LIG-A
Laser Interferometry Gauge
&
Accelerometer

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LIG-A (ESA CN 4000125653)
The Goals

LIG-A: The Goals

- Develop a **very low noise Laser Interferometry Gauge (LIG) down to low frequencies** ($\simeq 10^{-4}$ Hz)

- Interface it with a mechanically suspended TM (test mass) **exploiting its stable equilibrium position**

- Use **LIG to read the displacements of the test mass** (⇒ **LIG-A accelerometer**)

- **Setup a direct real time comparison of capacitance versus LIG readout** of the same test mass in the same environment in order to establish beyond question their respective performance

- Once the superiority of LIG is demonstrated, **the stable equilibrium of the test mass makes it possible to eliminate capacitors since they are no longer needed, neither to read nor to control the test mass**

High sensitive accelerometers in space strongly needed

Accelerometers in space needed as crucial components of missions devoted to space geodesy, space exploration and fundamental physics with or without drag-free control. With less challenging performance, also needed as ancillary instruments (e.g. to determine residual noise onboard ISS)

- **Accelerometers for space geodesy, space exploration & fundamental physics:**

  - need to measure: i) **inertial accelerations of TM** (resulting from non gravitational forces on the outer surface of the spacecraft, such as air drag and solar radiation pressure); ii) **local non gravitational accelerations on TM**, e.g thermal effects; iii) **gravitational accelerations at TM location** due to far away and nearby masses **(tidal effects)**, in order to separate them (and drive drag free control if any) to finally recover the purely gravitational motion and the physical quantities which determine it

  Note: the instrument itself cannot tell the physical nature of the acceleration measured (gravitational/inertial vs non-gravitational) ⇒ inappropriate to call it "gravitational (or inertial) sensor" ... it is simply an "accelerometer"

- Accelerations of interest (inertial, gravitational and non gravitational) have **low frequencies**, typical of the physical phenomena which generate them, and are **very small**

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- **Accelerometers with high sensitivity at low frequencies (down to** 10^{-3} Hz - 10^{-4} Hz**) strongly needed**

State of the art unsatisfactory

Capacitance accelerometers by ONERA played a key rôle in CHAMP, GOCE, GRACE, GRACE-FO, MICROSCOPE, and will fly onboard NGGM:

- Electrostatic suspension of TM & capacitance readout $\Rightarrow$ gaps must be very small (a few hundred micron)
- Equilibrium position of TM unstable $\Rightarrow$ capacitance control needed (to prevent TM from hitting the cage); requires very small gaps too
- Electric charges on TM (big effects, very dangerous!!!) discharged by connecting the TM to its cage with a thin gold wire
- $1/f$ low frequency noise of capacitance electronic readout $\Rightarrow$ sensitivity deteriorates at low frequencies

ISA (Italian Spring Accelerometer) flying on BepiColombo:

- Mechanical suspension of TM by means of thin lamellae (ensures also electric discharging)
- Equilibrium position of TM stable $\Rightarrow$ no TM control needed; launch lock and TM release proved not to be a matter of concern
- Capacitance readout $\Rightarrow$ gaps must be very small
- $1/f$ low frequency noise of capacitance electronic readout $\Rightarrow$ sensitivity deteriorates at low frequencies

LPF accelerometer not a solution

LPF has flown two TMs with:

- Electrostatic suspension, no gold wire ($\Rightarrow$ need to carry an active electric discharger)
- Equilibrium position of TM unstable $\Rightarrow$ capacitance control needed during runs & at release in order to reduce initial condition errors (control at orbit injection much harder than predicted, and still an issue for LISA: LPF collaboration, Adv. Space Res. 2021)
- Gaps increased to 4 mm (lower noise, but also lower cap sensitivity and lower control force authority): $\Rightarrow$ cap readout noise at $10^{-9}\mathrm{m}/\sqrt{\mathrm{Hz}}$, not $10^{-12}\mathrm{m}/\sqrt{\mathrm{Hz}}$ precision !!!

PHYSICAL REVIEW D 96, 062004 (2017) LISA Pathfinder Collaboration

Capacitive sensing of test mass motion with nanometer precision over millimeter-wide sensing gaps for space-borne gravitational reference sensors

- ... but LPF could count on a very low noise laser interferometer to drive the drag free control and ensure recovery of almost purely gravitational motion (capacitors mostly used to ensure TM control and avoid the onset of instabilities)

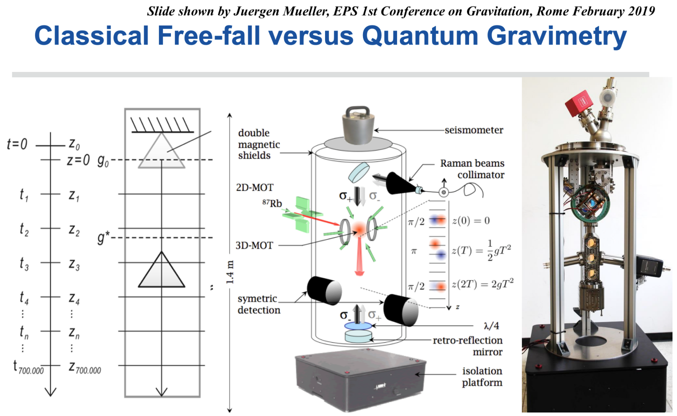
LPF was a high complexity high cost mission flying a hybrid, ad hoc instrument. It cannot be replicated on missions that simply need to carry an accelerometer onboard

Cold atoms not ready to replace bulk masses

- Cold atoms interferometers affected by vibration noise ⇒ build gradiometers instead of accelerometers to reject common mode vibration noise (Phys. Rev. A 65, 033608 (2002))

  ... however, space geodesy missions (e.g. GRACE, GRACE-FO, NGGM) need individual accelerometers, not gradiometers

- Light Pulse atom interferometers can count, by design, on only 3 data points per drop in correspondence of the 3 laser pulses (classical absolute gravimeters have many hundreds) ⇒ acceleration measured is an average value affected by systematic error (Phys. Rev. A 93, 023617 (2016); Phys. Rev. Res. 2, 012036(R) (2020))



... cold atoms do not appear to be ready to replace accelerometers with bulk masses

LIG-A accelerometer strategy

LIG-A strategy (1)

- Major breakthrough behind LIG-A: laser interferometry mature to replace cap readout in space (better performance; not limited by gap size and $1/f$ electronic noise; power & mass budgets already reasonable –demonstrated with our first LIG contract from ESA– and can be further reduced...)

- Not a big deal to interface laser interferometer with a TM in order to read its displacements in response to any acceleration, hence measuring it

- Major issue: the case for laser readout not compelling if capacitors are still needed to apply forces on TM (carrying both laser interferometer and capacitance system increases mass and power budgets, complexity and cost almost to the level of LPF instrument... not a great idea, hardly viable)

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  Why need to apply forces on TM? Only if TM suspended electrostatically (TM is unstable and needs control forces to be stabilized...)

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  No control force needed if TM suspended mechanically: equilibrium position stable (TM oscillates around it in response to any physical acceleration, which is the quantity to be measured)

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  LIG-A novel accelerometer: TM suspended mechanically (suspension very weak in absence of weight, ensures passive electric dischargiung) & LIG readout (no control forces needed, capacitors eliminated...)

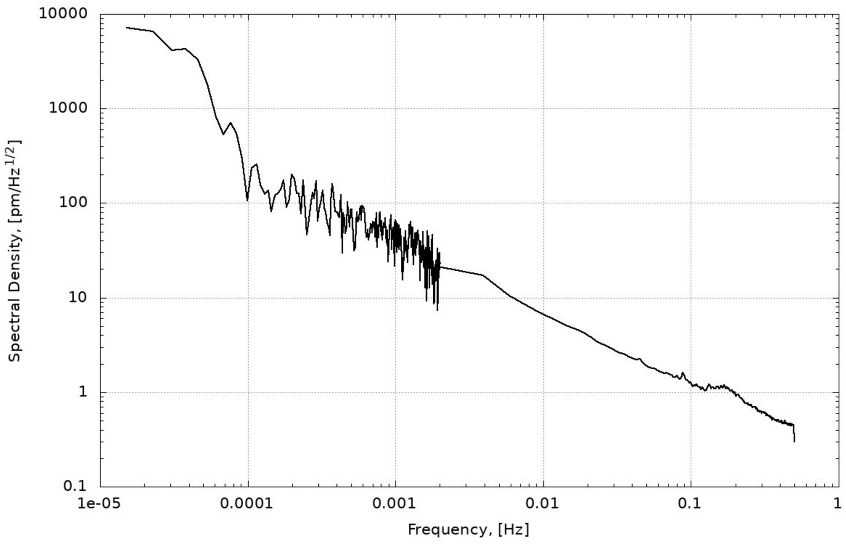
FAQ on Mechanical Suspensions (MS):

- *MS are too stiff*: true on ground, not in orbit (remember absence of weight!!!). In fact, it can be weaker than electrostatic suspension (**Josselin, Touboul & Kielbasa, Sensors & Actuators 78, 92 (1999) - foundation paper on ONERA capacitance accelerometers: .. electrostatic suspension... "*is the dominant stiffness, far greater than the gold wire...*"**).
- *ONERA cubic TM suspended electrostatically has 6 degree of freedom; ISA TM suspended with lamellae has only 1 degree of freedom*: MS with lamellae and TM as a plate is choice of ISA (3 orthogonal TMs in BepiColombo); **helical springs with cubic TM planned for LIG-A (appropriate choice of spring parameters yields similar low stiffness in all 6 degrees of freedom**, as demonstrated in "PGB (Pico Gravity Box), contratto USS 98056" study funded by ASI in 1998-2000)
- *LPF TMs are "free masses", hence less noisy than TMs with gold wire or MS:* LPF TMs not "free"', proof is that if electric voltage is turned off, the experiment ends (same as cutting the MS); gold wire of ONERA accelerometers is a *dummy spring* not optimized to reduce losses and thermal noise (connections with glue at two ends give large losses); **MS of LIG-A TMs to be manufactured by electroerosion from single solid piece of CuBe ensure low losses, high quality factor, low thermal noise** (techniques well known and widely tested on ground; tested by authors in GGG experiment, Pisa); no limitation on gap size further reduces noise from residual pressure.

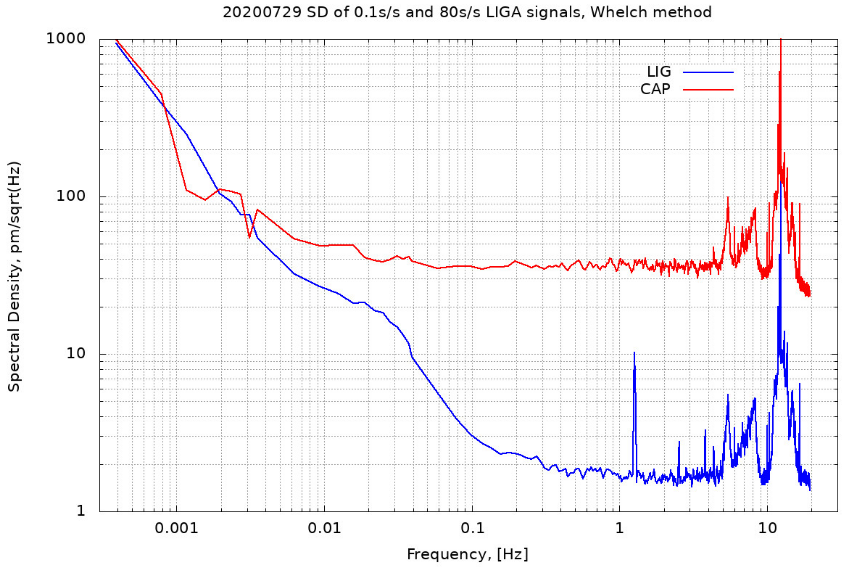
LIG-A results

LIG-A results (1)

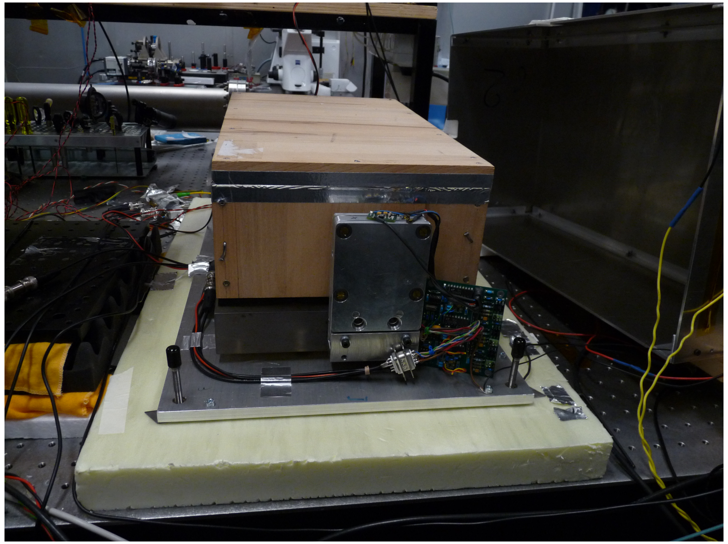
LIG has measured vey low displacement noise $30\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ @ 1mHz; increase @ lower frequencies is not laser interferometer noise.. likely due to local microseismicity



Direct realtime comparison of LIG readout (blue) with cap readout (red), never performed before: same ISA-GGG test mass interfaced with its cap readout electronics also also with LIG readout (via corner cube reflectors). The superior performance of LIG readout is apparent. Low frequency noise dominated by microseismicity



Optical head of LIG inside wooden box on zerodur board interfaced with ISA-GGG test mass (mounted on same board with its capacitance readout plates and electronics visible in the front). The same test mass can be read by both readouts at the same time for a rigorous comparison of their respective performance



Displacement noise translates into acceleration noise through the natural frequency of the test mass: the lower the natural frequency squared, the lower the acceleration noise

ISA-GGG test mass used for ground tests and not optimized yields: $\simeq 4 \times 10^{-8}\,\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$ @ 1mHz and $\simeq 5 \times 10^{-10}\,\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$ @ 1 Hz

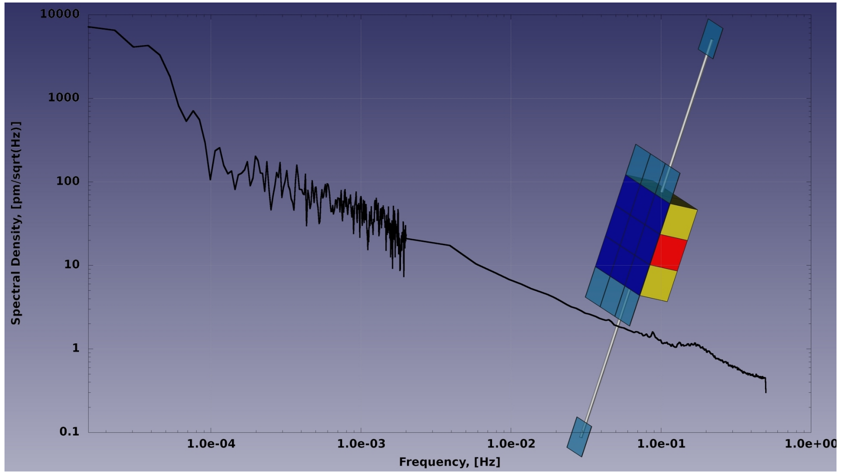
A test mass with 1.1×10^{-2} Hz (feasible with mechanical suspension in space), @ 10^{-4} Hz with measured LIG noise of $100\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ yields $\simeq 5 \times 10^{-13}\,\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$

By comparison: ONERA capacitive accelerometer to fly onboard of each NGGM satellite has a target of $3 \times 10^{-12}\,\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$ @ 1 mHz

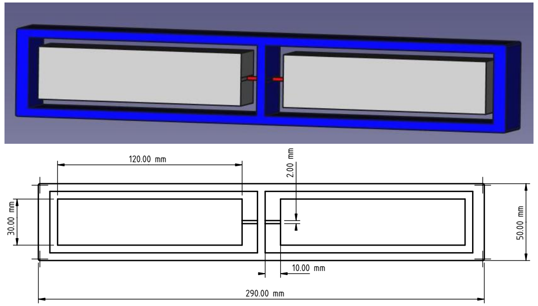
LIG-A-CubeSat in orbit demonstration

(recently approved by ESA for pre Phase A Study)

LIG-A-CubeSat (Laser Interferometry Gauge Accelerometer on CubeSat) proposal to ESA:
LIG-A validation feasible on CubeSat with no dragfree control, passive earth pointing attitude and “right” choice of sensitive axes



TM “butterfly” design sensitive to 1 translational + 1 rotational degree of freedom, fits in 3U



Test mass natural frequency: 0.07 Hz
@ 10^{-3} Hz, with measured LIG noise of $30\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ yields $6 \times 10^{-12}\,\mathrm{ms^{-2}}/\sqrt{\mathrm{Hz}}$

By comparison: ONERA capacitive accelerometer to fly onboard of each NGGM satellite has a target of $3 \times 10^{-12}\,\mathrm{ms^{-2}}/\sqrt{\mathrm{Hz}}$ @ 1 mHz, only a factor 2 better than LIG-A-CubeSat