LIG-A: Laser Interferometry Gauge & Accelerometer

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Final Report

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0 Introduction

This contract follows a previous LIG ("Laser Interferometry Gauge") ITI-type-A contract during which we have designed and realized in the lab a low noise laser interferometry readout. The goal of LIG was to achieve a noise level not exceeding $10\,\frac{\text{pm}}{\sqrt{\text{Hz}}}$ at 1 Hz with a compact, low consumption, laser gauge. At contract completion the LIG breadboard noise at 1 Hz was in fact even slightly lower than $1\,\frac{\text{pm}}{\sqrt{\text{Hz}}}$.

The present LIG-A ("Laser Interferometry Gauge & Accelerometer") ITI-type-B contract aimed at selecting an appropriate mechanical oscillator, characterizing its mechanical properties and transfer function, and interfacing it with LIG so that, by reading the displacements of the suspended TM (Test Mass), the acceleration that acted on the TM giving rise the observed displacements would be derived. Hence the name "accelerometer".

Our final goal is to realize an accelerometer for space applications (see Sec. 1) with very good low frequency sensitivity that outperforms the current capacitive accelerometers (see Sec. 2) and will eventually replace them.

This report is organized as follows.

In Sec. 1 we recall the need in space of accelerometers with very high sensitivity at low frequencies.

In Sec. 2 we describe the state of the art on the subject, how it is dominated by capacitive accelerometers and the limitations they are affected by.

Sec. 3 and Sec. 4 briefly discuss the hybrid instrument which has flown onboard the LPF (LISA-PathFinder) mission, and the ongoing efforts to develop gravity gradiometers for space based on light pulse atom interferometry and cold atoms as the test mass instead of a macroscopic body.

This leads us to Sec. 5 where we come to the core of our research, namely the key features of the strategy that leads to the design of our new LIG-A accelerometer and the reasons why this kind of accelerometer is extremely promising and may very well replace the capacitance accelerometers in the near future.

Finally, in Sec. 6 and its Subsections we report on the activity done within this contract. In particular, we report on: the improved low frequency performance of the LIG readout; the choice and characterization of the test mass interfaced with it in order to realize an accelerometer; the direct real time comparison of the capacitance versus the interferometric readout with the same accelerometer test mass showing the superior performance of the latter; the design of a single test mass with 6 degrees of freedom for a LIG-A type accelerometer with outstanding performance.

Sec. 6 ends outlining the possibility for a space demonstration of a two degrees of freedom LIG-A accelerometer and a very compact laser gauge within a short duration CubeSat flight of limited complexity and cost in a low Earth orbit.

1 Background: the need for accelerometers in space

Accelerometers onboard of spacecraft are needed in some cases as ancillary instruments (e.g. on the International Space Station-ISS to monitor the actual level of "microgravity" –residual noise–in various locations of the Station), but also as crucial components of space missions devoted to space geodesy and fundamental physics with or without drag-free control. In the latter cases they must have high sensitivity at low frequencies, down to 10^{-3} Hz or even 10^{-4} Hz.

Accelerations to be measured inside a spacecraft can be distinguished depending on the nature of the forces generating them: gravitational and non gravitational ones. Gravitational forces –caused by celestial bodies as well as by nearby spacecraft mass anomalies– produce the same acceleration on any test mass (to the extent that the equivalence principle is satisfied, which has been proved to very high precision). To the contrary, all non gravitational forces produce accelerations inversely proportional to the mass of the test body.

In the case of non gravitational forces acting on the outer surface of the spacecraft (such as drag from residual atmospheric density or solar radiation pressure effects) and not on the test mass inside it, the result is an inertial acceleration of the test mass relative to spacecraft equal and opposite to the acceleration produced by the same force on the spacecraft; because of the equivalence principle inertial accelerations are indistinguishable from gravitational ones and are therefore the same on any test mass regardless of its mass and composition. Thus, although they are due to non gravitational forces these accelerations might be confused with accelerations caused by real masses because the instrument used to measure them (the accelerometer) typically cannot tell which force causes which acceleration. In this case, inertial accelerations of the test mass relative to the spacecraft may be confused with gravitational accelerations due to local mass anomalies inside the spacecraft or to non zero tidal effects if the test mass is not located exactly at the center of mass of the spacecraft.

Another type of non gravitational forces are those which act directly on the test mass, such as in the case of local pressure and/or temperature effects, electric patch effects, etc... In this case, the acceleration of the test body is inversely proportional to its mass.

Assuming that local non gravitational accelerations, tidal accelerations and local gravitational accelerations from nearby mass anomalies of the spacecraft are all smaller than the acceleration target of the experiment, only the inertial accelerations resulting from drag and solar radiation must be measured so as to be able to recover, via software, the gravitational field that the spacecraft and the test mass are subjected to. If the spacecraft is equipped with a drag compensation (or drag free control) system, the inertial acceleration measured by the accelerometer serves as input signal for the control system that activates appropriate actuators (thrusters) located on the outer skin of the spacecraft in order to "zero" (in fact reduce) the measured inertial acceleration. In so doing the spacecraft is forced to follow the test mass inside it which –to the level of the controlled drag acceleration– is affected purely by the gravitational field of the central body (e.g. the Earth), plus gravitational perturbations from other celestial bodies, if any (e.g. the Moon and the Sun).

In this case the accelerometer measures inertial accelerations. For this reason some authors, specifically LISA and LPF scientists, have diffused the habit of referring to it as "inertial sensor". However, it is worth stressing that this name is correct only as long as all local non gravitational accelerations, tidal accelerations and gravitational accelerations from local spacecraft mass anomalies are negligible at the target level of the experiment. Should any such acceleration exceed the target, it will impair the drag free control system. The assumption –which would be wrong if this is the case– that the acceleration measured by the sensor is only the inertial acceleration caused by non gravitational forces acting on the outer surface of the spacecraft (hence equal and opposite to it) makes the thrusters activated by the control system to respond in the opposite direction with respect to what would be necessary instead in order to reduce the effect in question.

This is why it is more appropriate to refer to the instrument as "accelerometer" rather than as "inertial sensor", since that is undoubtedly what it is: an instrument that measures any acceleration acting on its test mass regardless of the force that causes it, on which nature it is unable –by itself– to provide any information.

Naturally, it is possible to investigate the signature of the acceleration measured, its dependence on all physical parameters, including the orbital ones, in order to establish its nature, reduce and/or model it so that the gravitational effect of interest can be recovered in a reliable way. Only in the case that the inertial acceleration resulting from external non gravitational forces on the surface of the spacecraft is the dominant acceleration measured by the instrument (all others being too small to matter), it would be correct to refer to this accelerometer as an "inertial sensor". This is the goal of a successful drag free control system, but cannot be taken for granted *a priori*. Moreover, depending on the acceleration target, an instrument can be an inertial sensor at a certain acceleration level but just an ordinary accelerometer should local accelerations (as defined above) larger than expected be detected

The less challenging use of an accelerometer in space is for the characterization of the residual noise inside large spacecraft such as the ISS. In this case the dominant noise sources are sonic vibration noise of the structure (typically at high frequencies) and human noise, while low frequency noise is less relevant.

In missions devoted to space geodesy and fundamental physics the frequencies of interest are much lower and the sensitivity required much higher.

In this context the LIG-A accelerometer is highly competitive because of two features it relies upon. First of all, the capability of the laser interferometry gauge LIG to measure displacements (between a target "mirror" and a reference "mirror") with very high precision and accuracy, even at very low frequencies. Secondly, the possibility –in weightlessness conditions– to realize a test mass very weakly coupled to the spacecraft, hence with a very low natural oscillation frequency (also known as the resonance frequency), a property that makes it extremely sensitive to all accelerations acting at frequencies below the natural one, the transfer function in this frequency range being 1. For a given sensitivity to displacements of the test mass, the corresponding sensitivity to the acceleration that has produced it is inversely proportional to the test mass natural frequency squared. Thus, the combination of a readout sensitive to extremely small displacements (also at low frequencies), and a test mass a with very low resonance frequency, naturally make the LIG-A accelerometer very sensitive in the low frequency range of interest for space geodesy and fundamental physics.

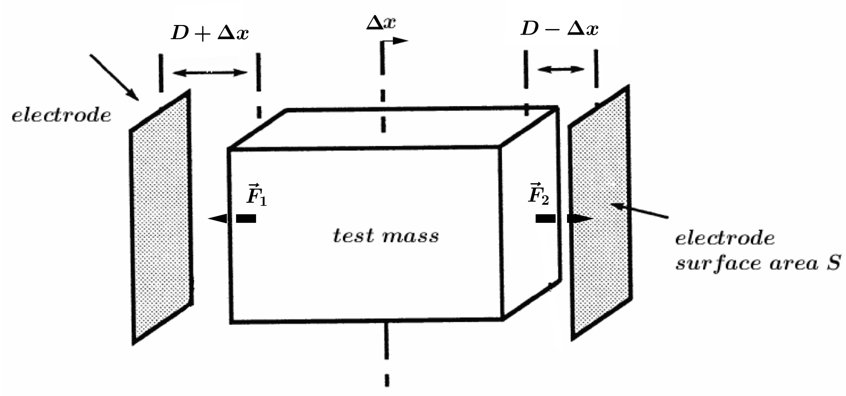
Being easily tunable (in terms of the natural oscillation frequency of its suspended test mass) there is no difficulty in realizing versions of it that are suitable for less demanding applications.

2 State of the art: ONERA and ISA capacitance accelerometers

Capacitance accelerometers built by ONERA (France) have been used since the mid 1970s, and have played a key rôle in CHAMP, GOCE, GRACE, GRACE-FollowOn and MICROSCOPE missions.

They are based on electrostatic suspension, capacitance readout and capacitance control of the Test Mass (TM); electric charges on the TM due to cosmic rays are discharged by a loose, thin gold wire connecting the suspended TM to the cage rigid with the s/c.

As shown in the simple sketch of Fig. 1 the electrostatic suspension works as a spring with negative stiffness. Hence, the TM is always attracted towards the capacitance plate it is closer to, and the equilibrium position with its center of mass at the same distance in between two plates is unstable (it is a potential top). An appropriate control force must be applied by the capacitors in order to bring the TM back to its central, equilibrium position whenever it is displaced by any force. The control force is also electrostatic, and needs as input signal the displacement from equilibrium measured by the capacitors (Δx in the sketch of Fig. 1). The detection voltage itself exerts a DC force bias (back-action), and its fluctuations produce noise at all frequencies.



Electrode's force is always attractive

$$F_2 - F_1 = \frac{1}{2}\varepsilon_\circ S V^2 \left(\frac{1}{(D-\Delta x)^2} - \frac{1}{(D+\Delta x)^2} \right) \simeq \frac{2\varepsilon_\circ S V^2}{D^3}\Delta x$$

$$F_2 - F_1 \simeq -k_{electrostatic}\Delta x \qquad k_{electrostatic} = -\frac{2\varepsilon_\circ S V^2}{D^3}$$

"negative" spring : test mass unstable, control force needed

Figure 1: Sketch of a test mass suspended electrostatically along the horizontal axis x with electric potential V, electrodes surface area S and gaps of size D in the case of a displacement Δx from the central equilibrium position. Since the electrostatic stiffness $k_{electrostatic}$ is negative the equilibrium position of the test mass is unstable and a control force is needed to avoid instability.

Gaps must be very small (a few hundred μm) for two reasons: *i*) to ensure sensitivity to small relative variations of the capacitance in correspondence of displacements of the TM; *ii*) to yield a strong enough control force capable to nullify any displacement and thus avoid the onset of instability. However, such small gaps inevitably produce an amplification of well known disturbances such as electric patch effects (local patches of electric charges have been a serious issue for the ambitious GP-B mission of NASA and do appear on equipotential surfaces because of inevitable irregularities) and disturbances due to residual pressure in the gap.

The founding paper on this instrument appeared in 1999 (Josselin, Touboul and Kielbasa, Sensors and Actuators 78, 92 (1999)).

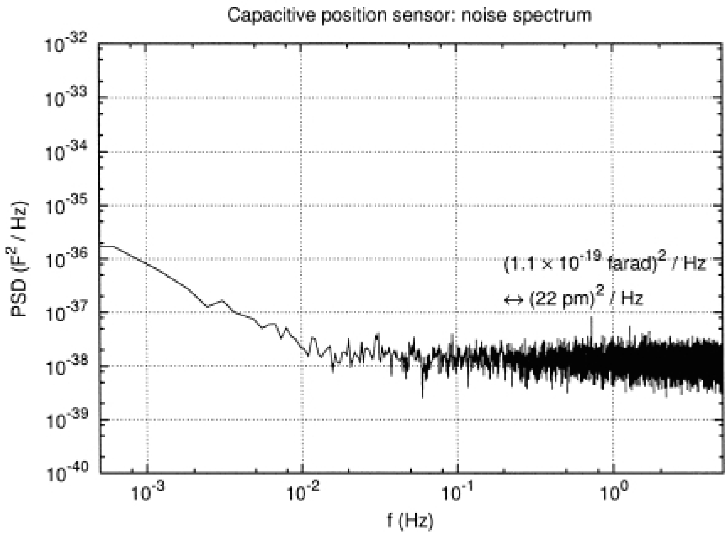


Figure 2: Noise spectrum of the capacitance position sensor by ONERA, with $300\,\mu$m gap, as published in Josselin et al. (1999). At $\nu \gtrsim 0.01\,$Hz noise is $22\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ flat. The knee at $0.01\,$Hz and noise growth below this frequency is attributed by the authors to the low frequency amplifier. The largest value shown in this plot just below $1\,$mHz amounts to about $280\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$.

This paper, in discussing the loose gold wire that connects the TM to its cage in order to eliminate the electric charges accumulated because of cosmic rays by grounding the TM, states that the negative electrostatic spring "*is the dominant stiffness, far greater than the gold wire...*": This means, in the words of the instrument proposers themselves, that the connection by means of the gold wire, which may be regarded as a *dummy* mechanical suspension spring, is much more soft than the electrostatic suspension provided by the capacitors. Hence, the preference for an electrostatic suspension is not dictated by the fact that a mechanical suspension would be too stiff (as it is usually the case at 1-g) resulting in the test mass not being sensitive enough to the tiny forces of interest. As we have seen, this not the case, and we should keep it in mind when considering a novel type of accelerometer based on a laser interferometry readout.

Thermal noise due to a low quality factor of the gold wire is there regardless of the fact that the wire is not designed to suspend the test mass and turns out to be a relevant source of noise. For this reason the attachments at its two ends (where most of the losses giving rise to thermal noise are known to occur) should be made according to the best procedures developed and tested successfully on ground in highly challenging experiments to detect gravitational waves by laser interferometry and to test the weak equivalence principle with torsion balances. Unfortunately this need is not usually recognised, resulting in a low quality factor and high thermal noise.

As reported by Josselin et al. (1999) and shown in Fig. 2 taken from their paper, ONERA accelerometers are limited by low frequency electronic noise. In the best ONERA accelerometer developed for the MICROSCOPE space mission the gap size was increased (600 μm instead of 300 μm) and the noise as measured on ground is reported in Fig. 3, indicating the difficulties in overcoming low frequency noise and improving on the results by Josselin et al. (1999).

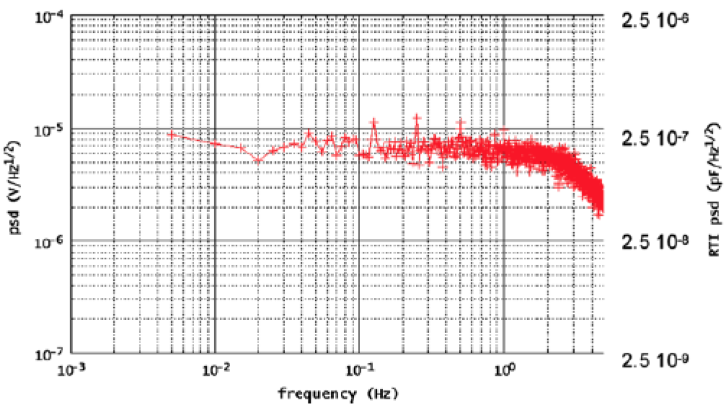


Figure 3: Noise spectrum of the Microscope accelerometer (600 μm gap) as reported by Touboul, Space Sci. Rev. 148, 455 (2009) and Rodrigues, Les Houches (2009). The calibration factor given was 6 μm for 1 V. With this number the horizontal line at $10^{-5}\,\mathrm{V}/\sqrt{\mathrm{Hz}}$ corresponds to a displacement noise of $60\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$.

In the case of ISA (Italian Spring Accelerometer), currently flying onboard of the BepiColombo mission, the TM is suspended mechanically by means of thin lamellae (which provide electric discharging too) and its displacements are read by capacitors. Mechanical stiffness –unlike the electrostatic one– is positive, hence it always provides a restoring force and therefore ensures a stable equilibrium position. ISA is used also in geophysical marine applications. By sharing a capacitance type readout with ONERA accelerometers it is also limited by low frequency electronic noise and by the need of very small gaps.

3 LPF: an *ad hoc* hybrid instrument, not a general purpose accelerometer

Two electrostatically suspended TMs have flown onboard the LPF (LISA PathfFnder) technology mission to demonstrate a high level of drag free control and almost undisturbed, purely gravitational motion of the TMs in preparation for the LISA mission.

In order to reduce the noise sources typical of the capacitive accelerometers discussed in the previous Section the gold wire has been eliminated (an active electric discharger had to be installed to replace it) and gaps have been increased from a few hundred μm to 4 mm. However, it is very important to stress that LPF carries also a high precision laser interferometry readout. It is teh signal of the laser interferometer that drives the drag free control loop while the capacitors ensure TM control throughout the mission and particularly at the start of any science run since the experiment cannot start unless the inevitable position and velocity release errors are properly reduced by the capacitors control forces.

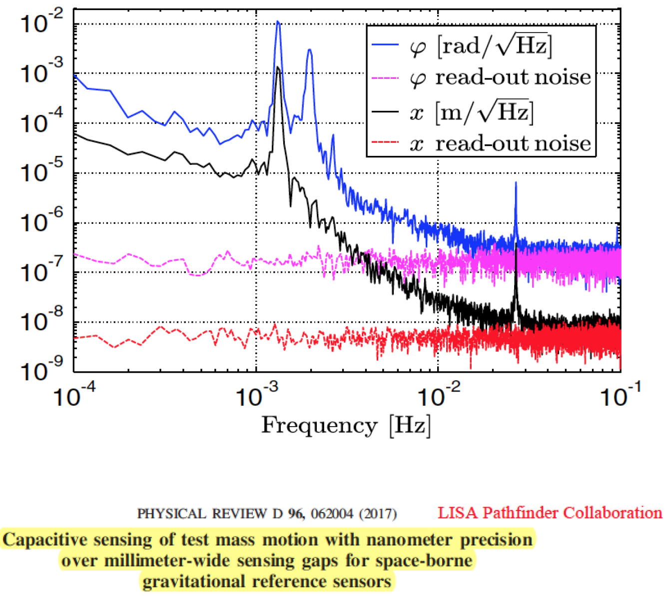


Figure 4: *Top (red curve):* Displacement noise spectrum of LPF capacitance readout as measured in ground tests by Bassan et al., Phys. Rev. Lett. 116, 051104 (2016), showing a level of several nm/$\sqrt{\text{Hz}}$. The low frequency electronic noise causing the typical "knee" shown in Fig. 2 is too small to appear at these levels. *Bottom:* Title and reference of the paper that has reported similar results obtained in space by LPF.

Albeit crucial –for TM suspension, TM control and the initialization of all science runs– the capacitive system of LPF plays a limited and very specific rôle (since the laser interferometer cannot apply the required forces), and it is not designed to be a stand alone high sensitive accelerometer. In point of fact its precision in the measurement of the displacement of the TM, on which the acceleration measurement relies, is at nanometer precision, as compared to a few tens of picometer precision of ONERA accelerometers.

This is apparent by comparing Fig. 4 with Figs. 2 and 3 of the previous Section. Fig. 4 reports the LPF capacitance readout noise as measured in ground based tests (Bassan et al., Phys. Rev. Lett. 116, 051104 (2016)) showing that it amounts to several $\mathrm{nm}/\sqrt{\mathrm{Hz}}$ level. At completion of the mission LPF scientists published the results of the capacitive system (Armano et al., Phys. Rev. D 96, 062004 (2017)) stating explicitly, in the title of the paper, that it has reached nanometer precision.

In challenging experiments that require a very low noise level of the TM, such requirement is utterly in contrast with the inevitable need to control the TM, because low noise requires large gaps but the larger the gap the smaller the force that the capacitors can apply.

Only a compromise is possible, which is what has been done for LPF, and will apply also to LISA. As reported by LPF scientists (Bortoluzzi et al., Adv. Space Res. 67, 504 (2021)) the compromise made may be very risky since it turned out that none of the TM releases of LPF was successful as ground tests predicted they should be. The residual position and velocity errors of the TMs were too large for the control force that could be applied by the capacitors, whereby *ad hoc* release adjustment commands had to be sent from ground before the control system could take over its job, thus allowing the runs which ensured the success of the LPF demonstration mission to be initiated. However –as the authors acknowledge in the paper– this procedure will not be applicable toLISA, because its distance from Earth much larger than LPF makes the travel time of commands from ground bigger than the time interval within which the TM must be controlled before it hits the enclosing cage.

It is apparent that the capacitive system of LPF is a very peculiar *ad hoc* instrument tested onboard of a very complex, challenging and expensive mission, while we are considering a general purpose accelerometer suitable as a small payload on a variety of s/c.

4 Cold atoms not ready to replace bulk masses

A new way of measuring accelerations is by dropping cold atoms and measuring their motion during fall by means of light pulse atom interferometers with techniques based on quantum mechanics.

A key advantage of this technique is that atoms serve as the test mass and at the same time provide (by means of three appropriate laser pulses) the key components of the readout interferometer. The precision of a single acceleration measurement improves as the square root of the total number of drops that are carried out to achieve such measurement.

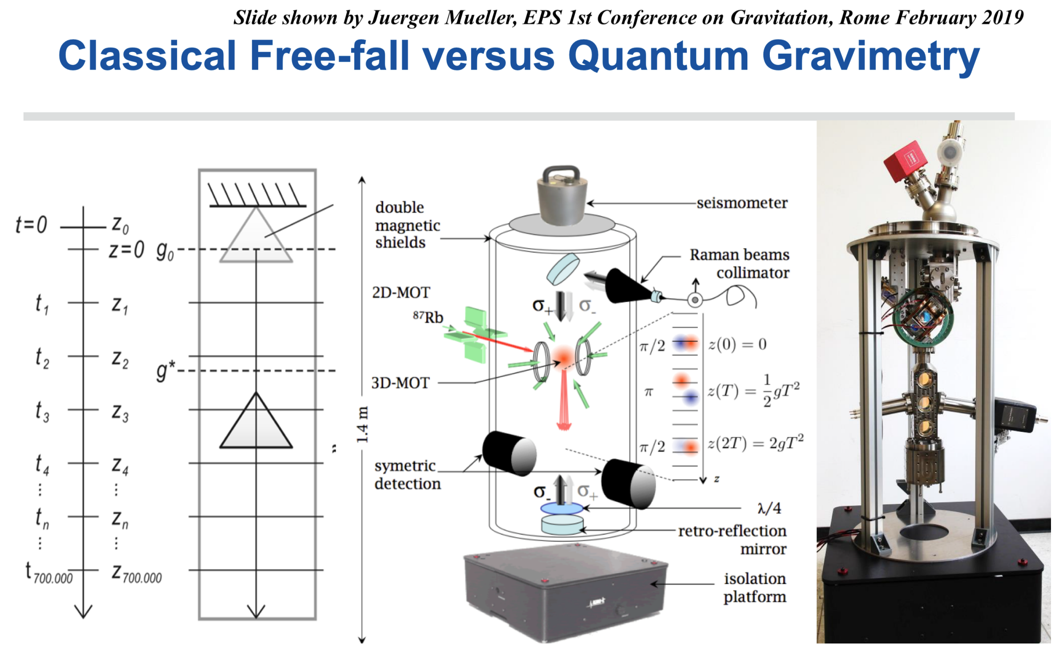


Figure 5: The sketch to the left refers to the classical gravimeter, in which the free falling test mass (a corner cube reflector) is tracked by a laser interferometer that measures its position at various times during fall providing a large number of time-position data points. The sketch in the middle refers to a cold atom gravimeter based on light pulse atom interferometry, in which the position of the free falling atom cloud is measured only three times in correspondence of the three laser pulses.

However, since the light pulse atom interferometer is based on three laser pulses, the acceleration relies on only three time-position measurements per drop. As clearly sketched in Fig. 5, this is unlike the case of the classical gravimeter, in which the number of time-position measurements per drop is much larger. As shown by Nobili (Phys. Rev. A 93, 023617 (2016)) with three data points only, no matter how good is the precision of each position measuremnet, the acceleration measured is an average value that differs from the real one by an amount (a systematic error) which grows linearly with the gravity gradient and quadratically with the time of fall. Thus, the acceleration measured by the atom interferometer is the real acceleration of the free falling atoms only if the acceleration is constant, which is never the case with the gravitational acceleration because the gravity field is non uniform.

The limitations resulting from this error in the actual use of light pulse atom interferometers on ground and in space have been recently investigated and are reported in Nobili et al. (Phys. Rev. Res 2, 012036(R) (2020)).

As fas as applications of atom interferometry to space geodesy are concerned the key issue is the following. It is well known that atom interferometers are highly affected by vibration noise, which has lead to the choice of building gradiometers –where vibrations are mostly common mode and therefore can be rejected– rather than accelerometers (see McGuirk et al., Phys Rev. A 65, 033608 (2002)). However, space geodesy missions such as GRACE, GRACE-FO and NGGM, and all drag free missions need an individual accelerometer onboard of each spacecraft.

These issues, in addition to the inevitable problems of a relatively new technology (e.g., the large size of the instrument) and the inherent difficulty in covering more than one degree of freedom, make it quite unlikely that cold atoms will replace bulk test masses in accelerometers for flight anytime soon.

5 Our new LIG-A strategy: laser interferometry, mechanical suspensions and no capacitors

The major breakthrough behind our novel LIG-A accelerometer is that laser interferometry is mature to replace capacitance readout in space with much better performance and numerous advantages, as we have shown with the development of LIG.

However, the case for laser interferometry is not compelling for the realization of a new accelerometer as long as capacitors remain a key component to control the test mass. A TM equipped with both laser interferometers and capacitors may be acceptable in very complex and expensive missions such as LPF and LISA, but as we have argued in Sec. 3 is it not viable for a general purpose accelerometer to be used in a variety of spacecraft.

At this point a clarification is in need on how the test mass of the accelerometer can and should be suspended. We often read about the test masses of LPF and LISA as being "free masses" because the gold wire has been eliminated and there is no "physical" connection to the enclosing cage. Indeed, there is no such thing as a "free test mass", because a non zero electrostatic stiffness –provided by an appropriate electric potential– does connect the mass to the cage. Proof is that, should the electric potential be switched off, the experiment would be terminated because –similarly to cutting the suspension wire of a torsion balance– there would no longer be a test mass. A suspension of some kind is needed because a really free test mass –in addition to the fact that its motion is poorly determined because of position and velocity errors at release– would quickly hit its cage after release due to air drag and/or solar radiation pressure acting on the outer skin of the spacecraft. Although some ways out could be envisaged, a test mass totally free inside the spacecraft has been ruled out by all scientists who have investigated the subject. Thus, the choice is only on which kind of suspension is to be preferred, based on its performance in relation to the most relevant issues, namely:

i) stability or instability of the equilibrium position,
ii) stiffness (the weaker the better),
iii) need for an additional electric discharger or not,
iv) gaps and related sources of noise (the larger the gap, the better),
v) losses and thermal noise (the lower the better),
vi) number of degrees of freedom that the TM is sensitive to (up to 6).

Item *i*) is the crucial one because it amounts to deciding whether or not the TM needs to be actively controlled. If the equilibrium position provided by the suspension is unstable there is no choice: forces are needed to control the TM for the entire duration of the experiment.

Having developed a laser interferometry gauge that can very well replace electrostatic capacitors in reading the displacements of the TM but cannot apply forces on it, we choose a stable equilibrium position whereby the TM remains close to it with no need of a control force. This leads to the choice of a suspension with positive stiffness, namely a mechanical suspension, thus getting rid of capacitors altogether.

Although a totally free TM is ruled out and a suspension is mandatory, the coupling must be as weak as possible for the TM to be as sensitive as possible to the tiny accelerations of interest, especially in space geodesy and fundamental physics missions.

A common misconception is that an electrostatic suspension is much weaker than a physical (visible!) mechanical one. This prejudice comes from our everyday experience, since we hardly ever have the occasion to watch a body levitated by an electrostatic force, while masses with mechanical suspensions are quite common (from automobile and motorbike suspensions to pendulums) but they are very stiff in almost all cases since they must withstand the local gravitational force. Instead, in the environment around the center of mass of an orbiting spacecraft we are in (almost) weightlessness conditions in which case the largest force to be counteracted by the suspension can be million times smaller than local gravity on Earth. Hence, the mechanical stiffness required in orbit is orders of magnitude weaker than on ground, the achievable stiffness being limited by manufacturing capabilities –unless appropriate suspension shapes are chosen.

This responds to the issue *ii*). Mechanical suspensions can be very weak, as pointed out by ONERA scientists in their founding paper (Josselin et al., Sensors and Actuators 78, 92 (1999)) where they explicitly note that the electrostatic stiffness is by far greater than that of the gold wire. The wire ensures electric grounding of the test mass, but being loose it is a "dummy spring". Instead, a "smart spring" can also suspend the TM around a stable equilibrium position. Thus, by choosing a "smart" mechanical suspension we solve also the issue *iii*), in that no active electric discharger is required.

From the type of suspension depend the disturbances and sources of noise to deal with.

A matter of concern is the size of the gaps between the TM and its cage (which is rigid with the spacecraft), because the effects of residual gas damping are known to be larger with small gaps. Ever since the GP-B mission of NASA was troubled by electric charge patch effects, this issue too has been taken very seriously. Although electric charges deposited on the TM by cosmic rays are discharged (by an active discharger in the case of GP-B), and despite the fact that the TM surface is –macroscopically– an equipotential surface, patches of electric charges are known to appear (and move...) on its surface –probably due to an inevitable, albeit low, roughness. One way to mitigate the effects of electric patches is by increasing the size of the gaps. As we have seen in Secs. 2 and 3, this is a problem with electrostatic suspensions, thus the issue *iv*) leads to choosing a laser interferometer to read the TM displacements (sensitivity not limited by the gap size) together with a mechanical suspension of the TM (stable equilibrium, no active control force, no capacitors).

Any kind of suspension does have losses that give rise to thermal noise, at room temperature in this case since we are not considering a cryogenic accelerometer.

Mechanical suspensions are a key component of all leading gravitational experiments, from the most advanced tests of the equivalence principle with rotating torsion balances to the successful detectors of gravitational waves by laser interferometry (they suspend the mirrors of the interferometers, which are the test masses sensitive gravitational waves). The success of these experiments has been made possible by the ability to realize mechanical suspensions with high quality factors and low thermal noise. The expertise is now available to everyone willing to make use of it, and this responds positively to the issue *v*).

The lesson to learn is that losses mostly occur at the two attachment ends where glue or screws are located. However, if the ends to be attached are designed with appropriate enlargements and the entire suspension is manufactured from a single solid piece in such a way that under the effect of a force acting on the suspended body no deformation of the suspension occurs in correspondence of glue or screws, losses are greatly reduced. In the Microscope experiment each end of the gold wire was attached with a droplet of glue, apparently with no enlargement, and this might have increased losses at the attachments.

The issue *vi*) in the list concerns the number of degrees of freedom that the test mass of an accelerometer is sensitive to. The total number is 6: 3 translational ones (to measure linear accelerations along 3 orthogonal axes), and 3 rotational ones (to measure angular accelerations around 3 orthogonal axes).

Most applications don't need to measure all these accelerations, and many they may require different sensitivities depending on the physical phenomenon of interest and the degrees of freedom affected by it. Nevertheless, it is very important that the test mass can in principle be sensitive in all 6 degrees of freedom, even though in many cases only measurements in some degrees of freedom are implemented.

In this respect the typical cubic test mass of capacitance accelerometers is a good solution. With an appropriate arrangement of the capacitors facing every side of the cube it is possible in principle to measure all linear and angular accelerations. At first glance a test mass with mechanical suspension appears to be less versatile in terms of degrees of freedom. For instance, the lamellae used to suspend the TM in the case of ISA capacitive accelerometer provide one sensitive axis for each TM. On BepiColombo, three such test masses are needed (orthogonal to each other) for the three translational degrees of freedom.

This may be a limitation for a compact instrument of wide use. However, it can be overcome by changing the design of the suspension and the test mass. Previous experience on helical suspension springs (e.g., ASI study on PGB-Pico Gravity Box) shows that helical suspensions can be used such that a single cubic TM is sensitive in all 6 degrees of freedom. The mechanical properties of this spring depend on various parameters (material, wire thickness, coil diameter, number of coils). By an appropriate choice of these parameters and a well established manufacturing procedure it is possible to obtain a very low stiffness in all degrees of freedom and low thermal noise.

Having covered all issues in the list, the case for the LIG-A novel accelerometer appears to rest on solid grounds.

6 LIG-A: current results and where we stand

6.1 Results and perspectives

Within the LIG-A project we have first built a laser interferometry gauge (LIG) of small size and small power consumption. It has achieved a very low displacement noise (Fig. 6, left) even at very low frequencies, featuring a standard thermal stabilization and no vibration isolation (except for operating in a good quality lab and for arranging the optical head, as well as the target and reference mirrors, on a zerodur base).

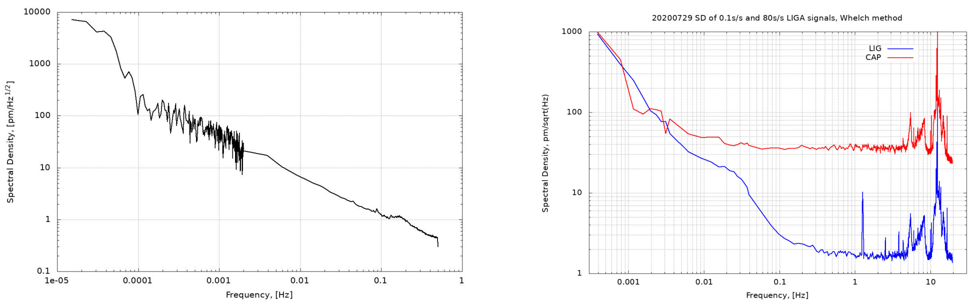


Figure 6: *Left:* Spectral density of displacement noise sensitivity of the LIG readout. *Right:* Real time comparison of the capacitance (*red*) and LIG (*blue*) readout when interfaced to the same test mass.

Then we have fully characterized the mechanical properties and the capacitance readout sensitivity of an ISA type accelerometer (ISA-GGG, originally used as an ancillary instrument in the GGG lab of INFN and University of Pisa) with the TM suspended by lamellae. Finally, we have interfaced the ISA-GGG accelerometer (one TM sensitive in 1D with its capacitance readout electronics) with the LIG interferometer adding also two appropriate corner cube reflectors so that the displacements of the TM could be read, at the same time, also by the laser ineterferometry readout both readouts in real time, making it possible a direct and rigorous comparison test never performed before. The expected superiority of the LIG readout is confirmed (Fig. 6, right), while at frequencies below 2 mHz both systems are dominated by local vibration noise.

From the displacement sensitivity reported in Fig. 6 (left plot) the acceleration sensitivity at frequencies below the natural one is obtained simply multiplying the displacement sensitivity by the natural angular frequency (or resonance frequency $\omega_\circ$) squared. Thus, for a given displacement sensitivity measured by the readout, the smaller the natural frequency of the test mass, the smaller the sensitivity to the acceleration that has generated the displacement. The dependence on $\omega_\circ^2$ makes it extremely important that the natural frequency is small, the smaller the better. Since $\omega_\circ^2 \simeq k/m$ this requires the stiffness k to be as small as possible (the mass m of the test body must anyway be compatible with a small and compact instrument).

The TM of ISA-GGG used to demonstrate the feasibility and potentiality of a LIG-A type accelerometer had been designed for use on ground in the GGG lab of INFN Pisa. Hence, the stiffness of the suspension was not as weak as it can be in absence of weight. In addition, being the test mass of a capacitive accelerometer, it was optimized for a capacitive readout (e.g., with a large surface area and rather small, 500 μm gaps for higher capacity and better sensitivity to small capacitance variations in response to tiny displacements of the test mass) and not for a laser interferometry readout.

The natural frequency of the test mass used was, in Hz, 5.8 Hz –that is 36.44 rad/s. This means that at 1 mHz the displacement sensitivity of $\simeq$ $30\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ measured by the LIG readout (Fig. 6 left plot) translates into an accelerations sensitivity of $\simeq 3\times10^{-11}\times 36.44^2 \simeq 3.98\times10^{-8}\,\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$.

Reaching a low displacement noise of the interferometer at 1 Hz is by far less challenging than it is at a mHz. Even within our previous ITI type A contract LIG (with no special care devoted to optical fibers and no temperature stabilization) we have reacbed, at 1 Hz, a noise smaller than $1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$. The improved results reported in Fig. 6 (left plot) clearly show the improvement, and although the plot has not quite reached 1 Hz because we wanted to cover a very wide range of low frequencies (down to about 10^{-5} Hz), noise at 1Hz certainly did not exceed $0.35\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$, which translates into an acceleration noise of $\simeq 4.6\times10^{-10}\,\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$.

In the LIG-A proposal submitted to ESA for the this contract we clearly stated the goals of the project:

"The baseline LIG-A accelerometer shall be sensitive in a wide frequency range, spanning 3 *frequency decades from* 10^{-3} Hz *to* 1 Hz*, with an acceleration noise going from* $5\times10^{-8}\,\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$ *at* 10^{-3} Hz *to* $5\times10^{-10}\,\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$ *at* 1 Hz*. Realization shall be limited to 1D."*

Thus, the goals have been met in both cases.

This Contract has made the case for a LIG-A accelerometer very strong. The physics of mechanical suspensions is well established, their behaviour is predictable and measurable making the design and construction of the oscillating test mass not a challenge. Manufacturing expertise is available to achieve low stiffness and high quality factors.

A cubic test mass with helical suspensions, appropriate connections for low losses and properly chosen design parameters can reach low natural frequencies (hence good sensitivity) in all six degrees of freedom.

Since each degree of freedom requires a laser interferometer, a more compact one than the current LIG is needed, especially in the most general case of a six degrees of freedom accelerometer.

In the proposal submitted to ESA for this Contract we also wrote that:

... we shall design a variant LIG-A accelerometer capable to reach the outstanding sensitivity of $\simeq 5\times10^{-13}\,\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$ *over* 1 *(low) frequency decade, from* 5×10^{-4} *to* 5×10^{-3} Hz*. The required weaker suspension can be realized in the lab at* 1 *g but would take considerable advantage by the absence of weight in space.*

With the displacement sensitivity of about $100\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ measured at 10^{-4} Hz (Fig. 6 left plot), the proposed, very challenging target of $\simeq 5\times10^{-13}\,\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$

can be met if the test mass has a natural frequency of $\simeq 1.1 \times 10^{-2}$ Hz, which can be manufactured on ground for use in absence of weight (with simple mechanical stops to avoid the disrupting effects of large vibrations during launch, as already used for ISA on BepiColombo).

The OSIP Call for mission Ideas opened by ESA in October 2020 came at the right time offering us the opportunity to propose a full in orbit demonstration of a LIG-A type accelerometer. The proposal *LIG-A-CubeSat (Laser Interferometry Gauge Accelerometer on CubeSat)* convincingly argues that a test demonstrating the capability to reach a low level of noise at low frequency can be performed on a small CubeSat. With a test mass natural frequency of 0.07 Hz it would be possible to reach $6 \times 10^{-12}\,\mathrm{ms^{-2}}/\sqrt{\mathrm{Hz}}$ at 1 mHz. More importantly, by an appropriate choice of the orbit and the accelerometer axis sensitive to linear acceleration the level of noise in orbit would be small enough to demonstrate this target with no need for the satellite to be equipped with a control system for drag compensatiomn. The design proposed makes the test mass sensitive also to rotations around one axis. The required suspension design can be manufactured similarly to suspensions realized and tested in the past by the proposers in the GGG experiment at the University of Pisa/INFN lab.

By comparison, at the same frequency of 1 mHz the ONERA capacitive accelerometer to fly onboard of each satellite of the NGGM space geodesy mission of ESA has a target of $3 \times 10^{-12}\,\mathrm{ms^{-2}}/\sqrt{\mathrm{Hz}}$, only a factor 2 better than *LIG-A-CubeSat*

The *LIG-A-CubeSat* proposal has been submitted in due time and despite some delay with respect to the original timeline, due to internal ESA budget issues, has been shortlisted and proposed for further investigation. Funding awaits the final approval of ESA DG.

Details on the various steps of the research activity carried out within the LIG-A Contract in order to achieve these very satisfactory results are reported in the following subsections.

6.2 How we got there

6.2.1 Reduction of LIG noise at low frequencies

At completion of the previous LIG Contract (ITI Type A) the displacement noise of the interferometer at 1 Hz was even better than the target but its increase at low frequencies was unsatisfactory and incompatible for an accelerometer of interest in space (see Fig. 7).

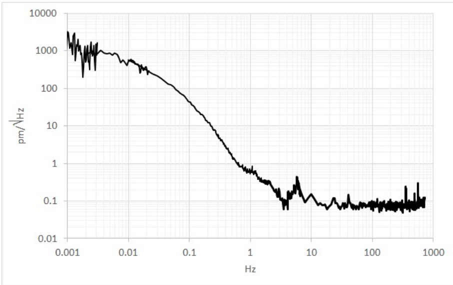


Figure 7: Spectral density of LIG displacement noise as obtained within the previous ITI Type A Contract. At 1 Hz the noise was better than the 1 pm/$\sqrt{\text{Hz}}$ target of that Contract. Reducing its increase at low frequencies was the first goal of LIG-A Contract.

Our analysis suggested that most of the low frequency noise might be due to the optical fibers. Although LIG is a heterodyne interferometer and we used polarization maintaining fibers, higher order noise is known to remain. It could be reduced by reducing the length of the fibers to the minimum (it requires appropriate cutting), and making the remaining fibers as stable as possible to avoid fluctuation noise due to length variation (see Fig. 8).

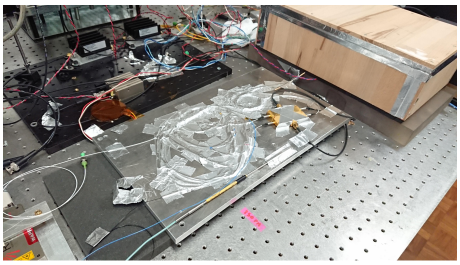


Figure 8: LIG optical fibers after appropriate cutting of excessive lenghts and fixing aluminum tape to reduce fluctuation noise.

As shown in Fig. 9 the result was encouraging. At 1 mHz noise was reduced by a factor of 10. Yet, $1/f$ electronic noise is expected in capacitive readout but not in laser interferometry, hence a value of $\simeq 200\,\text{pm}/\sqrt{\text{Hz}}$ at 1 mHz is not expected to be interferometer noise. It should instead be due to physical disturbances such as temperature effects and microseismicity.

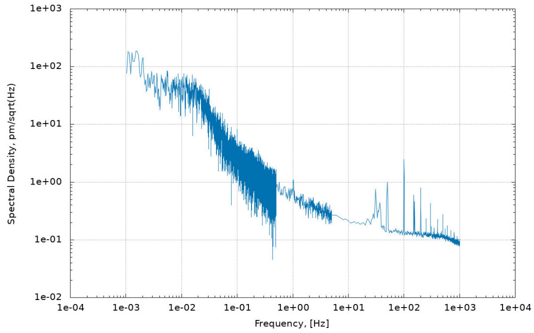


Figure 9: Displacement noise after mitigation of optical fibers' noise

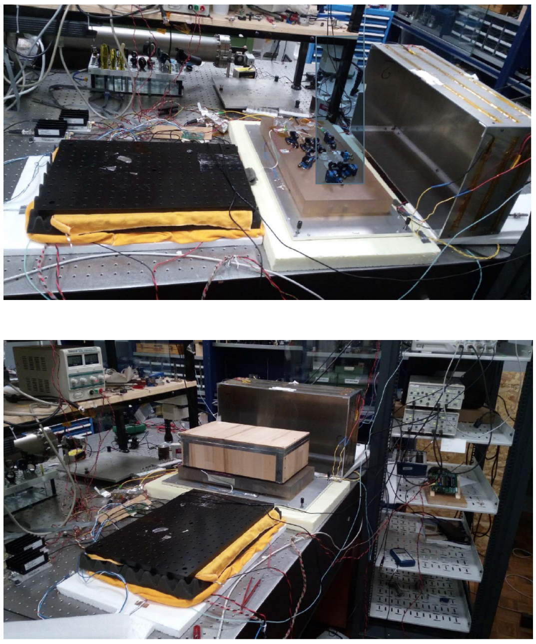


Figure 10: Pictures of the interferometer setup after implementing active thermal control. On the left hand side a black insulating foam covers the steel board to which are attached the optical fibers; it also hides from view the PT100 temperature sensor and the copper wires attached to the steel board included as actuators in the temperature control to loop. On the right hand side the zerodur board is visible with the optical head of the interferometer, covered with the wooden box and next to it the Al box with a PT100 temperature sensor and copper wires that will enclose the wooden box for thermal stabilization of the optical head of the interferometer.

Next step was improving thermal stability at low frequencies (see Fig. 10). Although the insulation and active control applied was rather straightforward, it led to the best displacement noise result reported in Fig. 6 left plot, with $\simeq 100\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ at 0.1 mHz and $\simeq 30\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ at 1 mHz.

In order to further improve on these results at low frequencies it would be necessary to reduce low frequency vibration noise due to local microseismicity and human activity. However, the good quality of our lab at INRIM-Torino in this respect turned out to be sufficient to achieve the goals of the Contract at $1\,g$.

6.2.2 Selection of the test mass and assembly of a LIG-A type acclerometer

Having realized a laser interferometer with very good displacement noise (Fig. 6 left plot) we need to interface it with a test mass sensitive to tiny accelerations in order to obtain an accelerometer to be tested against existing competitors.

In accordance with our strategy outlined in Sec. 5 we chose an ISA-GGG test mass suspended with 4 weak lamellae manufactured from a single piece of aluminum (see Fig. 11, left). The TM is sensitive to accelerations acting perpendicularly to the plate shown, which make the plate perform tiny rotations around the horizontal axis along the lamellae.

For the TM to be read by the LIG interferometer two Corner Cube Reflectors (CCR) are needed, one on the oscillating mass and the other on the frame it is suspended from (that shall be rigid with the spacecraft), to yield the target and reference signal respectively. The locations selected are shown in Fig. 11.

Figure 11: Test mass selected. On the left it is shown stand-alone. Four lamellae suspending the plate from the top are visible. In the picture to the right the same mass is integrated with the base structure –by means of 2 screws at the bottom– and located in between two capacitance plates which serve as pick-up plates, forming a capacitance bridge which allows to detect the displacements of the test mass from its equilibrium position in between them. The gaps between the test mass and each plate are kept at 500 μm by teflon washers. In blue are shown the locations where two corner cube reflectors shall be installed, one to serve as target point on the test mass and one on the base structure (right) to serve as reference point relative to which the displacements of the test mass will be detected by our laser interferometer. The red circle depicts the location on the capacitance plate where a hole shall be made for the laser to reach the corner cube reflector on the test mass. Thus, it will be possible to read the displacements of the test mass, at the same time, by the capacitors and by the laser interferometer.

In order to convincingly demonstrate the superiority of an accelerometer with a mechanically suspended testa mass and a laser interferometry readout we need to make a meaningful and rigorous comparison with a capacitive accelerometer.

The ISA-GGG test mass was very appropriate since it was already equipped with a capacitive readout. However, the comparison required:

i) the ISA-GGG capacitive accelerometer to be calibrated and run in the INRIM lab on the same optical bench of the LIG interferometer in order to establish its noise level in this environment;

ii) the TM of ISA-GGG to be equipped with CCRs and then, together with its capacitors and readout electronics, to be interfaced with the LIG interferometer so that both readouts could be operated at the same time.

The result of the measurement *i*) is shown in Fig. 12, confirming the natural (resonance) frequency of about 5.8 Hz previously observed in Pisa. We performed a similar measurement in a nearby INRIM lab where in the past the ISA-BepiColombo accelerometer had been tested, and the output data were still available. The old and new measurements showed very similar noise levels, thus ensuring that the capacitive accelerometer used for the comparison was reliable.

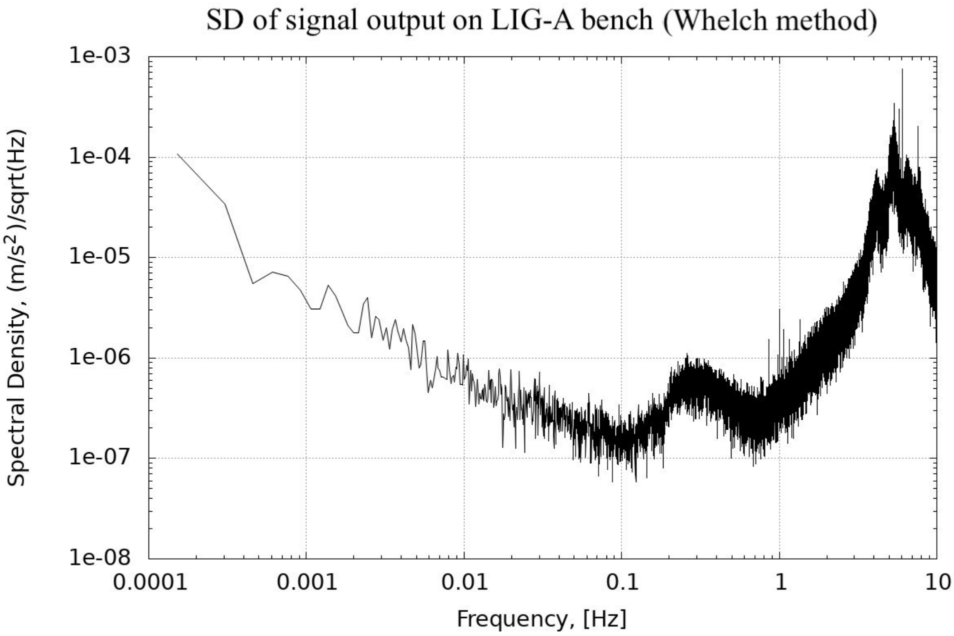


Figure 12: Spectral density of the acceleration measured by the capacitive readout at INRIM on the same optical bench of the LIG interferomter.

The reader may notice that the spectral density of noise reported in Fig. 12 for ISA-GGG is expressed in $\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$. For the laser interferometer we usually refer to displacement noise because it measures displacements directly and does not require calibration. Instead, the capacitive accelerometer is calibrated by applying various known tilts, and (to the extent that the equivalence principle is valid) a tilt is equivalent to a horizontal fraction of the local gravitational acceleration g. The transduction factor from acceleration to displacement is essentially the inverse of the natural angular frequency squared (below the natural frequency the transfer function between the acceleration applied and the displacement observed is 1). From Fig. 12 the spectral density of displacement noise is obtained multiplying the numbers on the ordinate axis by about 10^{-3}.

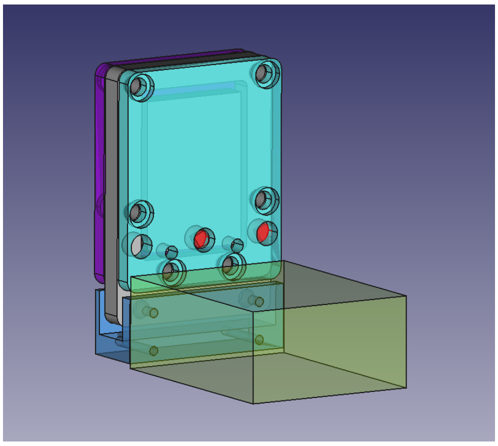


Figure 13: CAD drawings showing the location of the CCRs on the mechanical oscillator, shown as facing a portion of the zerodur board (in green, partially transparent) on which the optics of the LIG interferometer is arranged. The external capacitance plate has been made invisible in order to show the test mass free to oscillate. The central red spot indicates the target CCR located on the test mass (in grey). As the test mass makes tiny oscillations the target CCR moves back and forth along the horizontal direction perpendicular to the test mass (the sensitive axis). The other red spot depicts the reference CCR. It is attached to the fixed frame so that the interferometer can measure their relative displacements along the sensitive axis. On the capacitance plate (in light blue) facing the test mass two holes have been drilled for the laser rays to reach the corner cubes (in red). The position of the corner cube on the frame has changed from the original one shosn in Fig. 11 for practical reasons. A third hole has been drilled on the opposite side of the target CCR for symmetry reasons.

Fig. 14 shows the actual interface of the test mass –including the corner cubes, the capacitors and readout electronics (on the right hand side)– with the LIG interferometer. This completes step *ii*) listed above and the preparation for a comparative measurement.

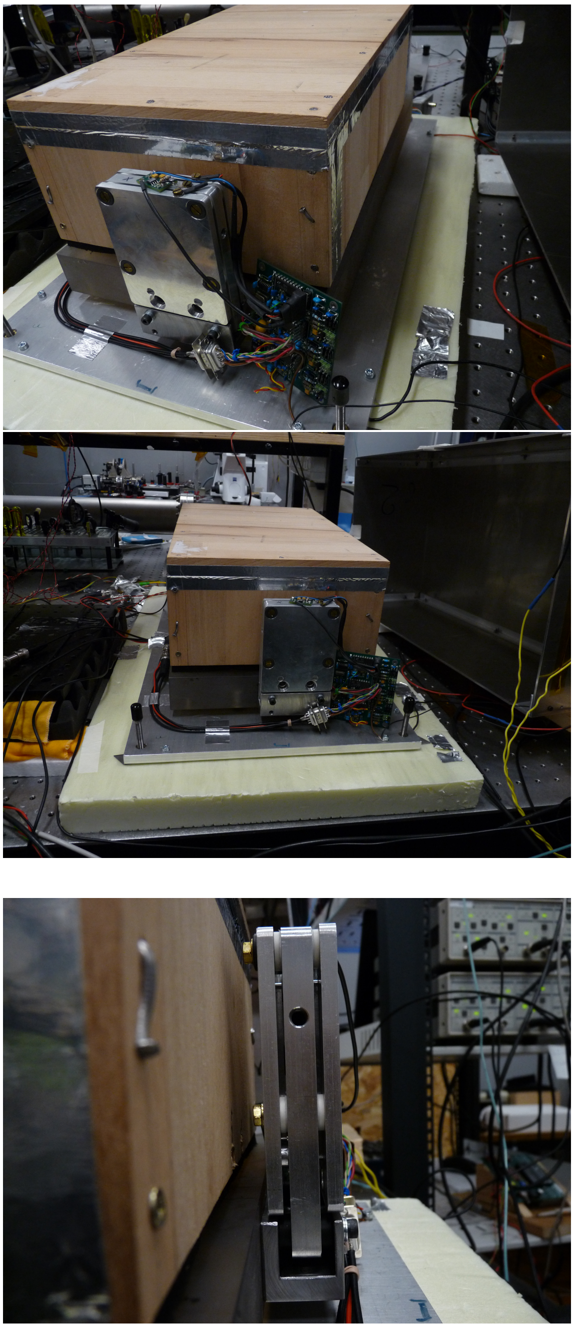


Figure 14: Different views of the wooden box enclosing the optical head of the LIG interferometer. The mechanical oscillator, with its corner cubes, the capacitance plates and the capacitance read-out electronics is shown attached to the zerodur board of the interferometer.

6.2.3 Rigorous comparison of capacitance versus laser interferometry readout, establishing the superiority of the latter

In order to compare the capacitance with the laser interferometry readout it is necessary that in both cases the intrinsic readout noise dominates –although not over the entire frequency spectrum– with respect to external noise sources related to the location and the environment.

In the case of ISA-type capacitive accelerometers external noise is rejected (to some extent) by operating two nominally identical accelerometers next to each other in simultaneity. Being dominated by very similar external disturbances the output noise of the two accelerometers are very close to each other. Thus, the difference of the two is smaller than each of them individually, and the relative contribution of intrinsic readout noise is higher –in some frequency range being the dominant one. The extent of rejection achieved depends mostly on the manufacturing precision of the two accelerometers, which determines to which level they can be regarded as "identical".

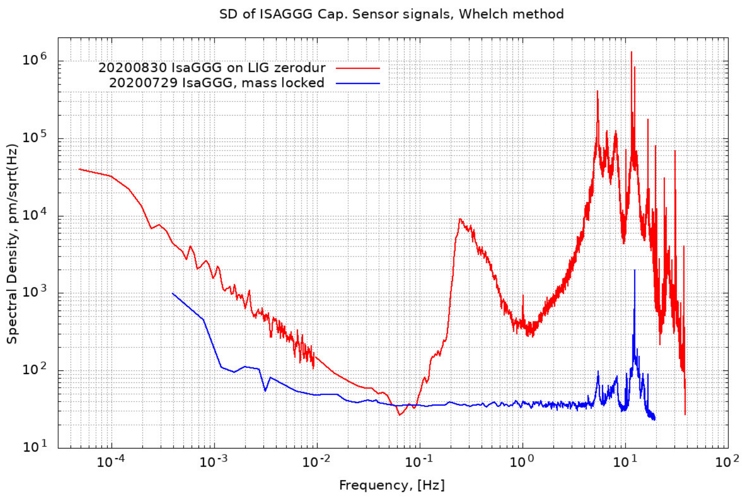


Figure 15: Spectral density of the displacement noise measured by the capacitance sensor when the test mass is free (*red curve*) and when the test mass is gently locked to the frame by means of plastic screws (*blue curve*) (the two runs have been performed at different times). In the blue curve, between 0.01 Hz and 5 Hz noise is almost flat, at a value between 30 and 40 $\mathrm{pm}/\sqrt{\mathrm{Hz}}$; this is most likely the capacitance readout noise

This solution is unpractical in the case of the readout comparison that we are trying to perform. It might also not yield a clear-cut comparison. The level of rejection depends on the respective manufacturing precisions. The residual, lower noise of the capacitive and laser reader after rejection, whose comparison should establish which one is less noisy, might in reality be due to different manufacturing precisions. Thus, it might simply result from different levels of rejection in the capacitive versus the laser reader, and not from a different noise of their respective intrinsic readouts.

For the sake of our comparison a simple way of rejecting external noise is by locking the test mass. Fig. 15 shows the displacement noise measured by the capacitance readout of the ISA-GGG test mass (after interfacing with the LIG interferometer) in two different runs taken at different times: one with the TM free to oscillate and another one with the TM locked to its frame (note that only a gentle lock is possible since it was not included in the original design). Between 0.01 Hz and 5 Hz an almost flat displacement noise of 30 to 40 pm/$\sqrt{\text{Hz}}$ when the mass is locked is likely to be ascribed to the capacitance readout noise.

At this point we could perform the run we were interested in, in which both the capacitive and the laser interferometry readout were operated in simultaneity with the same test mass (gently locked to reject external noise, as shown in Fig. 15 for the capacitive measurement).

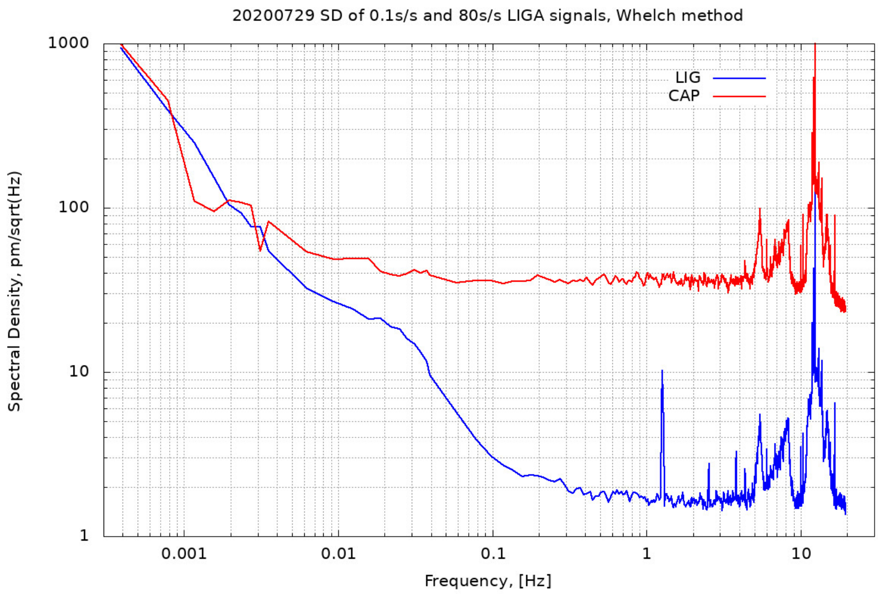


Figure 16: Spectral density of the displacement noise of the test mass as measured by the capacitance readout (*red curve*) and the LIG laser interferometer (*blue curve*). The test mass has been locked by means of plastic screws to the frame in order to reduce the displacements caused by local seismic noise when the test mass is totally free to oscillate.

The result of the comparison (already shown in Fig. 6, right plot) is reported in Fig. 16 and it is worth some comments since to our knowledge no such direct comparison has ever been performed before. The plot shows that above 3 mHz the laser readout noise is smaller than the capacitive one, up to about 40 times smaller. Below 3 mHz there is quite a steep increase of noise and the measured values are similar, suggesting that it is dominated by the same external disturbance, most likely low frequency seismic noise. Since readout noise of the laser interferometer is known not to depend on frequency, while the capacitance electronic noise is reported by scientists in the field to be affected by $1/f$ increase, we can safely conclude that our comparison demonstrates the superior performance of the LIG interferometer.

By comparing the displacement noise of Fig. 16 blue curve, measured by the laser interferometer during the comparison run with that measured by the same LIG interferometer without the test mass (the target and reference mirrors were fixed on the zerodur base) shown in Fig. 6 left plot, we notice that this is lower by a factor 3 at 0.1 Hz to a factor 30 at 1 mHz. The larger values measured during the comparison run may be due to the fact that in this run the test mass was locked but not hard locked, hence it was still somewhat responding to local disturbances. This is confirmed by the fact that both curves in Fig. 16 show a peak in correspondence of the natural frequency of the test mass at about 5.8 Hz. The larger peak at about 12 Hz is a second order resonance of the test mass already observed in the ISA-GGG accelerometer: being gently locked during the comparison run the test mass was still responding at its natural frequencies. This is proved also by the fact that in the resonance region the patterns of the curves referring to the two different readouts are very similar.

While all this is clear, and confirms the validity of the comparison run that establish the superiority of the laser readout, only the origin of the $10\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ peak just above 1 Hz measured by the laser interferometer and not by the capacitors is still unexplained.

6.2.4 Optimization of the test mass for sensitivity in all six degrees of freedom. CubeSat flight demonstration with two degrees of freedom

An ISA type test mass made of a plate suspended by lamellae as shown in Fig. 11 is sensitive only along the axis perpendicular to the plate, thus it is sometimes stated that mechanical suspensions are limited to only 1 degree of freedom while the cubic test mass of a capacitive accelerometer can be sensitive to all 6 degrees of freedom.

However, mechanical suspensions are not limited to lamellae (or wires). A very interesting possibility that we have investigated in the past is to use helical suspensions, whose main advantage is that they can be manufactured with very low stiffness. Absence of weight in orbit allows test masses to be suspended very weakly, but the limitation often comes from manufacturing. In the case of helical suspensions it is possible to play with the various parameters which determine the stiffness (material, thickness of the wire, diameter of each coil, total number of coils) in order to obtain the desired values in all 3 translational axes and all 3 rotation angles.

Helical suspensions can be used to make a cubic test mass sensitive in 6 degrees of freedom. The couplings can be very weak. Each degree of freedom would need a laser interferometer to read the displacements (rotations are inferred from displacements too), just as in the case of a cubic test mass with capacitors when sensitivity in all 6 degrees of freedom is required. The laser interferometer would need to be made more compact.

In the past we have investigated helical suspensions to achieve passive attenuation of vibration noise in space. In that case the quality factor should be low, and the spring can be manufactured from a wire. Instead, now we need high quality factors. This requires an appropriate choice of the material (the best candidate is CuBe) and the spring to be manufactured by electroerosion from a single piece, and appropriate heat treatment. These techniques are well known and the results can be measured.

As discussed in Sec. 6.1, it would be possible to reach the outstanding sensitivity of $\simeq 5\times10^{-13}\,\mathrm{ms^{-2}/\sqrt{Hz}}$ over 1 (low) frequency decade, from 5×10^{-4} to 5×10^{-3} Hz with a natural frequency of the test mass of $\simeq 1.1\times10^{-2}$ Hz, which is feasible with a helical spring and a small mass of the suspended body.

In the meantime, in response to ESA Call for Ideas we have submitted the *LIG-A-CubeSat (Laser Interferometry Gauge Accelerometer on CubeSat)* proposal to fly a LIG-A accelerometer with 2 degrees of freedom (one translational and one rotational) inside a CubeSat to be injected in a low polar orbit in Earth pointing passive attitude.

In this case the natural frequency will be 0.07 Hz, which makes it possible to reach $6\times10^{-12}\,\mathrm{ms^{-2}/\sqrt{Hz}}$ at 1 mHz with the LIG displacement sensitivity of about $30\,\mathrm{pm/\sqrt{Hz}}$, to be achieved with a more compact arrangement than the current one. Aiming at a better acceleration sensitivity would not be reasonable with a satellite not equipped with drag free control because residual air drag and solar radiation effects would exceed readout noise.

The current target relies on a clever choice of the orbit, the attitude of the spacecraft and the orientation of the accelerometer that minimize these disturbances on the accelerometer measurement. It is indeed quite remarkable that a short duration CubeSat mission of low cost and complexity can validate a novel, high sensitive accelerometer.