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An optical readout system for the drag free control of the LISA spacecraft

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ABSTRACT

LISA is an ESA–NASA joint project for the realization of a space interferometric gravitational wave (GW) antenna. LISA is designed for the measurement of GWs in a very low frequency band (0.1–100 mHz). The antenna is composed by three spacecraft (SC) in suitable heliocentric orbits placed at the corners of a huge equilateral triangle, each side being 5 million km long. The SCs are linked by lasers, forming a sort of optical transponder. By means of phase locking techniques, any round-trip phase delay change gives a measurement of a change in the SC distance (measured as light transit time), due to incoming GWs. An essential requirement is that the SCs are set as close as possible to pure geodetic motion, in the measurement frequency band. This is hardly fulfilled because the SCs are disturbed by several external forces, like solar radiation pressure, cosmic rays etc. In each SC there are two free falling proof masses (PM) that are as much isolated as possible by all external force but gravity. The relative position between each PM and the SC is measured, in six degrees of freedom, by the so-called inertial sensor (IS). The IS signal is then used for drag-free servo-loops that force the SC to follow the geodetic motion of the PMs. The current solution for the IS is the adoption of capacitive sensing. This gives a reliable device but poses several limitations due to back action and cross couplings. In this work, we present an optical lever sensor as an alternative solution. In particular we analyze the potential sensitivity and discuss the advantages in terms of relaxed specifications for the drag free control loops. We also report on bench-top measurements that confirm the performance in the required frequency band.

1. Introduction

The experimental search for gravitational waves started more than 40 years ago. Despite long years of technical developments and the adoption of two different detection techniques (resonant bar detectors, ground based interferometer), both arrived at the design sensitivity [1–3], there is still no direct detection of gravitational waves. The main problem for ground based detectors is the expected small signal to noise ratio (S/N) that, for a wide class of sources (gravitational collapse, coalescing binaries and pulsars) implies a rather low expected event rate. The result is that up to now ground based detectors only allowed to put upper limits for the GW amplitude and event rates in our galaxy and in the Virgo cluster. Next generation ground based interferometric detectors (Advanced LIGO, Advanced Virgo, LCGT etc. [4–6]) are expected to improve their sensitivity, with respect to the present one, up to a factor of 10 in almost all the measurement frequency band (10–10,000 Hz) increasing both the S/N ratio and the horizon and promising an event rate that should allow several detections per year. This exciting scenario is advised on a time scale of about 5 years, but its realization requires a lot of challenging improvements in crucial technologies, like mirror material and coatings, monolithic suspensions and high power laser sources, that still need full experimental demonstration.

Quite different is the expectation for the LISA (Laser Interferometer Space Antenna) project [7]. In this case, we are interested in the very low frequency band (0.1–100 mHz) and we expect plenty of both galactic and extragalactic coalescing sources with S/N up to 100 or 1000 and rate of several events/year. In the mean time we expect a lot of continuous sources (galactic binaries) detectable with very high S/N while the ones with small S/N are so numerous that give rise to a GW background noise. For a complete analysis of LISA science goal see [9].

LISA is a joint ESA–NASA project for the construction of a 5 million km long space interferometric GW detector. The LISA first concept goes back to the 90s. The project is now in the formulation phase and the general concept is well established. The launch is expected around 2020, with data taking starting about one year later, when the SCs reach their final heliocentric orbits. The antenna is formed by a huge equilateral triangle with three spacecraft,

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connected each other by laser beams, at the corners. Each spacecraft sends two laser beams to the other two and receives the light coming from them. By phase locking of the incoming light to a local laser oscillator, it is possible to measure the phase delay due to the round-trip travel time of the light. An incoming GW would change this phase delay and could be recovered by using a dedicated data processing called Time Delay Interferometry (TDI) [9–11] that allows keeping the GW signal while canceling some technical noise like laser frequency noise. The main advantage of a space GW detector is the possibility to have very long arm (5 million km for LISA) increasing correspondingly the effect of the GW strain. On the other hand, the long arm length limits the measurement band to low frequency (GW periods not much shorter than the light round trip time). Another advantage is the possibility to put the antenna test masses in pure free fall. The main drawback is that only a small fraction of the laser beam emitted by one of the SC can be collected by the telescope placed on another one so that it is not possible to reflect it back (like in ground-based interferometers) and the whole antenna must be operated as an optical transponder. Furthermore, due to the small amount of light, the shot noise limited displacement sensitivity ($\sim 4 \cdot 10^{-11}$ m/Hz$^{1/2}$) is orders of magnitude worse than the one of ground based detectors. A detailed description of LISA can be found in Refs. [7,12]; the actual design is defined by the trade-off among technical requirements and scientific goals. The result is a detector that allows searching GW from some interesting sources, like massive and super-massive black-hole merger, everywhere in the observable universe with S/N up to 1000. Other interesting sources are extreme mass ratio mergers, galactic neutron star/black-hole merger and galactic binary stars, observable with S/N between 10 and 100. These exciting numbers, promise for sure, in case of mission success, the detection of GW signals and plenty of accurate measurements, that will allow precise testing of General Relativity predictions in the ultra-relativistic case and the real beginning of GW astronomy. This scenario relies on the assumption that LISA can reach a sensitivity limited in high frequency (above 3 mHz) by laser shot noise (about $4 \cdot 10^{-11}$ m/Hz$^{1/2}$), and at lower frequencies by spurious acceleration noise (with a $1/f^2$ spectrum). To reach these specifications, it is crucial to maintain the LISA TM in pure free fall. One of the main effects that could force the TM to leave the geodetic motion is solar radiation pressure. Actually, the TM is surrounded by the SC that shields it from solar light, but the SC itself, because of radiation pressure, and other effects, would leave the geodetic motion and soon hit the test mass. This problem is solved by a drag free control loop. A suitable position sensor measures the relative position of SC and TM and, acting with micro thrusters on the SC, forces it to follow the TM motion.

2. The scientific case

As indicated in the previous section, the LISA drag free control loops, are a key element for the success of the mission The corresponding Drag Free and Attitude Control System (DFACS) is rather complex [7]. For each interferometer arm, the position of the spacecraft is controlled in order to follow the motion of the corresponding test mass. Since the two arms form an angle of 60°, this is not possible with a pure drag free control (with no action on the TMs). The only possibility is to control the SC position with respect to the two interferometer axes and to control, by electrostatic actuation, the position of each test mass, for the directions orthogonal to the corresponding interferometer axis. The drawback is that, within the loop bandwidth, for the transverse DOFs the test mass is not anymore in free fall, but it is subject to forces applied by the actuator itself. In the case of LISA, we assume high loop gain in the measurement band (0.1–100 mHz) and then the TM minimum deviation form free fall is given by the intrinsic noise of the position sensor used for the inertial sensor.[1] This would not be a problem if there were no cross couplings between the different degrees of freedom. Actually, this condition can only be fulfilled within a given extent, so there will be a residual noise cross coupling that could spoil the sensitivity of the interferometer.

In order to define the maximum acceptable cross coupling it is necessary to start from the design sensitivity of LISA [7,8]. The noise sources that limit the antenna sensitivity are detection noise (that is the noise in the measurement of the optical path length of the interferometer arms, dominated by laser shot noise, with strong requirements on laser phase noise) at high frequency and acceleration noise (due to stray forces acting on the TM and deviating it from free fall) in the low frequency region. Acceleration noise can be expressed as an equivalent detection noise when useful for computation purpose. A detailed analysis of the different sources of noise for the antenna is beyond the scope of this paper, and can be found in literature [7], here we will just recall the result, that is necessary for defining specification on noise and cross couplings for the sensors used in the DFAC loops. The current noise estimate gives a power spectral density with a $1/f^2$ slope in low frequency that becomes a white noise at higher frequencies, with a corner at about 3 mHz. The white noise level is expected to be $4 \cdot 10^{-11}$ m/Hz$^{1/2}$. Taking into account that there are two transverse DOFs for TM and two TMs per arm, and assuming that the noises add incoherently, we get an upper limit for the noise introduced by cross couplings in the drag-free servo-loops of 10^{-11} m/Hz$^{1/2}$. Introducing a safety factor of five, we hand up to a generally accepted upper limit of $2 \cdot 10^{-12}$ m/Hz$^{1/2}$(above 3 mHz, while the specification is relaxed as f^2 below the knee frequency).

The typical intrinsic noise for the capacitive sensor of LISA, already experimentally demonstrated on the prototypes, is $2 \cdot 10^{-9}$ m/Hz$^{1/2}$. This value is at the origin of the very tight requirement for cross-couplings below 0.1% that is the specifications for LISA [7]. Similar arguments give an upper limit of 0.2% for the cross couplings in the spacecraft attitude control, that again makes use of the IS signals for one of the angular DOFs (being the angular sensitivity of the capacitive sensor of the order of $3 \cdot 10^{-7}$ rad/Hz$^{1/2}$ and assuming a maximum de-centering of the interferometer beam on the TM of 1 mm).

Of course, the specification could be relaxed by improving the noise performance of the capacitive sensor that is not at a fundamental limit. This solution cannot be followed for technical reasons. The limit in sensitivity is imposed by the requirement of a quite large gap (4 mm) between TM surface and electrodes. Actually, this is already a tradeoff between different requirements. A smaller gap would allow a lower sensor noise but would give origin to an unacceptable level of back action noise due to stray forces caused for example, by electrode and TM charging by cosmic rays.

Nevertheless it is clear that cross couplings below 0.1% are generally very difficult to achieve in a real system while we quite often face effects of a few percent. This is not an intrinsic limit, of course, but is triggered by a lot of predictable and sometimes unpredictable mechanisms like machining and assembling imperfections, calibration and centering errors and so on. It is then evident that this very stringent specification is quite a delicate point for LISA and, if not fulfilled, could origin a reduced sensitivity with consequent reduction of S/N and GW signal detection efficiency.

Due to these considerations, the possibility to replace the capacitive sensors with another one, which could show a better sensitivity without reducing the free gap, has been considered since a long

[1] Other relevant noise sources can be actuation noise and external disturbances acting on the SC, but they are independent from the position sensor. For LISA, actuators and loop gains are designed in such a way that for transverse DOFs the sensor noise is the dominating one.

time; the obvious solution is the usage of an optical sensor [13–15,17]. In principle, such a kind of sensor could work even with very large gaps, giving a further reduction of all the electro-magnetic stray forces.

On the other hand, an optical device is generally a local sensor with a beam impinging on the surface of the TM. Therefore it is more sensitive to local deformation of the TM, mainly of thermal origin, with respect to a capacitive sensor that integrates over a large part of the surface. Nevertheless, due to the large thermal conductivity of the metallic TM and to the tight thermal stability requirements for the inertial sensor [16], we think that this effect can be neglected.

For the IS of a space project like LISA, the sensitivity is not the only issue to be taken into account. Reliability and simplicity are other important and maybe predominant aspects. LISA should work continuously for at least one year a few 100 million km away from the Earth, after one year of flight necessary to reach the final orbit and without any possibility of external intervention for repairing or fixing problems. Furthermore, the capacitive sensor will be tested on flight by the technology demonstration mission LISA-Pathfinder that will be launched in 2012 and, if successful, they will not be replaced by any different sensor, even if more performing, that has not been tested on flight.

Keeping in mind all these arguments, we started some time ago the development of an optical read-out (ORO) system intended not as a replacement, but as an integration of the capacitive one in order to give a backup solution in case the first fails. It is then essential that the ORO can be integrated, with minimal modifications, in the present design of the LISA inertial sensor. Of course, if the ORO is adopted and a better performance is demonstrated, it could become the main detector for the IS, provided that the capacitive one remains in place for backup, if necessary. In any case, electrostatic actuation will remain the only option for acting on the TM. The solution we adopted for the ORO is an optical lever sensor [12]. The principle scheme, the potential sensitivity and the actual possibility of integration in LISA have been already analyzed in detail in previous papers [12,16,17], so we will just recall them shortly in the next two sections. In the last two sections, we will report the experimental results obtained so-far in bench-top experiments and will discuss the advantages that the adoption of our ORO system could give to the LISA project according to the already experimentally demonstrated sensitivity and to its advisable further improvements.

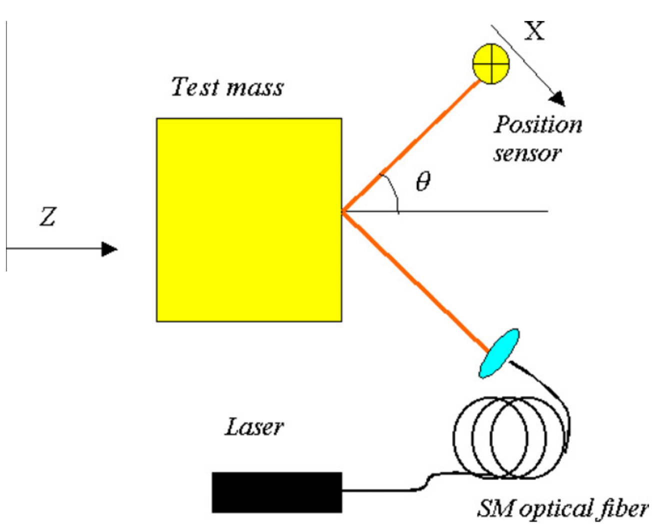

Fig. 1. Principle scheme of the ORO.

3. Principle of operation

In Fig. 1, it is sketched the principle scheme for the ORO. An optical beam is sent, through a single mode (SM) optical fiber, to the surface of the proof mass (PM) of the inertial sensor. The reflected beam is detected by a detector sensitive to beam position: quadrant photodiode (QPD) or position sensing device (PSD). A translation or rotation of the PM results in a displacement of the beam on the sensor. With a suitable combination of three beams and sensors, it is possible to recover all the six DOFs of the TM.

As for any optical system, there are several known noise sources that limit the ORO sensitivity. A detailed discussion is given in Ref. [13], here we just summarize the results. The most important limiting noise source in the frequency band of interest (0.1–100 mHz) is the current noise I_n of the photodiode trans-impedance amplifier. It can be estimated by using the formula [13]:

$$\tilde{x}_I = \frac{\tilde{I}_n(f)}{|dI/dx|} \approx \frac{\sqrt{N} \cdot L \cdot \tilde{I}_n(f)}{2 \cdot \alpha(\lambda) \cdot P_0} \approx 4 \cdot 10^{-10} \left(\frac{\tilde{I}_n(1mHz)}{1.7 \cdot 10^{-10}}\right) \left(\frac{1mW}{P_0}\right) \left(\frac{1mHz}{f}\right)^{1/2} \times \left(\frac{L}{1mm}\right) \left(\frac{0.45}{\alpha(\lambda)}\right) \left[m/\sqrt{Hz}\right], \qquad (1)$$

where L is the measurement range (i.e. the spot size in the case of a QPD), $\alpha(\lambda)$ is the photodiode responsivity ($\alpha(\lambda) \sim 4.5$ A/W at 830 nm for a Si photodiode), P_0 is the optical power and N ($N = 4$ for QPD) is the number of elements of the photo-detector.

As for any optical system, the ultimate limit is the shot noise computed according to Eq. (2), where η is the photodiode quantum efficiency and $\lambda = c/\nu$ the light wavelength. Taking into account reasonable light power (0.1–1 mW), the shot noise results negligible in the measurement band of LISA (0.1–100 mHz)

$$\tilde{x}_{sm} = \frac{e}{|dI/dx|} \sqrt{\frac{2\eta P_0}{h\nu}} \approx 3 \cdot 10^{-11} \left(\frac{830nm}{\lambda}\right)^{1/2} \left(\frac{1mW}{P_0}\right)^{1/2} \left(\frac{0.78}{\eta}\right)^{1/2} \times \left(\frac{L}{1mm}\right) \left[m/\sqrt{Hz}\right]. \qquad (2)$$

Eqs. (1) and (2) give the noise in terms of displacement of the spot on the sensor. To convert this in terms of TM displacement, we should add a factor that depends on the geometrical configuration ($1/\sqrt{2}$ for 45° incidence).

All the other modeled noise sources also are negligible in the measurement band. In the end, the ORO can reach a sensitivity well below 10^{-9} m/Hz$^{1/2}$ in the whole measurement band of LISA and is then potentially much more sensitive than the capacitive sensor. Of course, at such low frequencies there are other possible disturbances, like thermal and mechanical drifts, creeps etc., which can make it very difficult to experimentally demonstrate, with a bench top experiment, that the optical sensor can reach its potential sensitivity.

4. Integration in LISA

In principle, the actual integration of the ORO in the LISA inertial sensor would be very easy if taken into account from the beginning of the design. On the contrary, we must consider that the design of the inertial sensor of the LISA pathfinder mission, that is a technology demonstration mission for LISA, is already completed and that only marginal modification will be accepted for LISA in case of positive test. We have then assumed, as a starting point, the design of the Pathfinder inertial sensor. In this case, the layout of the electrodes leaves only a little space available for the optical beams to enter the electrode housing, hit the TM surface and get out again for reaching the position sensors. In a previous paper [19], to which we refer for further details, we report about a possible implementation that solves the problem by using the electrodes themselves as mirrors for directing the beams to the right paths. At the moment we adopt it as a reference solution, that can be updated according to the possible evolution of the IS design from Pathfinder to LISA.

5. Experimental tests

In this section we report on measurements devoted to the characterization of the ORO and to the experimental verification of its performance. We started with bench-top tests. After some very preliminary tests [13] with standard optical mounting, where the sensitivity measurement was limited by the relative motion of the optical components, we opted for a rigid set-up, manufactured by machining an optical bench shaped as a box, from a single stainless steel block. The aim is to have all the set-up as rigid as possible so that the residual measured motion of the spot on the sensor is due to the intrinsic noise of the sensor itself rather than to real motion of the test mass. The position sensors and fiber output couplers are directly mounted on the external part of the bench. A dummy test mass, with mirrors attached on it, can be placed at the center of the bench itself either rigidly fixed or mounted on translation stages (with PZT actuation and built-in capacitive readout) used for calibration. The set-up is symmetric so that differential measurement can be performed by sending beams on the opposite faces of the test mass. The entire set-up is housed in a thermal insulation box in order to reduce to a negligible level the effect of thermal drifts and air movements. The thermal insulation is a cubic polystyrene box, 4.5 cm thick and, 42 cm wide. The internal surface is covered by an aluminum foil. The temperature is monitored with AD590 thermistors. We measured, over a time scale of 10,000 s, a temperature drift inside the box below 7 mK, while the environmental temperature drift was about 130 mK. This corresponds to an attenuation factor of about 20. The residual temperature fluctuation is 0.2 K/Hz$^{1/2}$ at 0.1 mHz; the requirement for LISA-Pathfinder is below 20 μK/Hz$^{1/2}$ at 0.1 mHz [16]. It is then clear that the results obtained in the lab will not be affected by extra thermal effects on flight. In Fig. 2 it is shown an image of the rigid set-up.

With this set-up we have performed several measurement campaigns [18,19] for measuring the ORO residual noise with different type of optical sources, position sensors and fiber components. In particular we have used as optical sources He-Ne lasers, SM coupled laser diodes (LD) operating at 633 nm and 830 nm and fiber coupled super-luminescent LEDs (830 nm). As sensors we tested quadrant photodiodes (QPD) and position sensing devices (PSD). In the end, we tested both SM and polarization maintaining optical fibers and different types of fiber output couplers (with aspheric micro-lenses or graded index lenses).

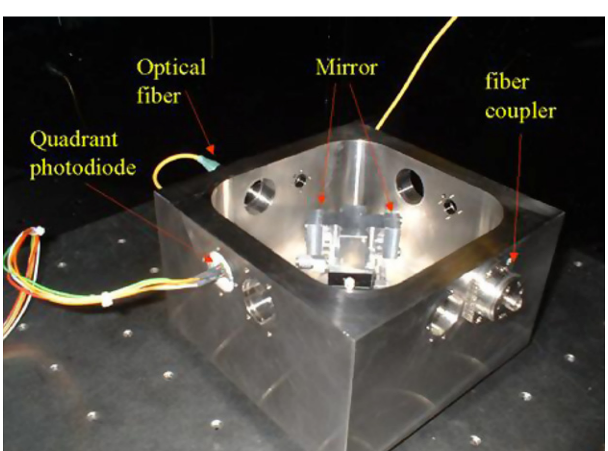

Fig. 2. Image of the bench-top rigid set-up.

For what concerns the sources, we got good results with fiber coupled He-Ne lasers (single longitudinal mode and stabilized in power or frequency). Unfortunately, this type of source is good for bench-top measurement but it is not suited for space operation, because it is fragile, power consuming and requires a relatively large space. Consequently it can only be used for preliminary tests but not as a reference solution for the ORO to be mounted on LISA, where solid state source (LD or LED) should be adopted.

On the other side, the measurements we performed with LD were generally noisier. The origin of the extra noise was individuated in mode hopping, that is the jump of the operation point of the source from one longitudinal mode to another and is common in Fabry–Perot LDs. This originates a sudden jump in both emitted power and wavelength. While the power change is corrected by normalization, the wavelength change gives an actual beam displacement that is originated at the dioptric surfaces at the fiber end (that is angle polished for avoiding back reflection) and at the collimator lens. Mode hopping can be considerably reduced by inserting in the optical path a Faraday optical isolator that cuts out any back reflection and by actively stabilizing LD temperature and current, but can be hardly eliminated at all. It is worth noting that a LD that undergoes a mode jump every few hours would be ok for the majority of applications, where relatively high frequency (above 100 mHz) are involved, but cannot be used in our case since we are interested in a very low frequency band (0.1–100 mHz) and each measurement lasts typically from few hours to several days. An alternative solution, that we plan to investigate in the next future, is the adoption of DFB (Distributed Feed-Back) or FBG (Fiber Bragg Grating) LDs that should be mode hopping free.

In the end, we successfully tested SM fiber coupled super-luminescent diodes (S-LED). These light sources are in between LDs and normal LEDs, in some sense. As LDs they provide an almost monochromatic beam, but with a relatively short coherence length (well below 1 mm). Furthermore, they are not lasing so they are mode hopping free. The short coherence length offers the further advantage that the system is essentially free from the effect of ghost fringes, due to multiple reflections within optical components or windows, which can, in some cases, spoil the sensitivity, as we will describe below. Moreover, S-LEDs (like LDs) are already available on the market with SM fiber pigtail and in compact standard packages (like Butterfly or Mini-Dil) so that their integration on the LISA flight hardware should be relatively easy.

As position photodetectors, we tested QPDs and PSDs. As expected, we got the best sensitivity results with the QPD, that we adopt as the reference solution. This can be easily understood by looking at Eqs. (1) and (2), because, once fixed all the other parameters, the sensitivity is inversely proportional to the measurement range (L) that is, in good approximation, equal to the spot size in the case of the QPD and to the detector size for the PSD. On the reverse, the PSD offers the advantage that the response is not depending on spot size and shape and so it is more stable in time, while for the QPD any change in spot size requires a new calibration and the shape of the spot can affect the measurement. An interesting aspect is connected to the presence of the photodiode window. In our first experiments, performed with He-Ne laser, we observed, for frequency below a few 10 mHz, an unexplained extra noise with a time varying spectrum (then non stationary). This effect disappeared when we removed the window from the photodiode, so we interpreted it as due to the presence of interference fringes across the spot due to multiple reflections in the window itself. Any change in the fringe pattern can result in a change of the spot's barycenter and is read as a beam displacement. In practice, in our device the position signal is proportional to the light power, while the noise connected to the window is proportional to the light phase as happens in an interferometer. For all the following measurement we always used windowless photodiodes, but we think that by using short coherence sources (S-LEDs) this effect should become negligible and we plan to devote dedicated tests to check this point.

It is useful to give some detail about the optical fiber components. In general we have adopted SM fibers in order to get a good and stable beam quality and to filter out beam position and angular jitter that would otherwise be dominating for a free space source. As a rule, we only used angle polished connectors in order to get a low back-reflection. We have tested both SM and polarization maintaining fibers, with or without Faraday Isolators inserted along the optical paths. We also tested, as fiber output focusers, aspherical micro-lenses or graded index (Green) lenses.

For the He-Ne laser we got the best sensitivity measurement with polarization maintaining fibers, while we could not find any significant indication that the Faraday Isolator was giving any improvement. For what concerns the output couplers, we got in general bad measurements with the green lens. We think that this is due to the bad beam quality, confirmed by visual inspection by projecting the beam on a far screen, but we cannot assert if this is a general problem or it is due to the specific components that we tested.

It is worth noting that these very low frequency measurements take very long time, each lasting several hours, or days (up to one week) if we are interested to frequency down to 0.1 Hz or below or we need averaging for improving the accuracy. Furthermore, any change in the set-up requires opening the thermal insulation box and then some time is required to get again a stable and uniform temperature before we can start a new measurement. So it is generally not so easy to be sure that in comparative experiments all the experimental conditions are the same. In some cases it is easier to identify the set-up which gives a good sensitivity rather than rule out, without doubt, the one giving not completely understood troubles. Generally the different set-ups show measurable differences only at very low frequencies, while they give usually similar results for frequencies above a few Hz (where the device is generally limited by readout electronic noise and mechanical vibrations). This implies that we cannot use high frequency measurement (which would be much faster) to extrapolate the low frequency behavior.

The LD measurement were always dominated by the noise due to mode hopping so that we could not get any information about the fiber optic components.

In the end, the S-LED measurements provided much more stable and reproducible results with no evidence of differences between using SM or polarization maintaining fibers. In this case we only used aspherical micro-lenses for the time being, but we plan to repeat tests with graded index lenses as well.

Fig. 3 shows the results of some sensitivity measurement performed with He-Ne laser (blue line) and S-LED (magenta line). In particular, we selected the results obtained with the set-up giving the best performances. Both the curves are the average of measurements performed with the same set-up at different times and in different frequency bands. On the same plot, are also reported the expected sensitivity of the capacitive sensor (orange line) together with the expected electronic noise (green line) and shot noise (red line), computed according to Eqs. (1) and (2) respectively, and their incoherent sum (cyan line). The noises have been computed for He-Ne assuming $P_0 = 0.3$ mW and $|dI/dx| = 0.25$ A/m but they change only slightly for the S-LED. Finally, the black line represents an approximation of the measured sensitivity (essentially the same with both the light sources) that we will use for further analysis.

From the analysis of Fig. 3, we can give some conclusion about the ORO sensitivity. First of all, it is verified experimentally that an ORO system based on optical levers and position sensors can give much higher sensitivity than the one achieved by the capacitive sensor designed for LISA. In our measurement, the improvement ranges from a factor of 2 at 1 mHz to a factor of 20 a 100 mHz. At lower frequencies, below 0.5 mHz, the ORO noise spectrum exceeds the design sensitivity of the (nominal) capacitive readout, but we think that this is mainly due to thermal and mechanical drifts rather than to sensor intrinsic noise. In any case, this is not very important for LISA, as we will discuss in next section.

One more interesting point, is that, in a large frequency band, the measured noise spectrum shows a $1/f^{1/2}$ slope. This slope is in agreement with the electronic noise model, but the absolute value is about a factor of four above the expected one. On the other side, the dark noise, essentially dominated by the current noise of the trans-impedance amplifier used to read the QPD signal, is in agreement with the model. We observed this discrepancy in all our measurements. At the moment, we are not able to explain this extra noise, but further investigations are going on. Below 1 mHz the spectrum shows a steeper slope that, as mentioned before, we think is not strictly related to the ORO readout. For frequencies above 10 Hz, the residual noise approaches the shot noise limit, in agreement with the model.

Finally we have started, in collaboration with the LISA group at University of Trento, the testing of the ORO with a four mass torsion pendulum facility designed for the ground testing of the flight hardware of LISA-Pathfinder and LISA. The goal was to test the performance of the device and to check that the back-action (essentially due to radiation pressure noise) is within the expectation. The tests performed so far are very encouraging, confirming that the ORO system can obtain a sensitivity better than the one of capacitive readout also in a situation as close as possible to free fall in a laboratory on the earth. A detailed description of set-up, results and further developments can be found in a dedicated paper [20].

6. Potential advantages for LISA

As explained in the previous sections, the main motivation for adding an ORO system as an extra readout to the inertial sensor of LISA is to have a second device that could be used as a back-up solution in case of failure of the capacitive one, introducing some redundancy with consequent mission risk reduction. Despite the fact that ORO developed in Napoli has not yet reached its potential limit, the experimentally demonstrated sensitivity already overcomes the one of the capacitive readout.

In the mean while, we have already a principle layout for the integration in the present design of the LISA IS. We think that the proposed principle solution is already mature enough for being adopted as a useful device in the design of LISA and to start the engineering and qualification studies.

Bearing in mind that the capacitive readout itself, after successful testing on LISA-Pathfinder, will certainly be mounted on LISA, we think that the better sensitivity of the ORO puts it in the condition of becoming the main sensor, keeping the capacitive one as back-up. As explained in Section 2, the main advantage would not be to improve the sensitivity of LISA as a GW detector, but to make it easier to reach the design sensitivity by relaxing the very stringent specifications on cross couplings for the DFACS servo-loops.

In Fig. 4, we compare the specifications on maximum cross couplings from transverse readout to the main interferometer axis, for the capacitive readout (red dotted line) and for the ORO. For the latter we show both the specifications for the measured sensitivity (blue solid line) and the one expected according to the noise model (black dashed line). In the computation, we assume that, in order not to spoil the LISA sensitivity, the maximum contribution to the noise budget for each IS channel is represented by a flat spectrum of $2 \cdot 10^{-12}$ m/Hz$^{1/2}$ relaxed as f^2 in low frequency, with a corner at 3 mHz. As we can see, for the capacitive readout the cross-couplings upper limit is as small as 0.1% for all frequencies above 3 mHz and gets above a more reassuring 1% only below 1 mHz. On the other side, the corresponding upper limit obtained

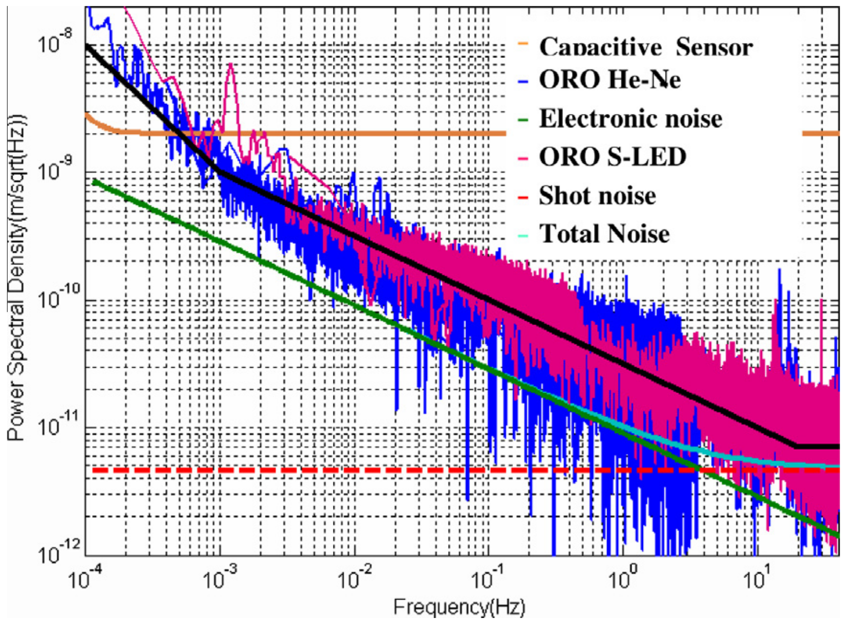

Fig. 3. ORO sensitivity with He-Ne laser (blue line) and S-LED (magenta line). Expected sensitivity of the capacitive sensor (orange line). Expected electronic noise (green line) and shot noise (red line) and their incoherent sum (cyan line). The black line represents an approximation of the measured sensitivity.

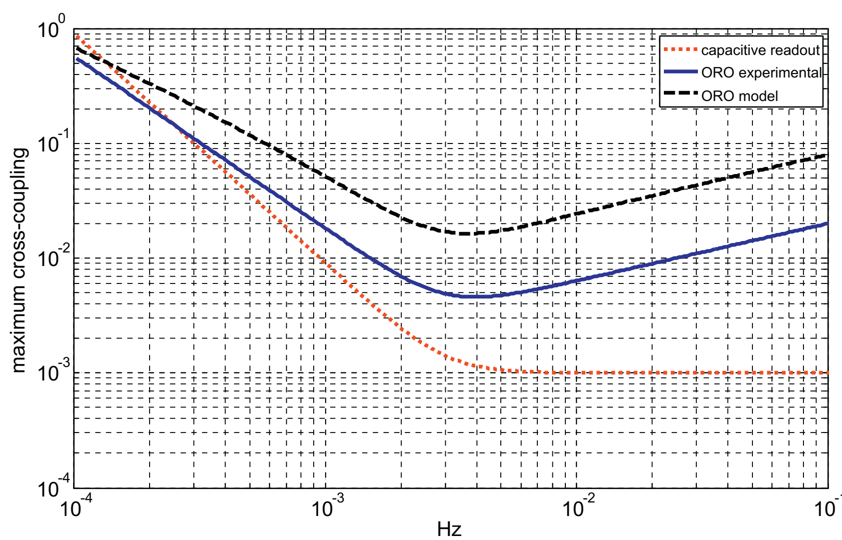

Fig. 4. Specifications on maximum feedback cross-couplings from transverse readout to the main interferometer axis, for the capacitive readout (red dotted line) and for the ORO taking the measured sensitivity (blue solid line) and the one expected according to the noise model (black dashed line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

from the measured ORO sensitivity is above 1% for all frequencies except for the 1.3–25 mHz interval and above 0.5% almost everywhere, with a minimum of 0.45% at 4 mHz. The specification could be even further relaxed if we could reach the potential limit sensitivity, going well above 1% in the whole frequency band.

7. Discussion

We have developed an optical read-out system to be added, as an extra readout, to the capacitive sensor already adopted for the drag free control of LISA. The system, based on optical levers and position sensors, is designed in order to be as simple and reliable as possible and has been preferred to other kind of optical sensors, like interferometers, that are potentially much more sensitive but in the mean while much more complex and expensive.

Bench top experiments show that the ORO system can reach a much better sensitivity than the one of the LISA capacitive sensor in the whole frequency band of interest. The currently measured sensitivity is not limited by fundamental noise sources, so that further improvements are still possible.

In a previous paper [19] we have already presented a layout that allows the integration in LISA with very small modifications to the current inertial sensor design, so this aspect seems not to be a problem.

Finally, we have discussed how the adoption of the ORO as a main sensor for the readout of the transverse DOFs of the LISA test masses would allow to relax by a large extent the very stringent specifications on cross-couplings in the DFACS of LISA, imposed by the position sensor intrinsic noise.

Summing up, we think that the obtained experimental results, and the considerations reported about design and potential advantages in terms of risk reduction and reliability for the project, show that the ORO system that we have proposed and are presently developing is mature enough for being adopted as a useful device for the LISA inertial sensor, in addition to the capacitive one.

Next steps should be further investigation of noise sources in order to get closer to the potential sensitivity, and the completion of test already started [20] with a torsion pendulum facility in order to study the reliability and check for the expected very low back action. In the mean while, we think it is worth starting engineering and qualification studies for going from the present breadboard device to a space-qualified design for LISA.

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