence principle and falls with the gravitational acceleration [6].

The proposed experimental scheme to measure the Archimedes force of the vacuum was provided considering the present small force detectors and the available superconductors materials of type II, like YBCO or BSCOO. This kind of materials can be considered as natural cascade of Casimir cavities, being structured as multilayer of superconducting planes separated by dielectric planes [7, 8]. By measuring the weight of the condensation energy of the layered-superconductor, we will able to measure the weigh of the vacuum fluctuations. The order of magnitude of this force is expected of about $10^{-16}\,N$. It can be measured by lock-in technique at modulation frequency of several mHz by inducing a periodic transitions from normal to superconducting state in the material by temperature modulation [6]. Being a very tiny force, an extremely sensitive balance, working at the temperature of about 100 K, is required. The Casimir cavities, i.e. two almost equivalent blocks of superconductor material which undergo modulate transition in thermal equilibrium with surrounding temperature modulated vessel, will be suspended to the balance like in fig 1.

To point up eventual hindrances, a prototype of such a balance, working at room temperature, has been realized. We describe it, illustrate the main results reached with it and discuss them with respect to the final measurement.

2. Experiment working principle

Assuming that the pressure of the vacuum fluctuation follows the equivalence principle, the force exerted by the gravitational field on a rigid Casimir cavity at rest on earth is directed upward and has been calculated to be [6, 9, 10]:

$$F = \frac{E_c}{c^2}\vec{g} \tag{2.1}$$

where E_c is the vacuum energy stored in the cavity, c is the speed of light and $\vec{g}$ is the earth gravitation acceleration.

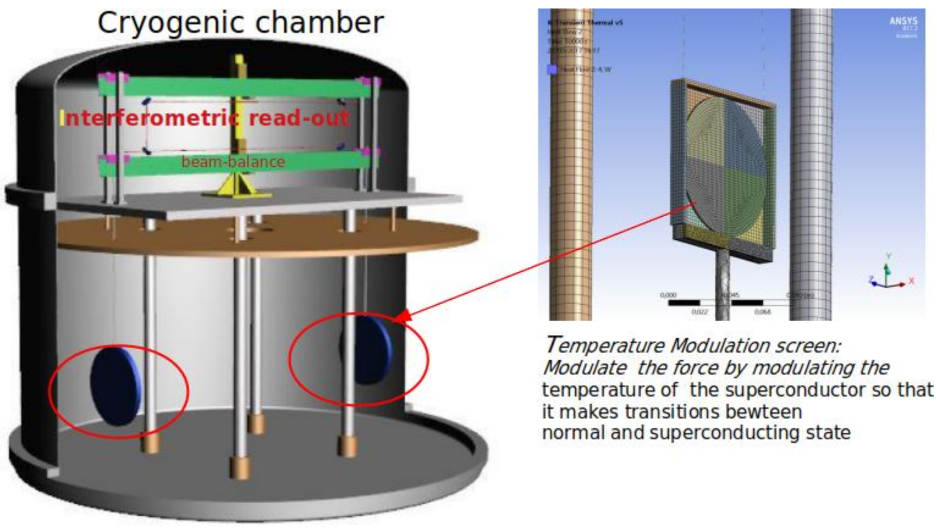

Figure 1: Scheme of the final balance. Each disc is suspended to one end-arm and surrounded by a metallic enclosure for thermal actuation (shown in the inset). The optical read-out is a Mack-Zender interferometer and the signal is taken with respect to a reference arm.

Being this force extremely tiny, the measurement must be performed by modulating the effect, i.e., by modulating the Casimir energy in the rigid cavity.
This can be performed modulating the reflectivity of the cavity, since when the reflectivity of the two planes is higher, all the vacuum modes that are not resonant in the cavity are better expelled from the cavity, resulting in a lowered weight [12, 13, 14, 15]. When the cavity plates are constituted by layers of superconductive material, the reflectivity modulation can be performed inducing

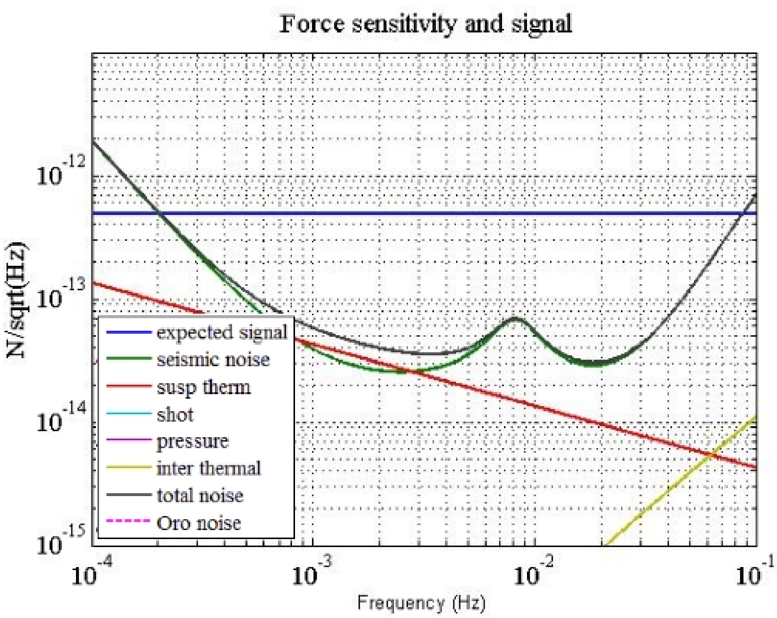

Figure 2: Noise budget compared with expected signal (blue line) and final sensitivity (black curve).

a transition of the material from the superconductor to not superconductor state, being the material reflectivity higher in the superconductive state. The transition from superconductor to not superconductor can be actuated by means of temperature modulation around the transition temperature.

In our experiment type II like YBCO or BiSCCO superconductors will be used. This kind of superconductors are layer structured: layers that perform the transition to superconductivity alternate to layers that remain dielectric. They provide a natural cascade of rigid Casimir cavities, whose condensation energy is expected to be influenced by vacuum fluctuation [6, 7, 8]. The percentage of condensation energy that is due to Casimir energy is still under evaluation and in the optimistic case is almost the totality [7].

Accuracy of the order of percent of weight measurement is expected, so it will be possible to uncertain the interaction of gravitational field with vacuum fluctuations even if the contribution will prove to be of this order of magnitude.

In figure 1 the proposed scheme of the measurement is reported: two discs of layered superconductor are suspended to the arm of the balance. The balance arm is aluminum made to maintain lower the weight and the momentum of inertia, that, with an arm length of 1.40 m and a mass of 1.7 kg, will be 0.72 $kg\ m^2$.

Both the discs suspended to the balance are made of the same material but with different doping. This allow the superconductive transition only for one of them when the same temperature modulation is applied, leading to the common phonon energy variation cancelation. The discs have a 300 mm diameter and 1 mm thick. The modulated heating is performed by heat two metallic enclosures around the superconductive discs (radiating heating). To achieve the temperature equilibrium, the modulation frequency has been estimated to be several mHz.

The read-out of the balance is optically performed by means of a Mach-Zender interferometer illuminated with 5 mW laser power. A vacuum chamber at the transition temperature of the samples (about 100 K) contains the whole system.

In Figure 2 the expected signal and sensitivity are reported for 1 months integration time. It is calculated for a seismic noise equal to the measured in the Sardinia site of SOS-Enattos [16] where the final experiment will be hosted (see discussion in last section) and thermal noise is calculated in the hypothesis of resonance frequency of 5 mHz and loss angle $\phi = 10^{-5}$. These two noises are expexted to be the main limitation to the final sensitivity, while other fundamental sources of noise, like radiation pressure noise, shot noise, internal thermal noise, are negligible.

3. Prototype description

In Figure 3 is shown a picture of the prototype. The Aluminum arm has a length of 0.56 m (shorter than the arm of the final balance) and a moment of inertia is 0.042 $kg*m^2$. It is coupled to the ground by means of soft joints designed to have a restoring force with a resonance frequency of few mHz when the center of mass of the arm is lying on the rotation axis. The technical design of the joints is reported in the inset of the figure. The peculiar semi-ribbon shape, with two separated

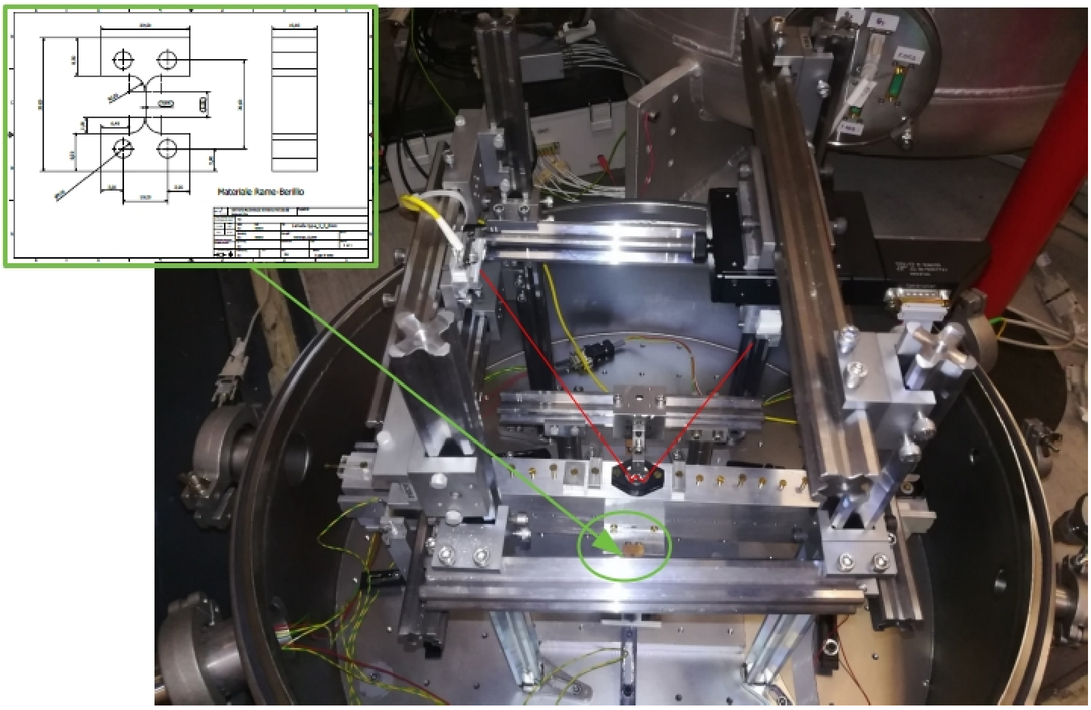

Figure 3: Picture of the Archimeds balance prototype. Inset: techinical design of the semi-ribbon joints of the balance.

bending points that remain in a couple of attenuation distance, warrant the desired recovering stiffness [18]. The ribbon length is 6 *mm*, the width is 10 *mm* and thickness is 50 μm. This design is optimized for the final balance, which will have the length of 1.4 *m* and the total moment of inertia (included the suspended superconducting samples) of 0.72 $kg * m^2$, but have been tested on the balance prototype to prove robustness and performances. The joint are made of berillium-copper. The resonance frequency can be suitable tuned by acting on some screws on the balance arm (see next subsection). During the tests it has been tuned to 3 *mHz*.

3.1 Center of mass positioning

As detailed described in [18], a crucial condition to not reintroduce seismic noise is to minimize the coupling among ground acceleration along arm direction and arm tilt. As it is known [17] a ground acceleration $\ddot{z}$ generates a torque τ on the arm equal to:

$$\tau = m\delta\ddot{z}. \tag{3.1}$$

being m the balance arm mass and δ the distance from center of mass to rotation axis. In our prototype is $m = 1.75\ kg$ and this noise is minimized when δ is of the order of few microns. In our estimations of the final Archimedes noise reported in Figure 2, we choose a conservative distance $\delta = 10\mu m$. This distance can be tuned by regulating a set of screws placed on the upper surface of the arm, having a vertical range of 20 *mm* and 10 *mm* with a sensitivity of about 1 μm for the finest screw rotation. The tuning is performed in air, then the system is evacuated and the

distance measured by measuring the resonance frequency. The performed simulations show that the stiffness of the joint contributes to the frequency for about $f_k = 3.2\,mHz$. The gravitational stiffness contribution is given by: $f_g = \sqrt{mg\delta I}$, where g is the gravitational acceleration and $I = 0.042\,kg * m^2$ is the moment of inertia of the arm. The resonance frequency is thus $f_R = \sqrt{f_k^2 + f_g^2} = 10.4\,mHz$ for $\delta = 10\,\mu m$.
Setting of working point within few microns are possible with high robustness and repeatability. In tests of several days it has been observed that working within the tens of microns of distances the system is more stable.

3.2 Balance sensing and control

The sensing of the balance prototype oscillation, i.e. the sensing of the torque exerted on the balance arm, is performed by a very sensitive optical lever: the light of a SLED (Superluminescent Light-Emitting Diode) is sent to a mirror lying at the center of the upper surface of arm and then reflected toward a quadrant photodiode with a gap of 100 μm. The distance between the mirror and the photodiode is $d = 0.32\,m$. The angle of incidence of the beam on the mirror is 0.05 rad. To have a suitably high sensitivity, the SLED beam is collimates to a 400 μm spot diameter.
A feed-back controls the balance position: the signal of quadrant photodiode is acquired at sampling rate of 1 kHz and low pass filtered; then electrostatic actuation is performed by means of aluminum plates placed on the sides of the arm. To properly rotate the phase, a couples of (real) zeroes are set before the resonance, while real poles after the resonance to recover the slope and further complex zeroes and poles to compensate for high frequency resonances are set. The open-loop unity gain is at 0.2 Hz.

The whole system, balance, read-out and actuators is under vacuum, with residual pressure of about $2 * 10^{-5}\,mbar$.

4. Results, next steps and conclusion

The test performed on the balance prototype have showed that there are not hindrances to realize the final apparatus for the measurement of the Archimedes force of vacuum. Several tests on the balance joints and on the robustness against thermal drifts and long term stability of the control system have been performed. They do not provide evidence of show-stopper problems. All mechanical parts, particularly the joints, do not show significant aging effects on the time-scale of the year, even when exposed in air. Feed-back stability of the orders of weeks of data taking is observed. The transfer function and working point are not significantly affected by lab-environment variations of temperature or humidity.

The torque sensitivity reached is shown in Figure 4. In intermediate frequency region from 0.1 to about 21 Hz, the sensitivity represents – at our knowledge – the best torque sensitivity in the world. Nevertheless in the region of particular interest for the final experiment, the lower frequency range from tens of mHz and lower, the sensitivity is limited by the high seismic noise of our laboratory. Figure 5 shows the latest measured with a Trillium accelerometer for a quiet night.

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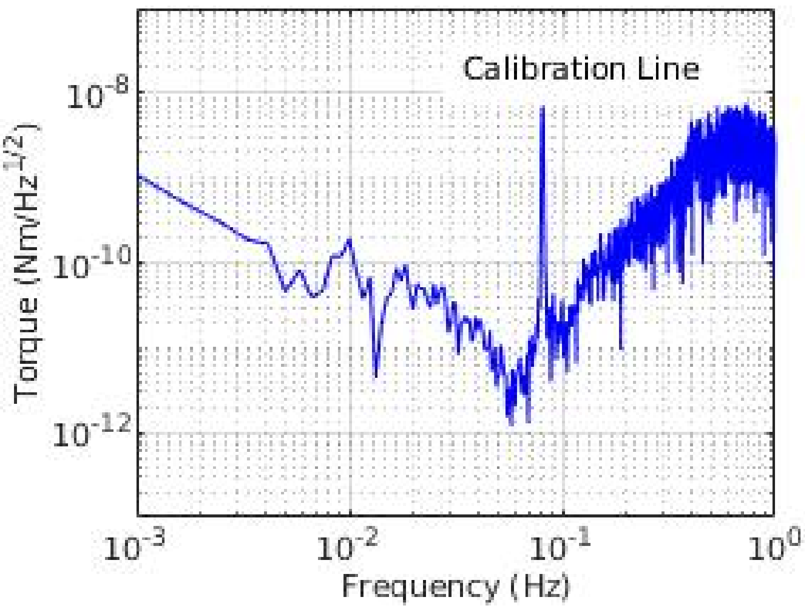

Figure 4: Prototype sensitivity.

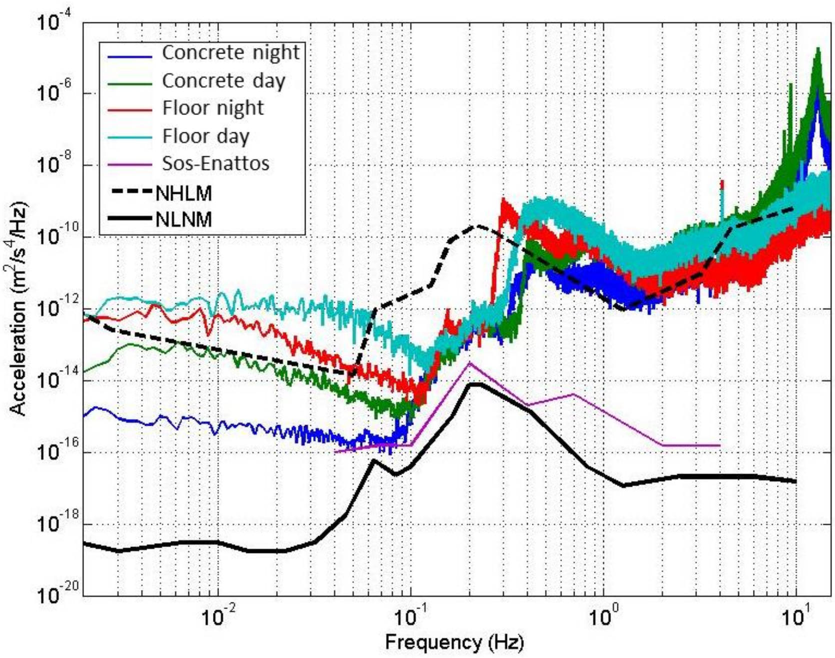

Figure 5: Seismic noise in our lab during day (cyan) and night (red), in a concrete plinth near our lab (green, blue), and in the Sos-Enattos mine (violet), compared with High and Low Peterson model

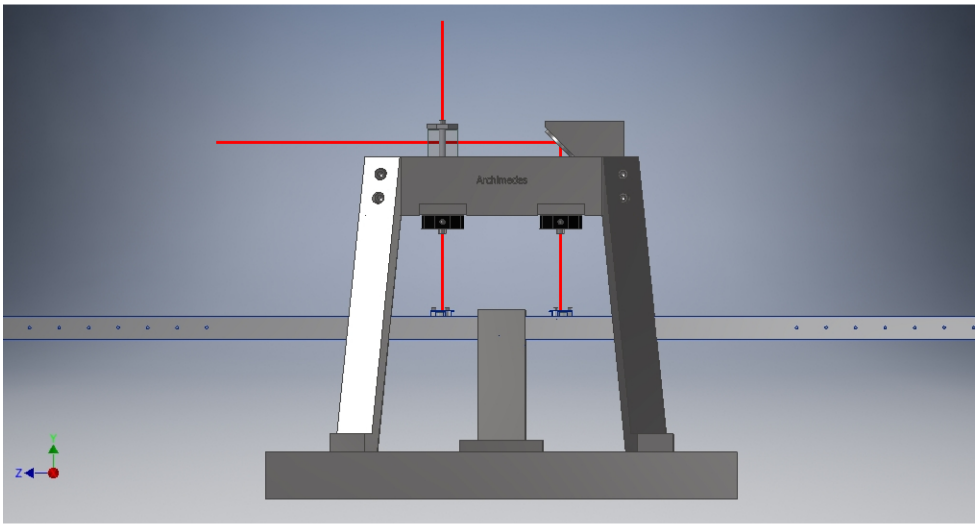

Figure 6: Cad view of the final balance with interferometric read-out.

In the same figure is reported also the seismic noise as measured in SOS-Enattos mine (Sardinia, Italy). The noise in the Naples laboratory is more than four order of magnitude (in power spectral density) with respect to quiet site in almost all frequencies from few mHz to few Hz. This conditions is important because it is yet not proved that there no noise down-converted in our system. SOS-Enattos mine is one of the lowest seismic noise site in Europe and has a low anthropic noise. An underground laboratory, named $SAR-GRAV$, is at present under construction there. We will move the prototype in this quieter place as soon as the laboratory will be ready to perform all the final test on the prototype sensitivity to help designing the last details of final experiment.

In meantime the next step is to switch from the optical level read-out to the interferometer one in order to increase the read-out sensitivity (we expect a gain of about two orders of magnitude). To do this a robust and rigid monolithic holder for the the interferometer has been designed and build (see Figure 6 and Figure 7). It will mounted on the same balance platform inside the vacuum chamber and will host two of the mirrors of the interferomiter. Tests will be soon performed.

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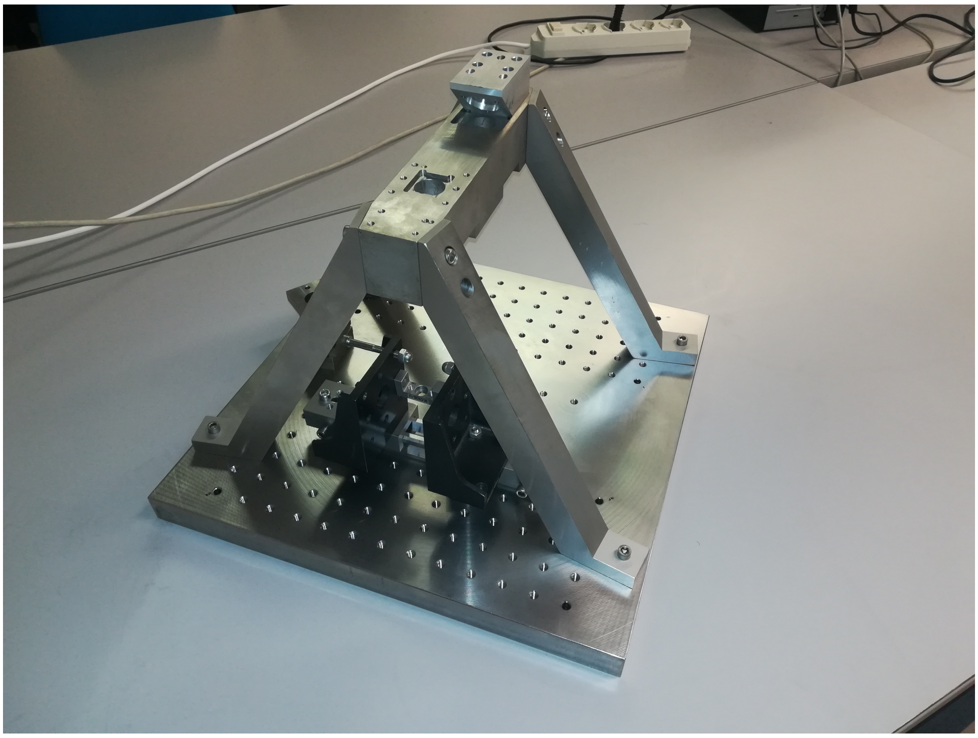

Figure 7: Aluminum monolithic holder for the iterferometric read-out.

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