

LIG-A-Cube: A high-resolution space accelerometer based on interferometric readout

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ABSTRACT

Inertial sensing is a common backbone across a broad set of space science missions, from satellite gravimetry and tests of fundamental physics to planetary exploration and GNSS constellations. The instruments currently deployed rely almost exclusively on the capacitive sensing of a proof-mass displacement, whose ultimate sensitivity is bounded by the electrode gap, by the residual-gas pressure and surface-charge noise that unavoidably scale with it. We report on the design and on the characterisation of LIG-A-CUBE, an ESA-funded activity conducted at INRiM to develop a compact triple-axis accelerometer based on a mechanically suspended 530 g copper-beryllium proof mass interrogated by fibre-coupled dual heterodyne Michelson interferometers at 1064 nm. A crossed-blade flexure and a titanium helical spring have been analysed by finite-element modelling and cross-checked against dedicated ground measurements. Both suspensions place the first mechanical modes between 0.35 Hz and 1 Hz. The interferometric reading system, based on two nominally identical twin channels sharing a common optical head, reaches a displacement noise floor of ≈ 10 pm/ $\sqrt{\text{Hz}}$ above 3 Hz and ≈ 3 nm/ $\sqrt{\text{Hz}}$ at 1 mHz. Combined with the mechanical suspension this leads to an acceleration resolution approaching 10^{-8} m s⁻² Hz^{-1/2} across the 1 mHz–100 mHz band. The instrument is positioned as a technology complementary to classical high end accelerometers based on electrostatic suspension and capacitive reading.

Keywords: accelerometer, heterodyne interferometry, space geodesy, mechanical suspension, low-frequency noise

1. INTRODUCTION

Satellite gravimetry has for two decades relied on on-board accelerometers to isolate the gravitational signal from the non-conservative forces acting on the platform: the twin-satellite architectures of GRACE [1] and GRACE-FO [2, 3], and the gradiometric payload of GOCE [4], have progressively refined our knowledge of the time-variable terrestrial gravity field down to sub-nano-g resolution. Comparable requirements underpin planetary gravity science (from the Italian Spring Accelerometer flying on BepiColombo, which supports the Mercury Orbiter Radio Science Experiment [5, 6], to the descent-phase measurements returned by the Rosetta Philae lander [7]) and fundamental-physics investigations, ranging from the recent equivalence-principle test performed by MICROSCOPE [8] and Gravity Probe B [9] to the sub-femto-g free-fall demonstration of LISA Pathfinder [10] in preparation for LISA. In parallel, the concepts of space-borne gravitational-wave observation are being extended by the Chinese TianQin and Taiji programmes [11], which similarly rely on drag-free proof masses whose relative motion must be measured with high precision.

The on-board accelerometer converts a mechanical quantity (i.e., the relative displacement of a proof mass with respect to the surrounding cage) into an electrical signal proportional to the input acceleration, once the transfer function of the mechanical suspension is known. In the flight-qualified instruments listed above, the transduction is capacitive: one plate of a differential capacitor is the surface of the metallic proof mass, while the second is bonded to the enclosing structure [12]. The modern implementation of this architecture, developed at ONERA in the late 1990s [13] and matured through more than two decades of on-orbit operation [14], is remarkably robust; it nevertheless presents well-documented trade-offs. Its sensitivity scales as $1/D$ with the electrode gap D and is inherently non-linear in D , so operation is restricted to a very small excursion about equilibrium. Narrow gaps concurrently amplify residual-gas damping and the noise contribution associated with surface patch-charge effects on nominally equipotential metallic surfaces [10, 12], while widening the gap directly degrades the read-out gain. Analogous limitations show up in the accelerometer error budgets of interplanetary probes, where the non-gravitational acceleration of the spacecraft has been identified as a dominant error source for the retrieval of the target science observables [15]. Alternative concepts have accordingly been actively pursued for the next generation of gravity missions, most notably hybrid electrostatic–cold-atom accelerometers [16] and cold-atom gradiometers based on light-pulse atom interferometry [17]; the technological readiness of both approaches is, however, still short of a flight-qualified single-instrument solution.

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Optical interferometry provides an attractive route around these compromises. Its displacement sensitivity is essentially independent of the working distance, the sensitivity is inherently linear over the full mechanical excursion of the proof mass, and sub-picometre resolution has been repeatedly demonstrated in space: at the inter-satellite scale by the GRACE-FO Laser Ranging Interferometer [3, 18] and at the intra-satellite scale by the LISA Pathfinder optical bench [10] and by the pre-formulation studies for LISA [19]. The parallel maturation of polarisation-maintaining (PM) fibre components inherited from the telecommunication industry has enabled fibre-fed heterodyne heads to be assembled with a form factor compatible with small-satellite platforms, exploiting flight-qualified building blocks derived from LISA-class gravitational reference sensors [22]. This convergence has driven a growing body of work on distributed constellations of miniaturised gravimetric satellites able to sample the time-variable gravity field at sub-daily time scales that remain inaccessible to the GRACE/GRACE-FO baseline [23, 24].

Along a complementary line, monolithic optomechanical inertial sensors, in which a fused-silica resonator is co-fabricated with the mirrors of a heterodyne interferometer, have projected thermal-noise floors of $\approx 5 \times 10^{-11} \text{ m s}^{-2} \text{ Hz}^{-1/2}$ at 1 Hz on gram-scale proof masses [25], and arrays of six or more such linear units enable gyro-free inertial navigation systems whose precision, once the thermal-noise limit is approached, becomes competitive with fibre-optic gyroscopes [26]. Within this landscape, the present paper reports on the design and on the first optical characterisation of LIG-A-CUBE, a triple-axis accelerometer developed at INRIM under an ESA contract. The instrument couples a compact copper-beryllium cubic proof mass to a soft mechanical spring and interrogates its motion with fibre-coupled dual heterodyne Michelson interferometers at 1064 nm. Section 2 introduces the design drivers, details the two candidate mechanical suspensions and describes the optoelectronic front-end and the optical head. Section 3 reports the first noise measurements, and Section 4 discusses the positioning of the instrument in the landscape of inertial sensors and outlines the next development steps.

2. INSTRUMENT ARCHITECTURE

2.1 Design drivers and suspension choice

In the ideal on-orbit configuration the proof mass would evolve along a purely gravitational trajectory inside the spacecraft, while the enclosing satellite is dragged with respect to it by every non-gravitational perturbation acting on the outer skin of the platform. This unconstrained configuration is not viable in practice: even a small residual velocity compounded by the drag and radiation-pressure forces acting on the satellite would rapidly bring the proof mass into contact with its housing. A weak link between the mass and the cage is therefore employed. Its stiffness k , combined with the inertial mass m , defines the natural angular frequency $\omega_0 = \sqrt{k/m}$ that fixes the pole of the acceleration-to-displacement transfer function of the sensor. Below ω_0 the mass displacement x is $x \approx a/\omega_0^2$, so that the equivalent input acceleration noise density becomes $S_a^{1/2}(f) = S_x^{1/2}(f) \cdot \omega_0^2$, where $S_x^{1/2}(f)$ is the displacement acceleration noise density. Sub-Hz sensitivity therefore requires simultaneously the softest suspension compatible with mechanical stability and a readout whose intrinsic noise, once divided by ω_0^2 , does not saturate the target acceleration budget.

The suspension solutions currently flown span nearly three orders of magnitude in stiffness. At one extreme, LISA Pathfinder demonstrated cubic proof masses of $\approx 2 \text{ kg}$ held in an almost purely inertial state by a residual electrostatic potential [10, 27], with drag-free control transferring the non-gravitational acceleration to the spacecraft. Electrostatically levitated masses have been the baseline of every satellite gravimetry mission of the past two decades [1, 3, 4] and of the MICROSCOPE equivalence-principle test [8]; they require an active control loop biasing the mass position and small ($\leq 600 \text{ }\mu\text{m}$) capacitor gaps [12]. At the stiffer end, mechanical hinge and spring suspensions have been baselined for planetary probes where the ambient gravitational environment is either large or poorly known a priori (BepiColombo/ISA [5, 6, 15], JUICE).

In LIG-A-CUBE we have adopted a purely mechanical suspension. The choice removes the need for an active control loop, decouples the equilibrium condition from any electrical bias (and thus from the drift of the associated electronics) and yields an inherently stable equilibrium configuration. Since the optical readout exerts no restoring force on the proof mass, the mechanical spring is the sole element defining the operating point, and it can be optimized entirely for the lowest achievable stiffness compatible with launch survival. The resulting design drivers are threefold: (i) an envelope compatible with the compact form-factor of the instrument; (ii) mechanical robustness sufficient to withstand launch loads and mass-release transients; (iii) a spring constant low enough to place the fundamental mode below 1 Hz while ensuring that the mass returns to its nominal position once weightlessness is recovered on orbit.

2.2 Proof mass

The proof mass has been implemented as a solid Cu-Be alloy cube of 40 mm edge, corresponding to an inertial mass of 530 g (Figure 1). Cu-Be has been selected based on its combination of non-magnetic behavior and mass density. The cubic geometry offers a symmetric platform on which up to three sensitive axes can in principle be implemented by replicating the optical head on mutually orthogonal cube faces, providing a natural upgrade path from a single-axis prototype to a multi-DoF sensor. The in-plane footprint allocated to the suspension is $40 \times 40 \text{ mm}$, matching the cube edge.

2.3 Mechanical suspension

Two suspension topologies have been assessed by static and modal FEM analysis and cross-checked against dedicated ground measurements: a crossed-blade flexure derived from the disc-coupling classically used to connect rotating shafts, and a 3D printed helical spring. Both have been sized to place the fundamental mode below 1 Hz along three orthogonal degrees of freedom to allow high sensitivity, while being relatively stiff along the rotating axis to stay aligned with respect to the reading system and being sufficiently robust to survive qualification loads.

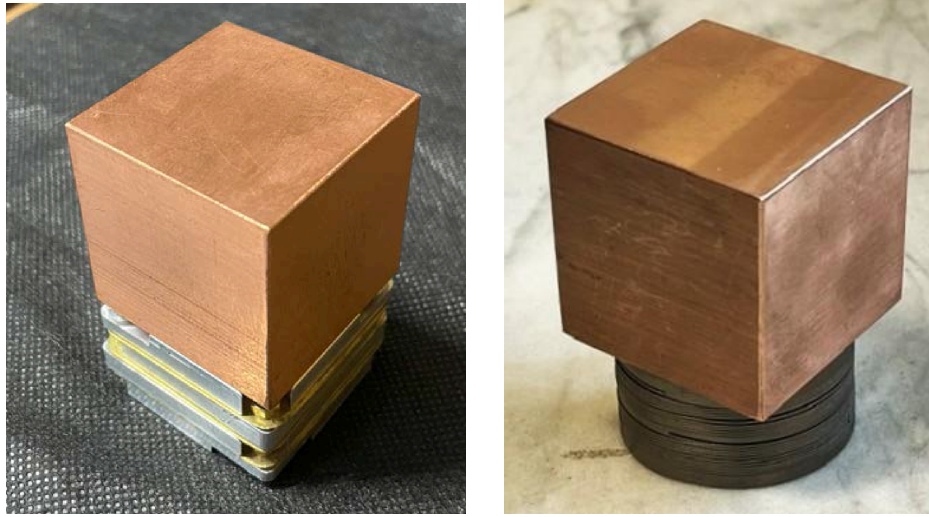


Figure 1. Proof mass in Cu-Be alloy with the shape of a cube with 40 mm side and mass of 530 g. Left: the mass is mounted on the blade spring; right: the mass is mounted on the helical spring. In both cases the spring is collapsed under the weight of the test mass.

2.4 Crossed-blade flexure

The blade flexure is built by stacking thin metallic membranes (0.1 mm-thick sheets of steel or Cu-Be) joined at the vertices as shown in Figures 1 and 2. Each elementary cell offers three degrees of freedom (two flexural rotations and a translation) while remaining essentially rigid along the axial direction. Stacking two such cells in series produces a suspension that is compliant on five degrees of freedom and stiff on the rotation axis, an arrangement well matched to the requirements of a translational accelerometer.

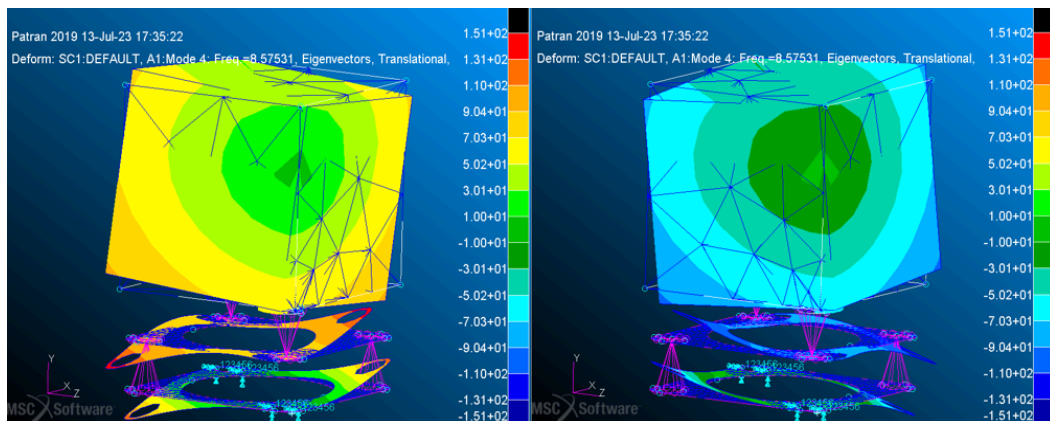


Figure 2. Finite element analysis of the test mass mounted on the crossed-blade flexure.

The bending stiffness of individual blades has been characterized on the dedicated test bench. Two opposite vertices of the specimen are clamped to a rigid support, while the remaining two are coupled to a carbon-fibre lever on which calibrated weights are applied to impose a known torque. The tilt of the lever is monitored by a chromatic-confocal probe operating at approximately 100 μm from the target surface. For 0.10 mm specimens the measured diagonal bending

stiffness is (1.93 ± 0.02) N mm/deg and the fundamental flexural mode is located at 122.67 Hz, in agreement with the modal analysis performed in MSC Patran with the Nastran SOL 103 solver.

Table 1 collects the four lowest modes computed for a two-blade suspension connected to the cubic test mass (x and z lie in the plane of the blade, y is perpendicular to it). A 0.10 mm blade yields a fundamental flex_z mode close to 1 Hz. Additional geometric variants have been explored numerically: in particular, drilling a 30 mm-diameter through hole in each membrane has been shown to reduce the fundamental frequency by approximately 20 %.

Table 1. Four lowest resonant modes computed for a two-blade suspension loaded with the 530 g Cu-Be proof mass.

Blade spring thickness / mm:	f_1 / Hz (flex _z)	f_2 / Hz (flex _x)	f_3 / Hz (long _y)	f_4 / Hz (tors _x)
0.10	0.98	0.99	3.33	11.65

2.5 3D printed helical spring

The alternative option under investigation is a “helical” spring structure. Starting from a commercial reference design, parametric FEM optimization has been carried out on coil thickness, on the number and diameter of the coils, and on the diameter of the central hole, using the torsional stiffness as the primary figure of merit. The resulting layout, (see Figures 1 and 3), features 20 coils subdivided into two counter-rotating sectors, with a coil thickness of 0.5 mm and a coil width of 8 mm; the chosen material is titanium alloy Ti-R58153, while the proof mass is identical to the one used with the blade suspension. The prototype was manufactured with Powder Bed Fusion with Laser Beam (PBF-LB).

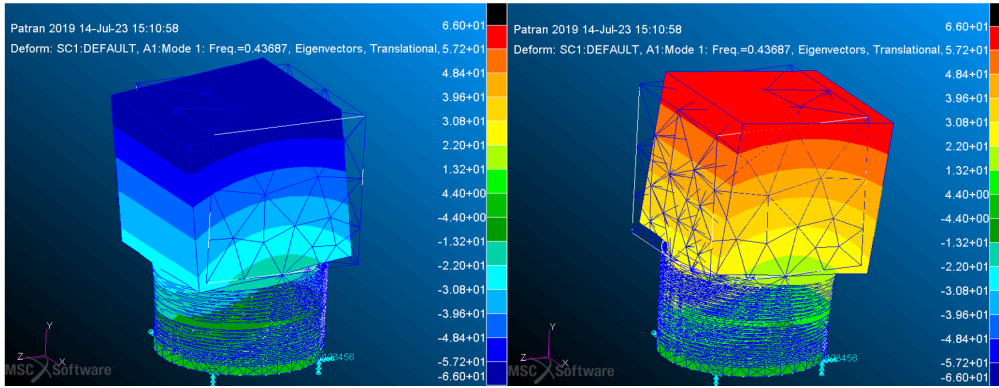


Figure 3. Finite element analysis of the test mass mounted on the helical spring.

The modal analysis (Table 2) predicts the two fundamental transverse modes at 0.44 Hz and a longitudinal mode at 1.13 Hz, values that are compatible with the target requirements and closely comparable to those achievable with the blade solution. A metallic prototype has been manufactured by laser powder-bed fusion additive manufacturing and characterized on the same experimental bench developed for the blade specimens.

Table 2. Modal frequencies of the helical suspension computed for a Ti-R58153 spring loaded with the 530 g Cu-Be proof mass.

Helical spring Material:	f_1 / Hz (flex _z)	f_2 / Hz (flex _x)	f_3 / Hz (long _y)	f_4 / Hz (tors _x)	f_5 / Hz (tors _z)
Titanium R58153	0.44	0.44	1.13	5.12	5.15

2.5 Interferometric readout

The optical read-out for each axis is realized as a dual heterodyne Michelson interferometer whose optoelectronic front-end is arranged on a fibre-coupled board (see sketch in Figure 4). A distributed-Bragg-reflector external-cavity laser (RIO Orion, $\lambda \approx 1064$ nm) with a specified linewidth below 10 kHz and an output power of ≈ 10 mW is directly launched into a polarization-maintaining fibre. Downstream of the first fibre splitter, the two arms are frequency-shifted by two acousto-optic modulators (AOMs) driven around 150 MHz, whose difference frequency (tunable between 1 kHz and 100 kHz) sets the heterodyne frequency. All accessory components (splitters, polarizers, in-line isolators) are PM-fibre coupled. The overall topology follows that of our earlier stand-alone prototype [28], with the essential addition of a second nominally identical interferometer sharing the same laser source and the same optical bench. Cross-correlation between the two twins interferometers allows uncorrelated noise contributions to be identified and provides an experimental bound on the ultimate readout limit [21].

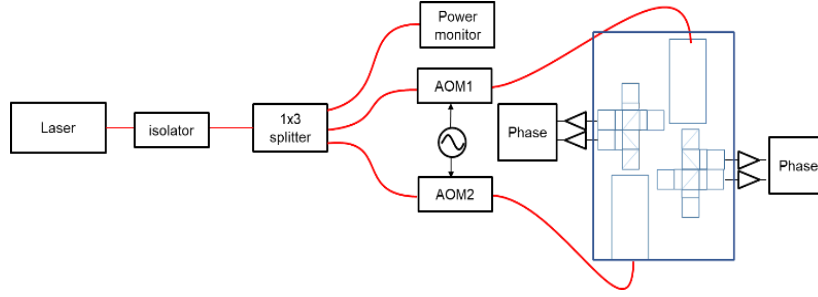


Figure 4. Simplified schematic of the fiber based optical bench with laser, AOMs, ending at the right side with the interferometric optical head.

The optical head is the core of the sensor. The scheme and the picture are reported in Figure 5. It has been implemented as a rigid arrangement of bulk components glued to an Invar spacer with a UV-curing polymer (Norland 61) specifically formulated for opto-mechanical bonding. The individual optics feature a 10 mm clear aperture: this size represents a compromise between the compactness of the head and the practical constraints of a manual assembly-and-alignment procedure. The use of dedicated micro-positioners would enable a further reduction of the optics down to 5 mm, with a substantial saving of the total head volume. The four photodiode signals produced by the two twin interferometers are digitized by a commercial ADC and demodulated by a commercial phasemeter implemented on the reconfigurable Moku:Pro platform.

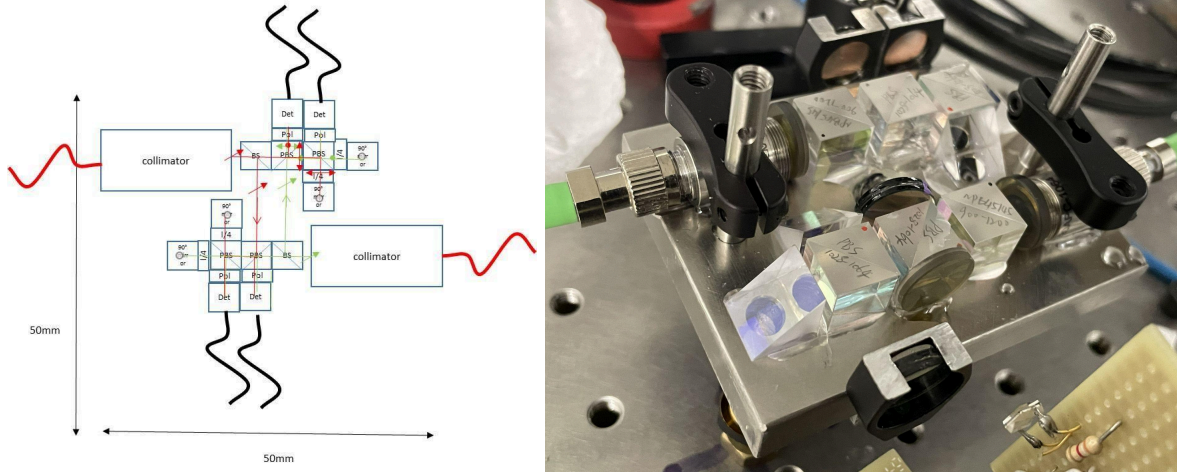


Figure 5. Left: block diagram of the double interferometer; right: picture of the interferometer

3. PRELIMINARY CHARACTERIZATION

The purpose of the measurements reported here is the characterization of the intrinsic noise floor and the stability of the interferometric bench, decoupled from any dynamics of the mechanical suspension. To that end the four output beams of the two twin interferometers are folded back onto four fixed corner-cube retroreflectors bonded to the same Invar structure, so that any residual fluctuation appearing in the demodulated phase can be unambiguously ascribed to the readout chain. The bench is bolted to the optical table of a clean-air laboratory area and the phase differences between the four heterodyne signals are extracted by the phasemeter functionality of the reconfigurable Moku:Pro platform.

On the left of Figure 6 shows a representative snapshot of the four raw detector signals at a heterodyne frequency of 10 kHz. The amplitude spectral density of the displacement noise measured on the two twin channels, labelled 1 and 2, is reported on the right of Figure 6. Above 3 Hz both interferometers reach a white plateau at $\approx 10 \text{ pm}/\sqrt{\text{Hz}}$, in agreement with the quadrature sum of the shot noise at the photodetectors, the input-referred current noise of the transimpedance amplifiers, the finite dynamic range of the ADC and the numerical noise of the phasemeter. Cross-correlation of the two channels reveals no significant common-mode contribution in this band, indicating that 1 and 2 behave as effectively uncorrelated sensors down to the noise-floor level. Below a few hertz the spectrum rises with a slope consistent with a thermo-mechanical drift of the PM fibres, combined with the non-ideal behavior of the PM connectors under environmental temperature fluctuations — an effect that has been reported for fibre-fed heterodyne heads and mitigated in more recent quasi-monolithic implementations [21].

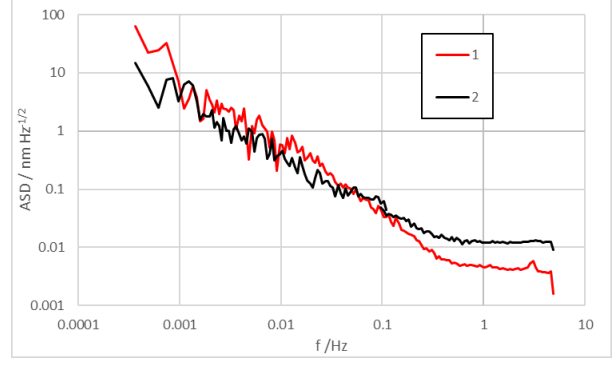


Figure 6. Left: the four raw detector signals at a heterodyne frequency of 10 kHz. Right: Amplitude spectral density of the displacement noise of the two interferometers

4. DISCUSSION AND OUTLOOK

A displacement resolution of $\approx 3 \text{ nm}/\sqrt{\text{Hz}}$ at 1 mHz, combined with a mechanical suspension whose fundamental mode has been designed in the 0.35–1 Hz range, leads to an equivalent input acceleration resolution close to the target of $10^{-8} \text{ m s}^{-2} \text{ Hz}^{-1/2}$ across the 1 mHz–100 mHz band and reaches the $10^{-11} \text{ m s}^{-2} \text{ Hz}^{-1/2}$ close to 1 Hz. The instrument is expected to match the high-end requirements for navigation and gravimetric space missions without making use of complex electrostatic suspension, without the need of blocking systems in the launch phase and with expected sensitivity superior to what achievable with classical capacitive sensors.

Next steps will foresee the testing at the Einstein Elevator facility [29] to check the behavior of the mass spring systems in representative micro gravity condition. Further work will be devoted to the realization of a more compact interferometric head, built with the aid of a robotic arm, that we expect to be more stable in the millihertz region.

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