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Development of an Optical Read-Out System for the LISA/NGO Gravitational Reference Sensor: A Status Report.

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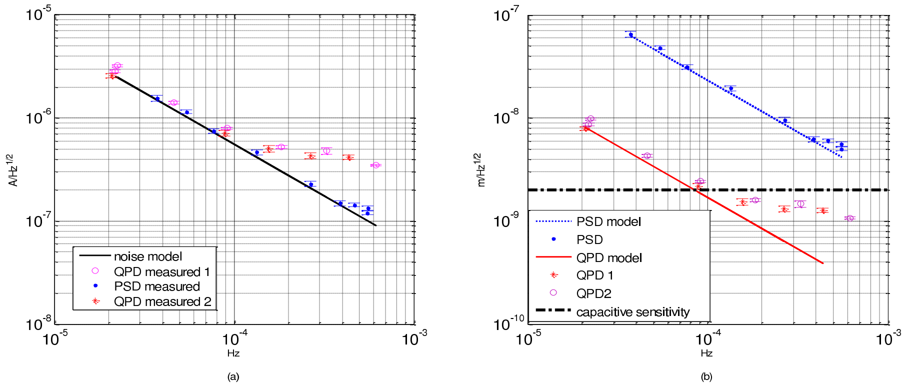
Abstract. The LISA group in Napoli is working on the development of an Optical Read-Out (ORO) system, based on optical levers and position sensitive detectors, for the LISA gravitational reference sensor. ORO is not meant as an alternative, but as an addition, to capacitive readout, that is the reference solution for LISA/NGO and will be tested on flight by LISA-Pathfinder. The main goal is the introduction of some redundancy with consequent mission risk mitigation. Furthermore, the ORO system is more sensitive than the capacitive one and its usage would allow a significant relaxation of the specifications on cross-couplings in the drag free control loops. The reliability of the proposed ORO device and the fulfilment of the sensitivity requirements have been already demonstrated in bench-top measurements and tests with the four mass torsion pendulum developed in Trento as a ground testing facility for LISA-Pathfinder and LISA hardware. In this paper we report on the present status of this activity presenting the last results and perspectives on some relevant aspects. 1) System design, measured sensitivity and noise characterization. 2) Possible layouts for integration in LISA/NGO and bench-top tests on real scale prototypes. 3) Search for space compatible components and preliminary tests. We will also discuss next steps in view of a possible application in LISA/NGO.

1. Introduction

In this paper we report on the present status of the development of an optical read-out (ORO) Acernese et al. (2004) system for the LISA (NGO) inertial sensor. The present design of the GRS is based on capacitive sensor; our goal is to integrate the ORO in the capacitive one without changing the present sat-up and electrode shape. The motivation is twofold: A first point is risk reduction: the ORO could be a back-up sensor in case the capacitive one fails after the launch. This becomes still more important for NGO because in this case, with only two arms, the failure of a single Inertial Sensor would compromise the mission. A second aspect is sensitivity improvement: any reduction of the noise or the sensor used for Drag Free and Attitude Control System (DFACS) would relaxed specifications on cross couplings (CC). Present requirement on CC is 0.1 % that is a very strong specification. In the following sections we will describe the proposed ORO set-up, report on Bench top and suspended tests on sensitivity, describe possible layouts for implementation in LISA and results with bench-top prototype and report on first results and next steps for space qualification.

2. ORO principle of operation

For the ORO we adopted an optical layout as simple as possible, based on optical levers and position detectors. An optical beam is directed, trough an optical fiber attached to the Spacecraft (SC) to the TM surface. The reflected beam is sensed with a quadrant photo-diode (QPD) or a position sensing device (PSD) also attached to the SC. Any movement of the TM respect to the SC determines a displacement of the light spot across the position sensor. With suitable combinations of beams and sensors it is possible to recover some or all of the different degrees of freedom (DOF) of the TM. A detailed description of the principle of operation can be found in references Acernese et al. (2004); Acernese et al. (2005); Rosa et al. (2011); here we just recall some basic concepts and report on the most recent results. A first point is the requirement for the ORO. The specifications for the reference capacitive readout system for the IS are 2 nm/ $\sqrt{Hz}$ in position and 200 nrad/ $\sqrt{Hz}$ for angles Bender et al. (2003). For a backup sensor it would be enough to provide the same (or even a slightly worse) sensitivity. In order to have an improved performance and then to relax cross coupling specifications we think that an improvement of a factor 2-3 in a large part of the frequency range would already be interesting while a factor of 10 would be more than enough.



(a) (b)

Figure 1. Dependence of noise on input power for QPD and PSD: (a) expressed in A/ $\sqrt{Hz}$, (b) expressed in m/ $\sqrt{Hz}$

The expected ORO sensitivity depends Acernese et al. (2004); Acernese et al. (2005) on sensor geometry, detector type, spot size, measurement range (that is the spot size for QPDs and the detector size for PSDs) and readout electronic noise and is limited, in the LISA frequency band, by the current noise of the trans-impedance amplifier used for photo-diode readout. In a previous paper Rosa et al. (2011) we reported about an unexplained extra noise. We have now performed a more systematic study to characterize the observed noise. In figure 1 we report the measurement of the noise level at 1 mHz as a function of the input power for both type od sensors, while leaving unchanged all the other characteristics of the experimental set-up. The plot assumes that the noise scales in frequency as 1/ $\sqrt{Hz}$ as is confirmed by the measurement. As we can see in figure 1 (a), for the QPD the measured noise is in agreement with the noise model up to about 0.15 mW while there is extra noise above this power, while with the PSD there is almost no extra noise up to 0.5 mW. If we look at the noise expressed in m/ $\sqrt{Hz}$ (figure 1 (b)), we can see that, as expected, with the QPD we get a better sensitivity (at the cost of a reduced measurement range), but, by increasing the power, the difference is progressively reduced due to the observed extra noise.

In figure 2 we show the sensitivity measured using a QPD and a PSD with the same set-up and almost the same input power (~ 0.55 mW) As we can see, in both cases the measured noise

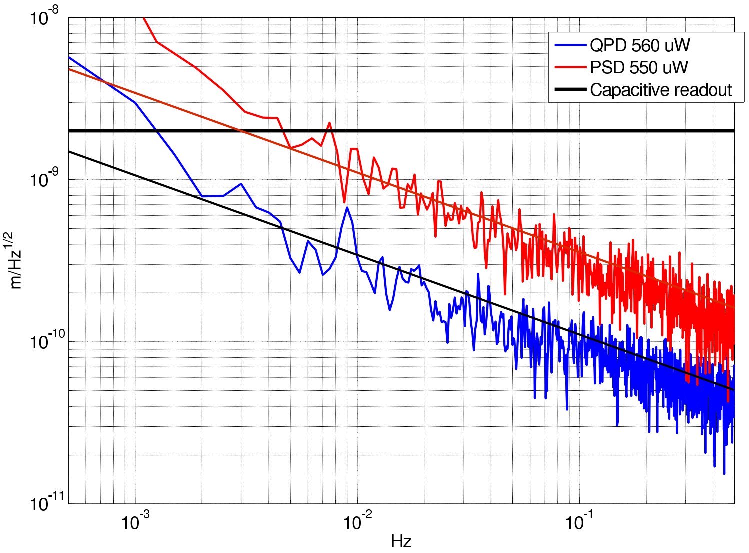


Figure 2. Comparison of noise measured with PSD e QPD with the same input power

is well below the specification for capacitive readout of 2 nm $\sqrt{Hz}$. For the QPD there is an improvement down to 1 mHz that arrives at a factor of 10 for frequency above 20 mHz. The measurement range is 0.4 and 4.7 mm respectively. Despite the observed extra noise, we can see that in any case the ORO system reaches a sensitivity that would be interesting for both a back-up sensor or as a better main sensor.

Aside to bench-top experiments we also tested the ORO system on the four mass torsion pendulum facility developed in Trento These tests permitted to verify the improvement in sensitivity with respect to capacitive readout Cavalleri et al. (2009). We also developed ORO systems as auxiliary sensors for the torsion pendulum facilities in Trento Recently a device based on multiple reflection allowed to improve the sensitivity of the Trento facility by one order of magnitude (see paper by G.Russano at al. in this volume).

3. Integration in LISA

Another delicate point is the definition of the layout for the integration in LISA, now eLISA/NGO. At mentioned before we wont to keep unchanged the present geometry of the IS, and in particular the shape and size of the electrode. So we are forced to arrange the optical beam in the small space left free by the electrodes, through some holes in the electrode guard-rings. The most difficult TM surface to reach are the ones along the vertical (z) axis. In this case the so called caging mechanism, necessary for blocking the TM during the launch, completely covers the upper and lower parts of the IS. We proposed to use the electrode themselves as mirrors to direct incoming beam to the TM and the reflected one out of the electrode housing. In a previous paper Acernese et al. we describe in detail this solution and report on experimental tests on a bench top prototype that, with a suitable combination of 3 beams and 3 position sensors, allows to recover all the 6 DOF of the TM. Recently, following the evolution from LISA to NGO end considering the some DOFs (the displacement along the interferometer optical axis (x) and the two rotations around axe orthogonal to this axis) are already measured by the main interferometer, we developed and tested, with a on scale bench-top model, a simplified set-up that allows to measure independently the remaining DOFs (that are the displacements along axes orthogonal to x axis and the three rotations. In our set-up, the TM is mounted on calibrated PZT actuators that allow to move the TM on the relevant DOFs. This allows to measure the optical matrix that links the sensor output to the TM movements. The layout, sketched in figure 3 is based on 3 beans (two impinging on the upped and lower z faces of the TM and one on the lateral (y) face) and 3 position sensor. We have measured the optical matrix that is in agreement with the analytical model within a few %.

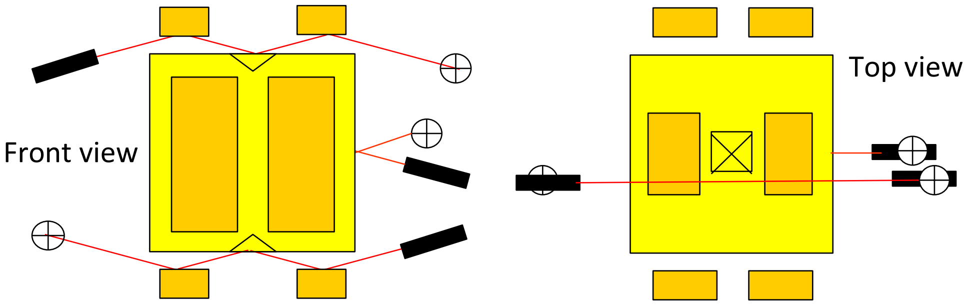


Figure 3. Optical layout (not using the x face) tested with a bench-top prototype. We can see the cubic TM surrounded bay the (darker) IS electrodes, the optical beams using some electrodes as mirrors and the position sensors.

4. Search for space qualified components

A last point that we recently started to investigate, is the availability of space compatible components for the ORO. It is worth to specify that we don't wont to build flight hardware. Our goal is to check if they already exist space qualified components and to identify possible criticality. The main ORO parts are: readout electronics, light sources, fiber components and collimators and light detectors. We started wit readout electronics. We identified a space qualified component (OP27AJ/QMLR) that is equivalent to the OP amplifier that we use in our readout electronics (OP27EP) We realized some electronic cards with the space qualified parts and tested it with the ORO in comparison with the electronics realized with the standard components. The result was completely satisfactory since we observed the same noise level and the performance was not distinguishable in the two cases, so we think that there is no problem at all with electronics. Next step will be to look for the other parts. At the moment is seems that it should be possible to find S-LEDs and position sensors, while the most delicate points, that require deep investigations, are probably the fiber collimators, which must follow severe requirements (for example on magnetic clearness) since they are very close to the TM, ant the assembling procedure for the optical fibers in the IS vacuum chamber. Nevertheless, no show stopper has been identified so-far.

5. Conclusion

We have proposed and developed an optical readout system for the LISA/NGO inertial sensor. Both bench top and suspended tests confirm that the ORO sensitivity can be better than the capacitive one, above 1 mHz. The noise level is well characterized, even if not completely understood and allows to make predictions and trade-off between sensitivity and measurement range. There are possible layouts for the integration in the present design of the inertial sensor, verified with bench-top models. Study of space compatible parts is just started: electronics is not a problem and it looks that there are available component already tested on flight: Further studies are required. Summing up we think that the ORO is a good candidate as a back-up sensor for the eLISA/NGO inertial sensors, with promising potential sensitivity improvement with respect to the capacitive one.

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