LIG
Laser Interferometry Gauge

Goal, motivation, achievements & future prospects

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LIG (ITI contract 4000116275/16/NL/MH/GM): The goal

Develop a read-out based on laser interferometry which can effectively replace (with better performance) current capacitance read-out in accelerometers for use in space

- Realize a laser gauge with displacement noise of $10\,\frac{\mathrm{pm}}{\sqrt{\mathrm{Hz}}}$ at $1\,\mathrm{Hz}$
- Provide a compact breadboard of the laser gauge
- Discuss prospects for:
  (i) achieving displacement noise of $1\,\frac{\mathrm{pm}}{\sqrt{\mathrm{Hz}}}$ at $1\,\mathrm{Hz}$
  (ii) noise reduction at low frequencies: $1\,\mathrm{mHz} \leqslant \nu \leqslant 1\,\mathrm{Hz}$

LIG: the motivation

Accelerometers are needed onboard of s/c since the birth of space age

- **Accelerometer:** test mass weakly coupled to its cage (cage inside spacecraft and rigid with it) plus **device to read relative displacements** caused by:

  - all forces acting on the s/c and NOT on test mass (drag & solar radiation pressure)
  - **local non gravitational accelerations** originated inside the spacecraft acting on TM only

  The physical quantity to be measured are displacements

  Measured displacements plus physical properties of test mass/spacecraft coupling (i.e. transfer function)
  $\Rightarrow$ *accelerations acting on test mass*

- **Space geodesy, space exploration, fundamental physics**

  - need to measure **inertial accelerations** (resulting from non gravitational forces on spacecraft outer surface and not on TM) & **local non gravitational accelerations** to separate them out and thus recover purely gravitational motion and the physical quantities which determine it

  -need to measure **gravitational accelerations** directly

Accelerometers and drag free control

- **PROVIDED THAT local non gravitational accelerations on the test mass are smaller than inertial ones (and/or modelled to that extent)**
  $\Downarrow$
  the accelerometer displacement reading provides the inertial acceleration
  $\Downarrow$
  which serves as input to drive the spacecraft (in a closed loop with thrusters as actuators, & sufficient propellant) so that it follows the test mass as if unaffected by non gravitational forces (yielding nominally "pure" gravitational motion)
- *Only under this condition the accelerometer is an <u>inertial sensor</u> and can be used for drag free control*
- *Any local non gravitational acceleration (e.g. radiometer effect due to combination of residual pressure and thermal gradient) which were misinterpreted as an inertial acceleration resulting from a non gravitational effect on the s/c outer surface, would result in a positive feedback thus impairing drag free control*

- Accelerations of interest (gravitational and non gravitational) have **low frequencies**, typical of the physical phenomena which generate them
- Accelerations of interest (gravitational and non gravitational) are **very small** $\Downarrow$
- **Electric charge effects** (charging due to cosmic rays, patches of electric charge on conductors...) much bigger: major issue to be taken care of

- **Spacecraft sonic/vibration noise typically at very high frequencies:**

  - can be of practical relevance but does not compete with gravitational and non gravitational effects of interest

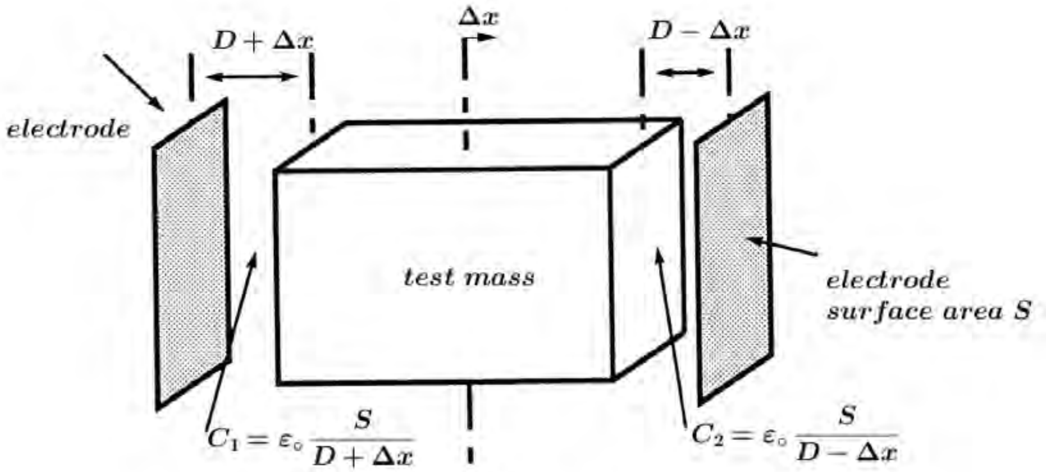
  - requires the test mass of the accelerometer to be coupled to the s/c with very high resonance frequency $\omega_\circ$ (kHz) to detect accelerations with $\omega < \omega_\circ$

  - displacement sensitivity $\Delta x \propto \frac{1}{\omega_\circ^2}$ $\Rightarrow$ very small displacements expected

  - requires readout with very low noise at very high frequency

... not addressed within LIG

Capacitance displacement sensors and readout:
the limitations



$$C_2 - C_1 = 2\varepsilon_\circ S \frac{\Delta x}{D^2 - \Delta x^2} \simeq 2\varepsilon_\circ S \frac{\Delta x}{D^2}$$

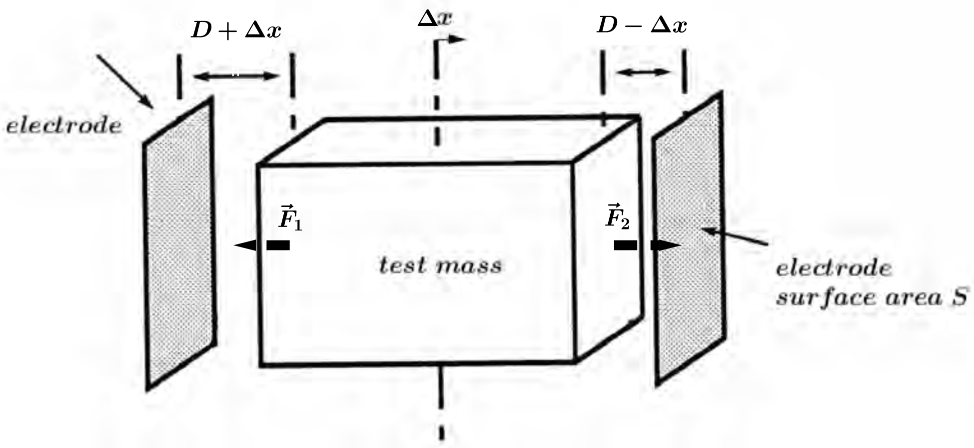
$$\frac{\Delta C}{2C} \simeq \frac{\Delta x}{D}$$

- capacitance $\propto \frac{1}{D}$
  $\Downarrow$
  limited to displacements over small gap D
  (a few mm is already too much..)

  very small gaps are mandatory for good sensitivity (a few hundred μm only)
  $\Downarrow$
  other limitations become dominant if gaps are very small
  (electric effects from patches of charge even if TM is electrically grounded, gas damping noise..)

- calibration is needed (Volt $\rightarrow$ displacement)
  Its stability must be checked and maintained

- cap sensor=analog sensor
  needs very high SNR
  $0 - 1\,$cm motion; $0 - 1\,$V
  $1\,$pm $\Rightarrow$ $100\,$pV
  $1\,$pm $\Rightarrow$ 10^{10} SNR



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

- ONERA (*Josselin et al., 1999*):
  "the central position in the electrostatic cage is an unstable equilibrium, a *potential top*"
  The negative electrostatic spring "is the dominant stiffness, far greater than the gold wire.." ($|k_{electrostatic}| \propto \frac{1}{D^3}$)
- TM offcentered by construction: the detection voltage itself exerts a DC force bias (back-action); it fluctuates ⇒, noise at all frequencies...
- TM discharging: loose gold wire (*dummy spring*), does not cure charge patch effects which are larger for small gaps ($\propto \frac{1}{D^2}$)
- Cap readout natural choice since caps are needed anyway to correct offcenter and for TM stabilization

PRL 116, 231101 (2016) PHYSICAL REVI

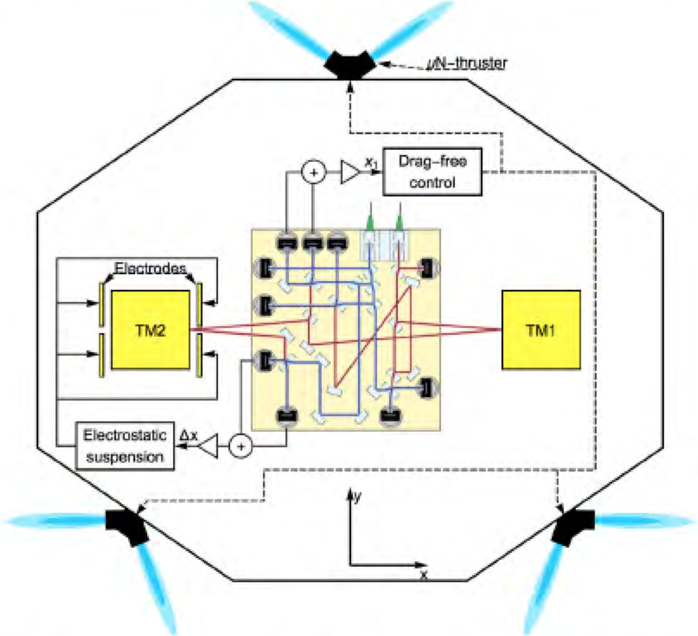
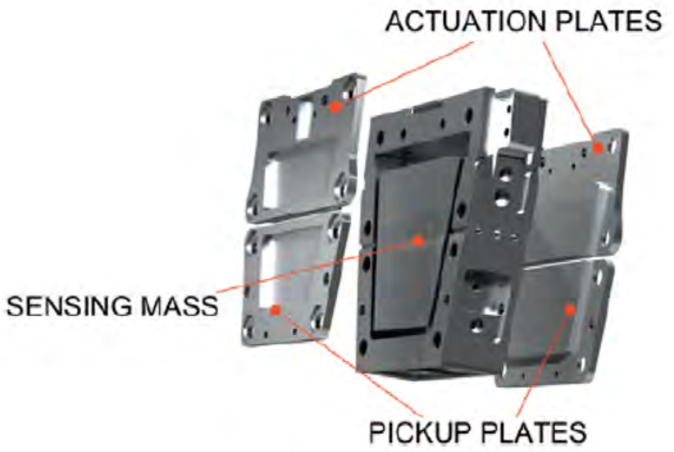
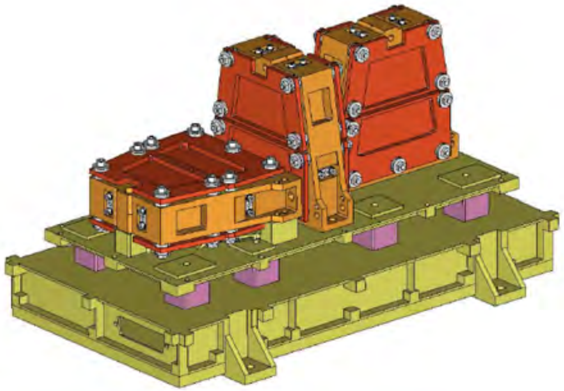


FIG. 2. A schematic of LPF. The figure shows TM1, TM2, and the optical bench beam paths for measuring Δx and x_1. The measurement of Δx drives the electrostatic suspension of TM2, which applies the necessary electrostatic forces by means of the electrodes represented by the four gold plates facing TM2. All other electrodes surrounding the TMs are not shown. The measurement of x_1 drives the drag-free control loop that uses the micronewton thrusters to exert forces on the spacecraft. The figure depicts the x and y axes we use in this Letter, while z is normal to the figure.

- **LISA-PF accelerometer**: similar electrostatic suspension setup but 4 mm gap (instead of 300 to 600 μm) and no gold wire
- Cap readout (low sensitivity, mostly used for TM control)
- Active UV discharging of TMS (as in GP-B mission of NASA)
- ... plus laser interferometry readout (high sensitivity) drives drag free control loop;
  another laser interferometer reads relative displacements of 2 TMs (38 cm apart) and drives electrostatic capacitors control of TM2 to follow TM1

ISA (Italian Spring Accelerometer) to fly on BepiColombo





- Test mass suspended with low stiffness high quality mechanical flexures (manufactured by electroerosion from single piece): **mechanical oscillator with positive spring constant** (stable.. & exploits zero-g)
- Passive electric discharging of TM for free...
- Capacitance readout
- Actuation capacitors:
  a) can lower the stiffness (by exploiting the negative electrostatic spring... more useful at 1-g..) ;
  b) can apply known signals to the oscillator for checking and calibration purposes;
  c) can bring the capacitance bridge to its zero (equilibrium)

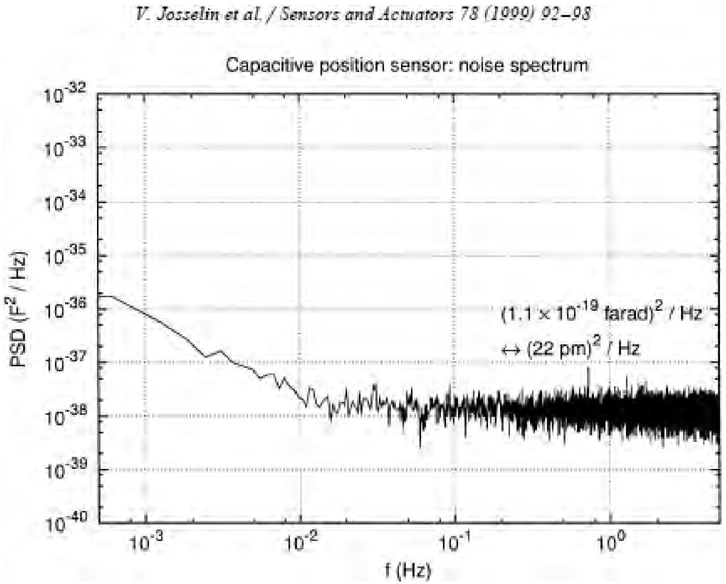
- **... if laser interferometry readout is used all capacitors can be eliminated because the oscillator is stable...**

Heterodyne laser interferometry for accelerometers in space:
the advantages

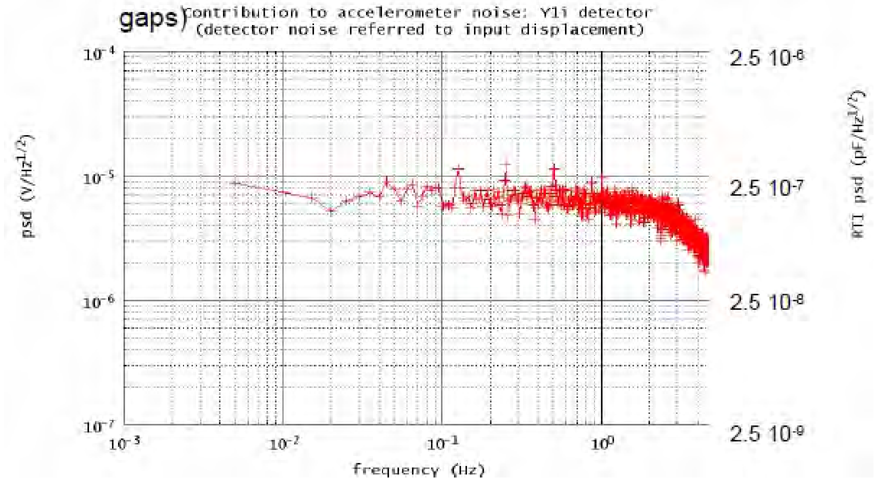
- laser interferometry $\propto D \quad \Rightarrow$ **no limitation from size of gap** ...
- laser interferometry sensor is
  partly digital (for motions $> \lambda$ it counts fringes)
  partly analog (for motions $< \lambda$)
  $0 - 1\,\mathrm{cm}$ and $\lambda = 1\,\mu\mathrm{m}$
  $1\,\mathrm{pm} \Rightarrow 10^6$ SNR (10^4 times lower than cap sensor)
- **calibration not needed:** λ very accurately measured & directly traceable to SI *meter* unit:
- heterodyne interferometer: signal is AC, measures phase difference (or time delay) and **the displacement signal is easily digitized to a very small fraction of λ, with $\lambda \simeq 1\,\mu\mathrm{m}$**

... the most direct and natural way of measuring a displacement.
Is now mature enough for cost effective use in space

Capacitance readout: state of the art



1 V ~ 0.025pF ~ 6 μm (with 600μm elect/mass gaps)



ONERA in 1999:

Noise is $22\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ **flat down to** $10^{-2}\,\mathrm{Hz}$.

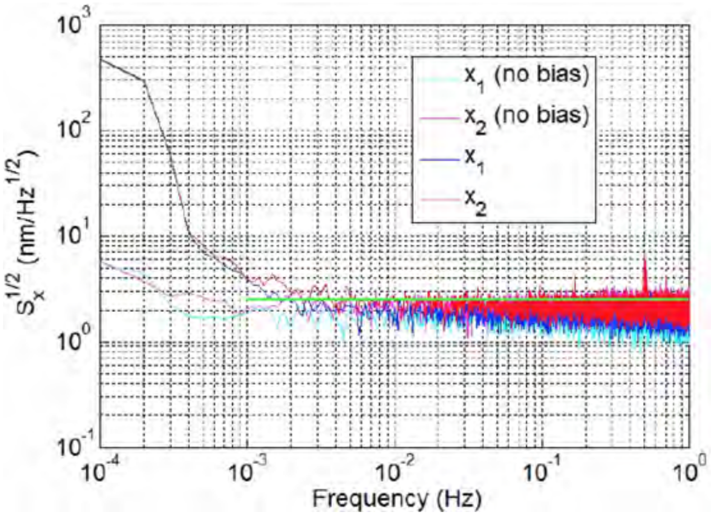
Noise increase $\lesssim 10^{-2}\,\mathrm{Hz}$ **attributed to low-frequency amplifier and still a limitation to-date**

ONERA, Microscope accelerometer noise before launch:

From calibration the $10^{-5}\,\mathrm{V}/\sqrt{\mathrm{Hz}}$ line corresponds to $60\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$.

Noise is at 30 **to** $40\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$**.**

Starts increasing below $10^{-2}\,\mathrm{Hz}$; not reported below $5 \cdot 10^{-3}\,\mathrm{Hz}$ (Rodrigues, talk at Les Houches 2009)



LISA-PF capacitance readout noise as reported in 2010 at the 8th LISA Symposium

PRL **116,** 051104 (2016) PHYSICAL REV

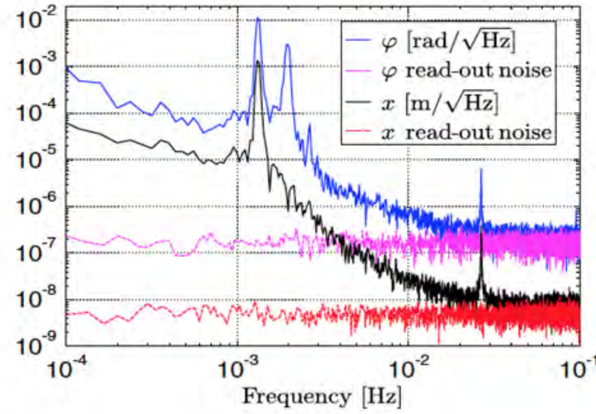


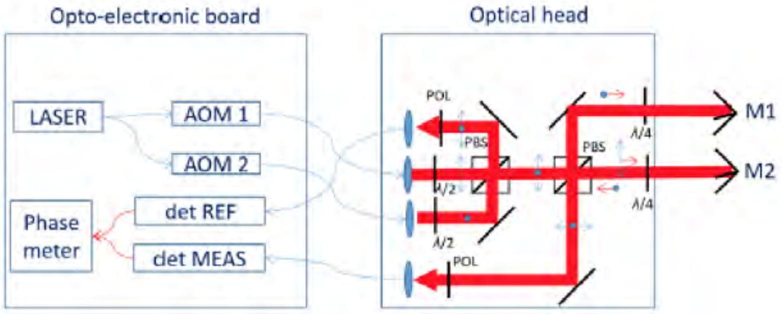
FIG. 2. Amplitude spectral density of the translational (x, black) and rotational (φ, blue) DOFs of the double pendulum. The useful "free-fall" band extends above the resonances (1.3 and 2.0 mHz) till 30 mHz, where read-out noise becomes dominant in both spectra. The peak near 25 mHz results from the beats of a swinging doublet mode (see Ref. [14]).

LISA-PF capacitance readout noise as measured with double pendulum in 2016 (red curve)

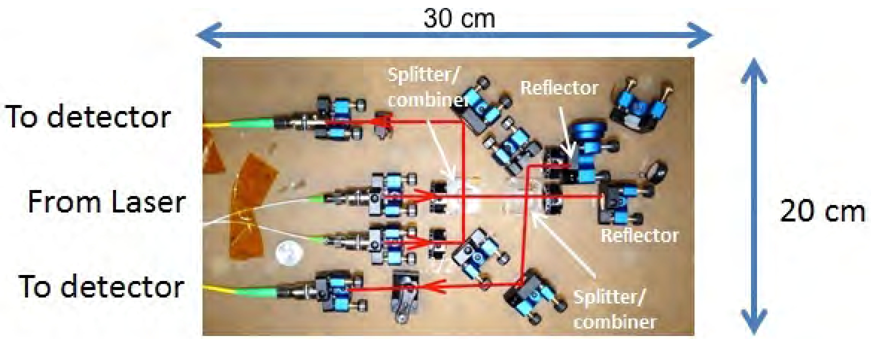
Noise is at $\frac{\mathrm{nm}}{\sqrt{\mathrm{Hz}}}$ *level; noise increase at low frequency buried underneath*

LIG heterodyne interferometer

LIG heterodyne interferometer setup

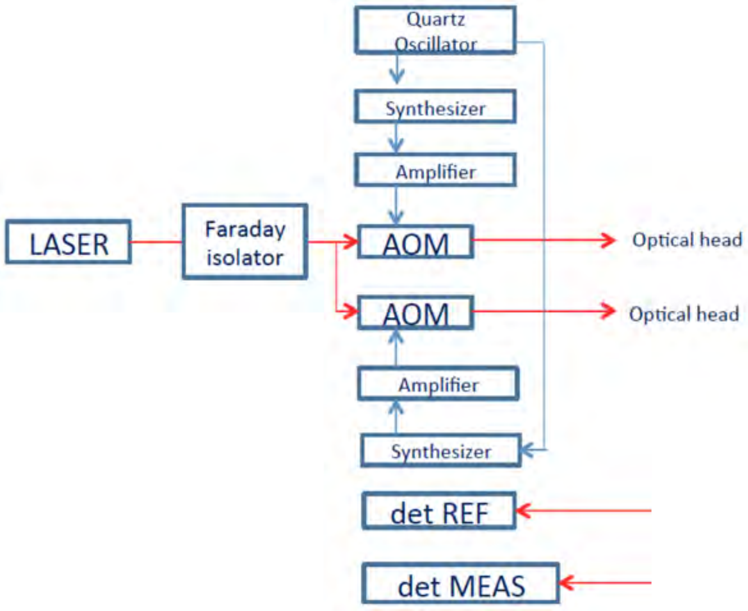


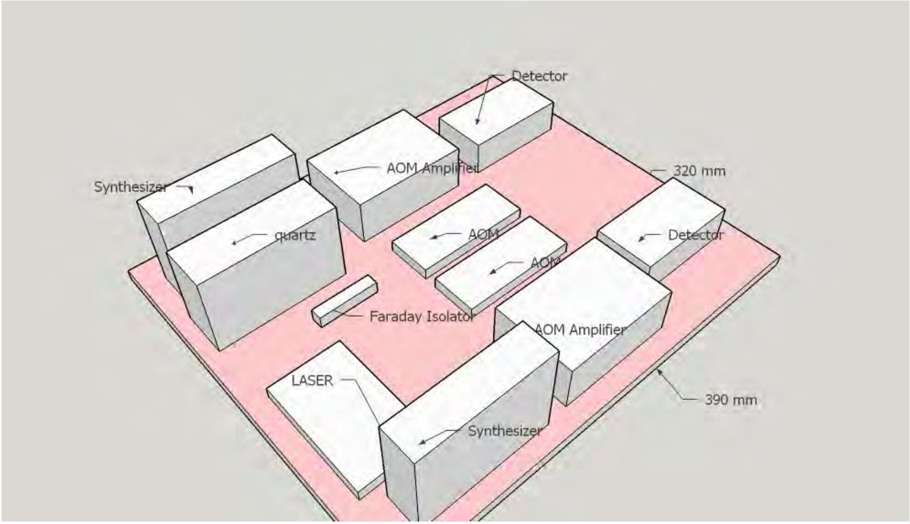
Optical head on zerodur board



- ORION RIO (PM) laser $\lambda = 1064\,\mathrm{nm}$; $11\,\mathrm{mW}$ available, $1\,\mathrm{mW}$ used
- AOMs $80\,\mathrm{MHz}$ and $80.1\,\mathrm{MHz}$, heterodyne frequency $\nu_{het} = 100\,\mathrm{kHz}$
- Free-running laser (no frequency stabilization)
- Measurement in air; optical head inside box with foam to prevent turbolence

LIG setup: the opto-electronic board

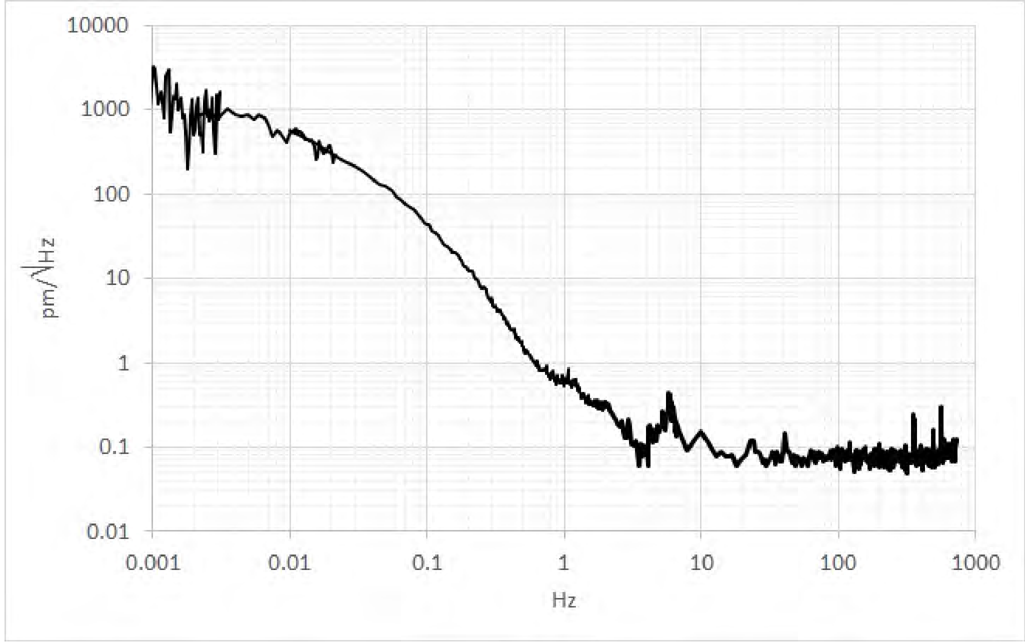




- Total mass: 2.35 kg
- Dimensions: 39 cm × 32 cm

Spectral density of LIG measured displacement noise

Measured displacement noise

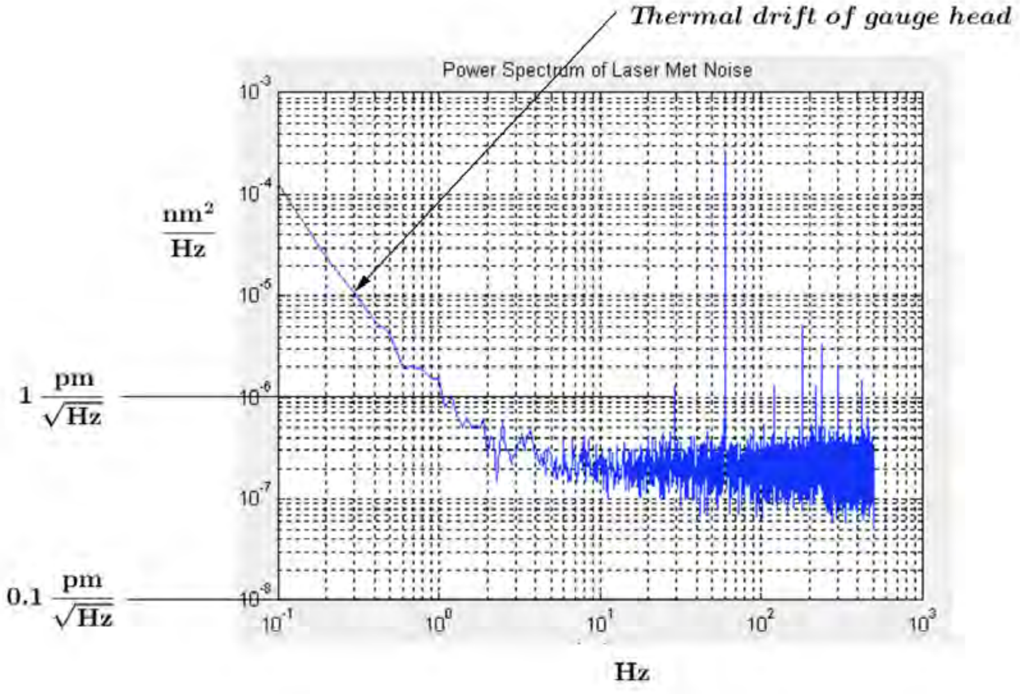


- **At** $1\,\mathrm{Hz}$ **noise measured** $0.6\frac{\mathrm{pm}}{\sqrt{\mathrm{Hz}}}$**: lower than LIG target of** $10\frac{\mathrm{pm}}{\sqrt{\mathrm{Hz}}}$ **by more than 1 order of magnitude**
- At high frequencies noise measured: $0.1\frac{\mathrm{pm}}{\sqrt{\mathrm{Hz}}}$ limited by electronics noise (ADC converter and digital demodulation); not yet interferometer noise
- At $\nu \leqslant 1\,\mathrm{Hz}$ analysis shows that noise is not due to air, neither to thermo-mechanical deformations nor to local terrain noise. Optical fibers appear to be the culprit and are under investigation for LIG follow-up

Comparison with other heterodyne interferometers

SIM laser gauge noise in the early 2000s (Mike Shao, JPL)

Heterodyne laser gauge (based on spatial separation) $\lambda = 1064\,\mathrm{nm}$ developed at JPL for SIM mission



- $\nu \geqslant 1\,\mathrm{Hz}$ noise behaviour very similar to LIG (but larger)
- $\nu < 1\,\mathrm{Hz}$ real thermal drift measured (not due to interferometer noise)

LISA-PF laser gauge noise: on ground

Class. Quantum Grav. **28** (2011) 094002 F Antonucci *et al*

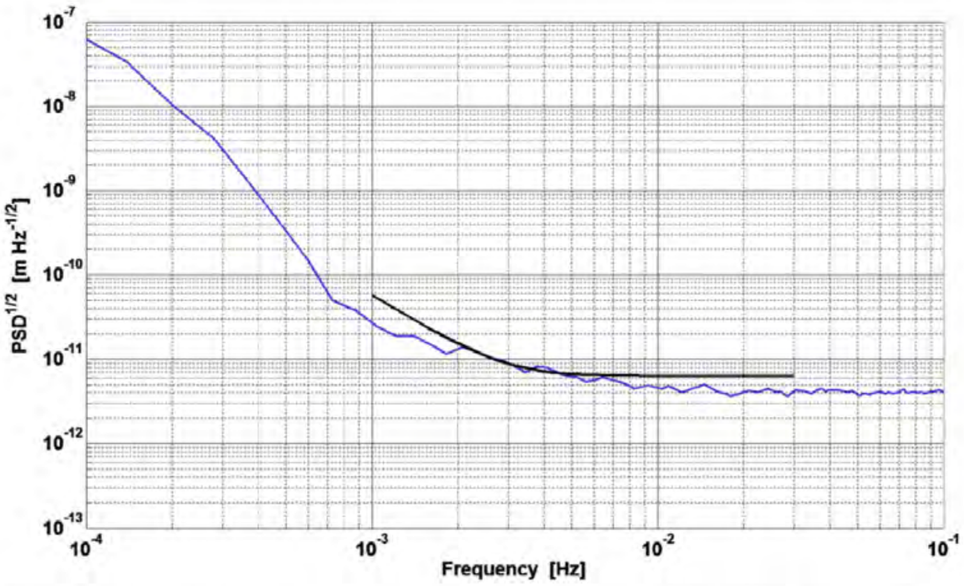
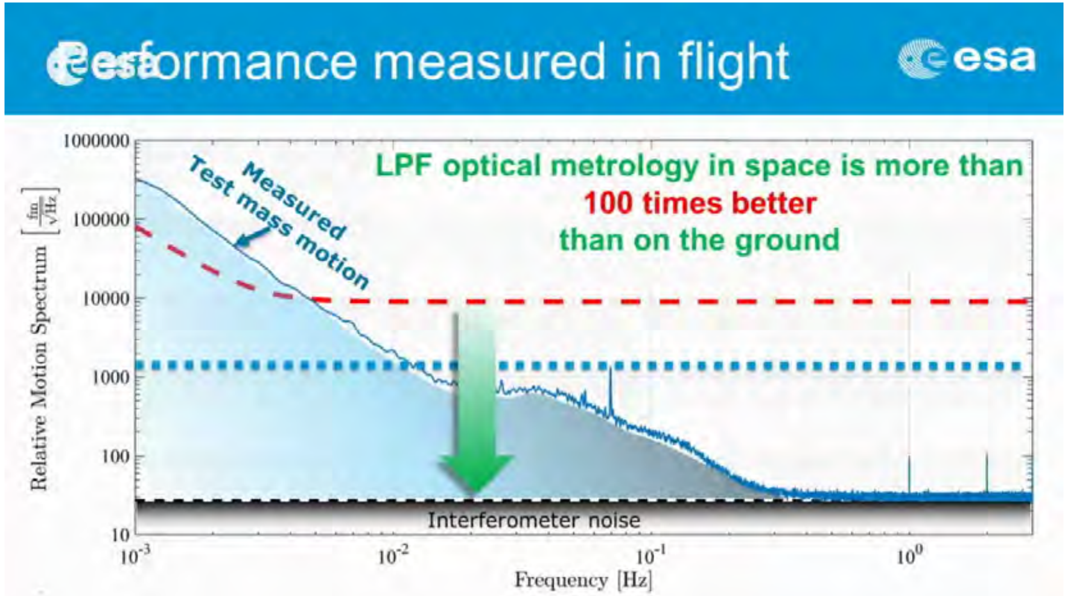


Figure 2. Square root of the PSD of the output of the x_{12} interferometer within the flight model of the entire chain of the optical metrology. Only the optical bench is replaced by an engineering model. Noisy long line: experimental data. Shorter smooth line: requirements. The increase below about 0.7 mHz is attributed to the laboratory environment.

- $\nu \geqslant 0.008\,\mathrm{Hz}$: $4\frac{\mathrm{pm}}{\sqrt{\mathrm{Hz}}}$ measured in the lab

LISA-PF laser gauge noise: in space



- Plot shown by Martin Hewitson during ESA press conference on 7 June 2016.
  Lowest interferometer noise measured in space is about 100 times lower than on ground: $0.03\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ (3.3 times better than lowest LIG noise).
  At 1 Hz: $30\,\mathrm{fm}/\sqrt{\mathrm{Hz}}$ (20 times better than LIG)
  Close to 1 mHz the noise currently reported with LIG is $1\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$, only 3.3 times larger than reported here as measured by LISA-PF in space. Unlike in LIG, where it is a spurious effect due to the optical fibers, here it is reported as a physical effect which must be subtracted
- **Spacecraft noise much lower than ground noise: LISA-PF dominated by solar radiation pressure ⇒ favourable to measurement of small effects (spacecraft at about 600-700 km altitude: residual drag only a few times larger than solar radiation pressure, hence also much less noisy than ground labs)**

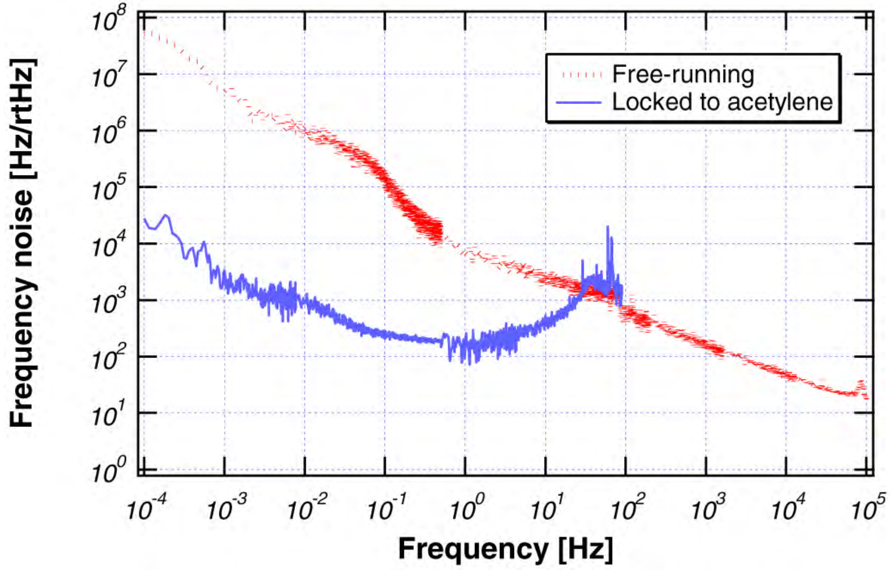
Laser interferometers designed for kHz and above

Gerberding et al., Metrologia 2015

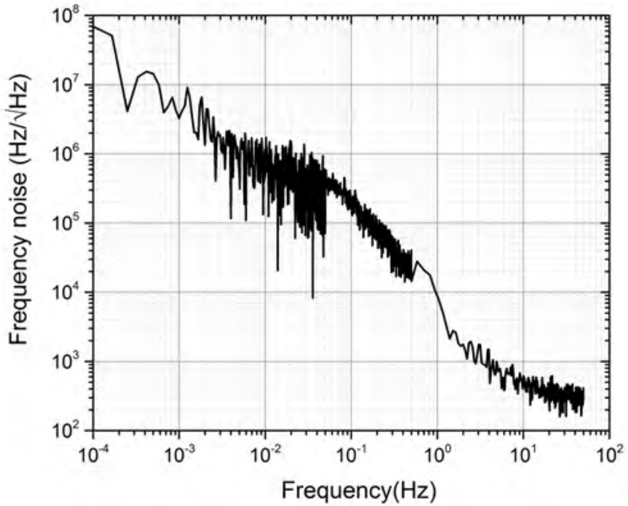
- Laser interferometers based on low finesse Fabry-Perot cavities with very small gap ($50\,\mu$m) to be coupled with oscillators with very high resonant frequency ($> 10\,$kHz)
  Suitable to measure very high frequency disturbing effects.
  Not suitable to measure effects at frequencies $1\,\mathrm{mHz} \leqslant \nu \leqslant 1\,\mathrm{Hz}$ (and even lower) of wide interest in space and addressed by LIG.
- At 1 Hz noise reported: $2\frac{\mathrm{pm}}{\sqrt{\mathrm{Hz}}}$

Frequency noise and laser frequency stabilization

Laser frequency noise



- *Numata et al., 2010*: reduction of laser frequency noise by frequency stabilization ($\lambda = 1542\,\mathrm{nm}$)



- *Pisani et al., 2016*: measured frequency noise of free running (not stabilized) laser ($\lambda = 1542\,\mathrm{nm}$)
  Same as Numata's frequency noise (free running, red curve)
  Absolute frequency measured with optical frequency comb at INRIM, directly traceable to SI second
- **No laser frequency stabilization needed for LIG (free running laser ok)**

Conclusions and prospects for the future

- Displacement noise at 1 Hz smaller than target by more than 1 order of magnitude
- Compact breadboard ready
- Prospects:
  - How to reach $1\,\frac{\mathrm{pm}}{\sqrt{\mathrm{Hz}}}$ at 1 Hz: we have measured $0.6\,\frac{\mathrm{pm}}{\sqrt{\mathrm{Hz}}}$
  - Reduce current noise at $1\,\mathrm{mHz} \leqslant \nu < 1\,\mathrm{Hz}$

  Current investigation shows that it is due to optical fibers and there are ways to reduce it.

LIG-A project: Laser Interferometry Gauge & Accelerometer

- Assemble LIG with ISA-type oscillator
- Produce breadboard of 1-axis accelerometer with laser gauge and no capacitors
- Preliminary goal: $5 \cdot 10^{-8} \frac{\mathrm{ms}^{-2}}{\sqrt{\mathrm{Hz}}}$ at $10^{-3}\,\mathrm{Hz}$ to $5 \cdot 10^{-10} \frac{\mathrm{ms}^{-2}}{\sqrt{\mathrm{Hz}}}$ at $1\,\mathrm{Hz}$. Limited by stiffness (natural frequency), low values needed to improve sensitivity: at 1-g not easy to realize and test an oscillator with low natural frequency
- Design a variant LIG-A which can reach $\simeq 5 \cdot 10^{-13} \frac{\mathrm{ms}^{-2}}{\sqrt{\mathrm{Hz}}}$ between $5 \cdot 10^{-4}\,\mathrm{Hz}$ and $5 \cdot 10^{-3}\,\mathrm{Hz}$

  .... remember that low stiffness / low natural frequency are easy to realize at zero-g!!