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Ground testing, with a four mass torsion pendulum facility, of an Optical-Read-Out for the LISA gravitational reference sensor

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Abstract. In the last few years the Lisa group in Napoli has developed an Optical Read-Out (ORO) system based on optical levers as an auxiliary and backup readout for the Gravitational Reference Sensor (GRS) of LISA. Bench-top measurements, with a rigid set-up have successfully proven that the ORO fits the requirements for sensitivity both in translational and rotational DOFs, exceeding the capacitive sensor performance in a wide range of frequencies. Last year an ORO system designed in Napoli in collaboration with the Trento LISA group, has been installed, as an auxiliary readout system, on the four mass torsion pendulum developed in Trento. In this paper we report on the testing of this ORO device and its performances in comparison with the capacitive one; we also outline further improvements and their advantages for the torsion pendulum facility performances.

1. Introduction

The GRS, also called inertial sensor, is one of the key elements of LISA [1]. It is a position sensor that measures, on six degrees of freedom (DOF), the position of each test mass (TM) with respect to the spacecraft. The GRS signals are used in the drag free control loops to force the spacecraft to follow the TM geodesic motion. The reference solution for LISA, also adopted for the LISA-Pathfinder technology demonstration mission, is a capacitive sensor, developed by the LISA group in Trento [2]. The Trento group has also developed torsion pendulum facilities for the ground testing of the prototypes and models of the GRS designed for the LISA-Pathfinder mission. In particular, a single mass and, more recently, a four mass torsion pendulum facilities have been developed. For a complete description of these devices refer to references [2] and [3].

As an alternative to GRS capacitive readout, optical readout (ORO) systems have also been proposed [4, 5, 6, 7, 8]. In particular, the LISA group in Napoli has proposed and developed an ORO system, based on optical levers and quadrant photo-diodes (QPD), that allows to improve the sensitivity of the GRS [5, 6, 9]. The main goal of this activity is not the replacement of the capacitive sensor (that will be tested on flight with LISA-Pathfinder) with an optical one, but the integration of the two in a single GRS system in such a way to get a back-up sensor in case the other fails after the launch of LISA, with consequent mission risk reduction. Furthermore, the ORO system can be more sensitive than the capacitive readout, and thus using ORO for satellite control on the Y and Z axes and θ rotation around the TM x axis, where there is no interferometric readout, could allow to relax the specification on cross-couplings in the drag-free control loops. This can be achieved adopting the ORO as the main sensor or using its signals for subtracting the extra noise of the capacitive readout.

For the capacitive readout, we assume as reference sensitivity 2 nm/Hz$^{1/2}$ in displacement and 200 nrad/Hz$^{1/2}$ in angle. For the ORO, a sensitivity performance exceeding the one of the capacitive readout system has been already demonstrated with bench top experiments on a rigid set-up in Napoli [6, 9].

Last year, in collaboration with the Trento group, a prototype of the ORO has been installed on the four mass torsion pendulum facility. The goal is twofold; the first one is to check the performance of the ORO in a situation that is as close as possible to free fall and to compare the noise with contemporary measurements with both ORO and capacitive readout, aiming to verify the improvement in sensitivity provided by the ORO. The torsion pendulum could also measure (or put upper limits to) any excess force noise created by the ORO. The second motivation is that the potentially more sensitive ORO can improve the performance of the torsion pendulum device as a facility for ground testing of the LISA-Pathfinder hardware.

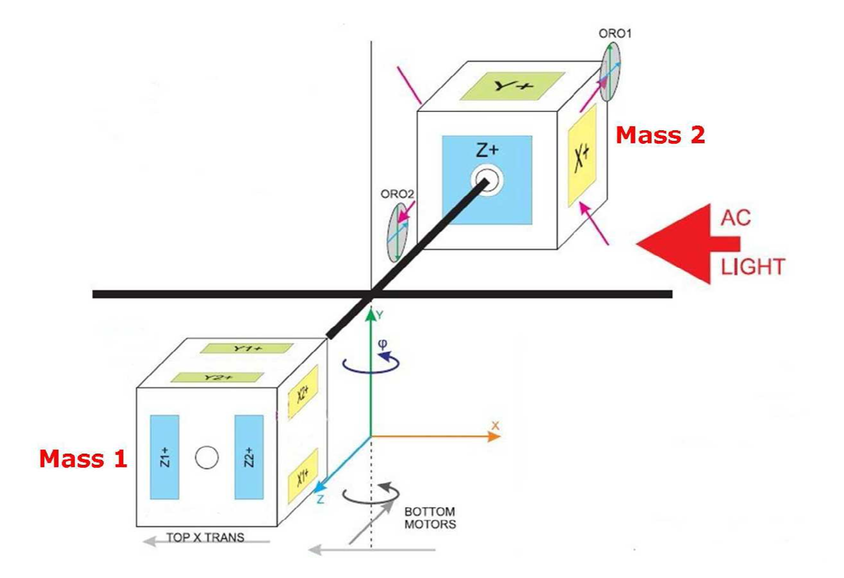

Figure 1. Schematic view of the sensors on the four-mass torsion pendulum. The EM, measuring all the six DOFs, is mounted around test mass 1. The STC (measuring two displacements, X and Z) and the ORO (measuring φ, η and X) are mounted on TM 2. An autocollimator, that uses a laser beam reflected by a mirror placed above the pendulum payload shaft, is used for calibration.

At the time of measurement the torsion pendulum was used for the testing of the engineering model (EM) of the LISA-Pathfinder GRS that was mounted around one of the four test masses. On the opposite test mass, there is another sensor, called stiffness compensator (STC) mainly used for improving readout sensitivity. Due to the electrode configuration, the STC is only sensitive to displacements in three DOFs, while the EM measures all the six DOFs. The ORO was mounted on the STC, in a configuration with two beams and two QPDs that allows the independent measurement of two angles and one displacement (φ, η and X). In particular, each QPD provides two signals (proportional to horizontal and vertical displacements of the spot across the detector area). The two vertical signals are used for separating pendulum η and X, while the horizontal ones provide independent measurements of φ (that we average for noise reduction). The light sources used for the ORO are super-luminescent LEDs (S-LED), coupled to single-mode optical fibers, operating at 820 nm (total power about 400 nW). There is also an autocollimator that provides a measurement of the rotation around the vertical axis, and is used for calibration of all the other signals. In figure 1 there is a scheme of the various sensors.

2. Noise measurement

In this section we report on the results of a measurement campaign where the ORO and the capacitive readout were operative at the same time. The aim is to compare the measurement of the TM position (both in displacement and angle) to the ones of the capacitive sensors (mainly the EM, that is the model for LISA).

In figure 2, we report the measurement for the rotation around the vertical axis (φ). As we can see, the ORO measurement (blue line) is more sensitive than the EM capacitive one (red line), confirming the results obtained in bench-top experiments [9]. The ORO sensitivity (~ $2{\cdot}10^{-8}$ rad/ $Hz^{1/2}$ above 10 mHz) corresponds to a beam displacement across the QPD of about $8{\cdot}10^{-10}$ m/ $Hz^{1/2}$. On the same plot, are shows the estimated pendulum thermal noise and the expected ORO noise (computed according to the bench-top results). It is worth noting that the EM φ signal reported in Fig.1 doesn't represent the best capacitive readout available on the torsion pendulum, that is instead obtained as the difference between the X displacement measured by EM and STC divided by the arm-length distance (between the two TM centers), and is a white noise currently at a level of about $2.5{\cdot}10^{-8}$ rad/$Hz^{1/2}$; anyhow, as long as we are interested in the ORO as a back-up solution for LISA, we are interested in comparing it with the performance of the EM alone.

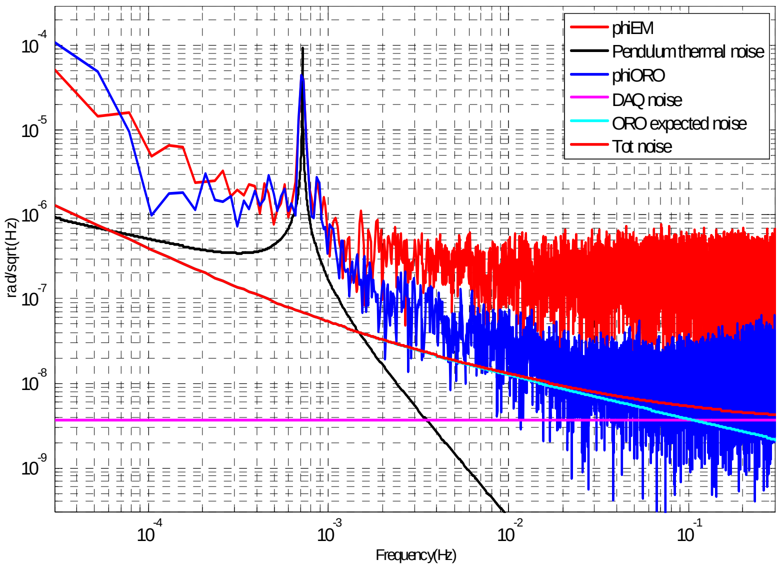

Figure 2. ORO measured φ sensitivity (blue line) compared to the one of the EM capacitive sensor (red). The EM sensitivity is limited to ~ $2{\cdot}10^{-7}$ rad/ $Hz^{1/2}$, while the ORO reaches $2{\cdot}10^{-8}$ rad/ $Hz^{1/2}$.

In figure 3, it is shown the same measurement for η (rotation around the horizontal axis connecting the two TMs). In this case, the capacitive readout is limited by sensor noise (~ $3{\cdot}10^{-7}$ rad/ $Hz^{1/2}$), while the ORO one, in a large frequency interval, is limited by the residual TM motion and reaches $2{\cdot}10^{-8}$ rad/ $Hz^{1/2}$ in high frequency

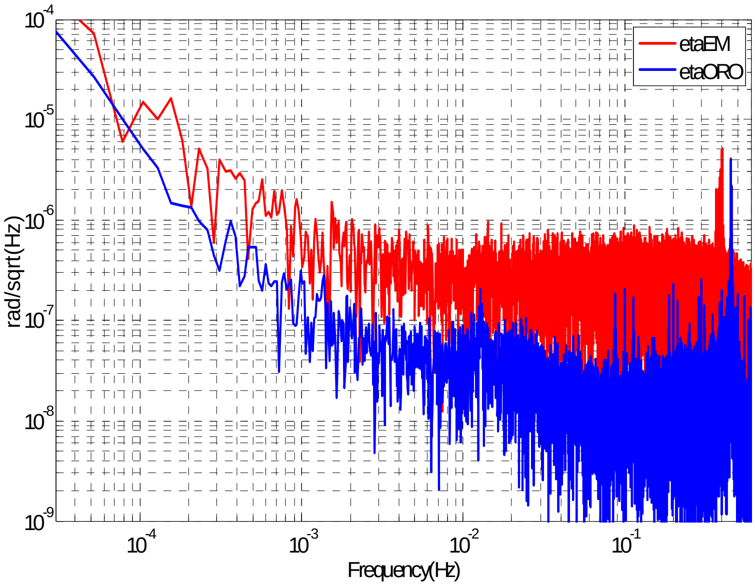

Figure 3. ORO measured η sensitivity (blue line) compared to the one of the EM capacitive sensor (red line). Also in this case, the EM sensitivity is limited to ~ $3{\cdot}10^{-7}$ rad/ Hz1/2, while the ORO reaches $2{\cdot}10^{-8}$ rad/ Hz1/2.

In fig. 4, the X signals (i.e. the measurement of the TM X position inside the sensor) of ORO (blue line), EM (red line) and STC (black line) are shown. All three sensors measure essentially the same signals, dominated by the residual simple pendulum swing mode motion and different readout performances are not appreciable The differential signals XSTC-XEM (orange) and XORO-XEM (magenta) are also shown. They are proportional to the pendulum torsion angle φ, and are dominated by the true pendulum torsion motion around and below the 0.7 mHz resonance and by the combined readout noise at higher frequencies. As both signal combinations show the same level of noise, we can conclude that the dominant term of the incoherent sum is coming from the EM (common to both combinations), and place an upper limit on the ORO noise level not to exceed the EM one (2 nm/$Hz^{1/2}$) above about 5 mHz.

3. The ORO as an auxiliary sensor for the torsion pendulum

Up to now, we dealt with the characterization of the ORO as a sensor for the LISA mission. The ORO is also interesting as a sensor for the torsion pendulum, if it can improve its performance as a ground testing facility for the LISA-Pathfinder hardware. Form this point of view, the most important measurement is the torque, that is used to place upper limits on the surface forces originating in the GRS (until now, such tests have studied the EM GRS used in this study, while tests on a prototype of the flight model design will begin in the near future. For this measurement, it is normally used the differential measurement of the two position sensor mounted on the opposite test masses (EM and STC), already shown in figure 4. This is, thanks to the rather long arm between the two test masses (20 cm), the best measurements of φ. In the same way, we can use the differential signal of ORO end EM.

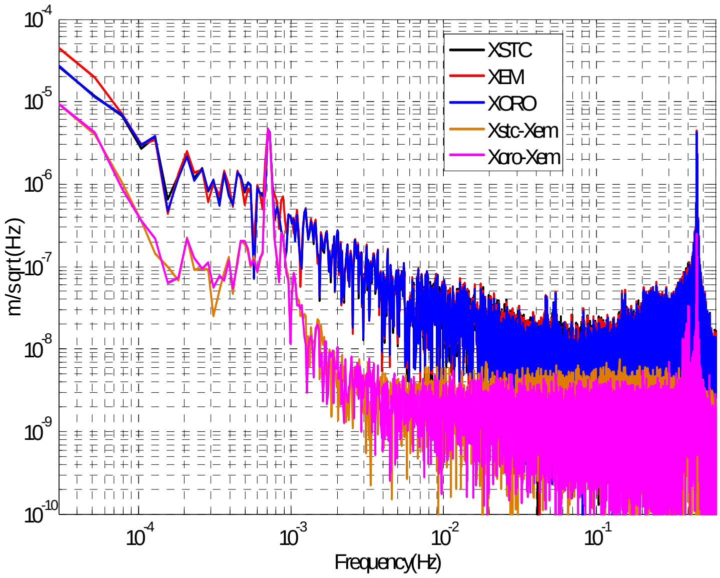

Figure 4 - Measured noise power spectrum of the ORO (blue) X readout, compared to the one of the capacitive sensors (EM in red, STC in black). The differential signals X_{STC}-X_{EM} (orange) and X_{ORO}-X_{EM} (magenta) are also shown. They allow to measure, in high frequency, the incoherent sum of the noise of sensor couples.

In figure 5 it is reported the residual force noise spectrum measured as the difference of TM displacements. The magenta and black lines represent the upper limit to the force noise obtained with ORO-EM and STC-EM combinations respectively. On the same graph, the limits posed by using the measurements performed on a single test mass with only the ORO (blue) and only the EM (red) are also shown.

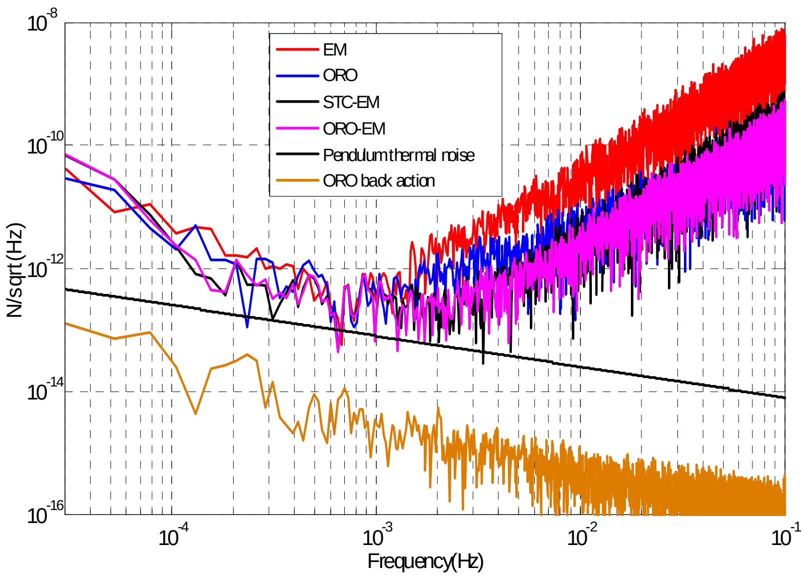

Figure 5. Residual force noise measured as a differential signal with EM-ORO (magenta line) and EM-STC (black line). The corresponding measurement with one single sensor is also shown: EM (red) ORO (blue). The orange line reproduces the ORO back-action, estimated form the measured S-LED power fluctuation.

As we can see, ORO and STC essentially allow reaching the same limit. This could be improved by inserting a second ORO on a different test mass so that the total noise of the differential measurement (presently limited by the capacitive sensors) will be limited by the incoherent noise of the two OROs. Other solutions, using a single ORO and multiple reflections, to directly measure φ, even if in a configuration not representative of the one proposed for LISA, are also being considered.

In figure 5 is also shown the upper limit to the ORO back action (orange), due to radiation pressure fluctuation, estimated from the measured power fluctuation of the light beams impinging on the QPDs. Clearly, the back action is not directly measurable because it is much below the torsion pendulum thermal noise. It could be only measured if artificially increased by modulating the S-LED's power.

4. Conclusion

We have tested the performance of an optical read-out system for the LISA GRS on the four-mass torsion pendulum facility operating in Trento. The results are encouraging, confirming that, as expected, the ORO shows a better sensitivity compared to the capacitive sensor in the interesting frequency band (this is directly measured for angles, while we only put upper limits for displacement).

We also verified that the ORO can already be used as e sensor for the torsion pendulum facility in place of one of the two capacitive sensors, obtaining the same sensitivity in force noise measurements.

Further upgrades of the ORO system, presently under definition, should permit to improve the performance of the pendulum as a ground testing facility for the LISA-Pathfinder hardware.

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