# Some Progress In The Development Of An Optical Readout System For The LISA Gravitational Reference Sensor

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**Abstract.** In this paper, we report on the progress in the development of an optical read-out (ORO) system for the inertial sensor of the LISA gravitational wave antenna. The device is based on optical levers and position sensors and is intended to be integrated in the present baseline design for the LISA inertial sensor, which is based on capacitive readout of the test mass position. In particular, we report some improved measurement of the sensitivity of this device, performed with a bench-top rigid set-up and tests on a real scale prototype.

**Keywords:** Optical read out, Drag free control, GW detectors..
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## INTRODUCTION

The usual solution for satellite drag free control, adopted as a reference solution also for the LISA Gravitational Reference Sensor (GRS), is the usage of capacitive sensors. The obvious alternative solution is some kind of optical read out (ORO) system; this offers very small back action and is potentially more sensitive than the capacitive one. The replacement of the capacitive sensor with an optical one, has been already proposed since a long time and different schemes have been suggested [1,2,3,4,5], but none has been developed in detail and experimentally demonstrated in the configuration suitable for flight on LISA. On the other side, a capacitive readout system has been already developed and tested on a torsion pendulum by the group of Trento University [6], and it is the reference solution to be tested on flight in the LISA Pathfinder mission. For this reason, it is very likely that, in case of successful test on flight, the capacitive sensor will remain as the reference solution also for LISA. Nevertheless, the demand for mission risk reduction and for extra information on couplings among the different degrees of freedom (DOF), leads naturally to think about a back up solution for the GRS. The goal of our activity is the development of an ORO system, based on optical levers, to be integrated in the present design of the GRS which uses capacitive sensor and electrostatic actuators. This work has been

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started since a few years [2,3]; in the present paper, we give a status report of the ORO activity in Napoli.

## GRS REQUIREMENTS AND ORO SENSITIVITY

Due to the extreme sensitivity required for GW detection, the specifications for the position sensor are very stringent for both the displacement sensitivity and the back action, which is the unwanted force that the sensor itself might apply on the test mass. According to the present design of the antenna [7], the sensitivity of LISA will be limited by position noise (essentially interferometer shot noise $\sim 4\ 10^{-11}$ m/Hz 1/2) above $\sim 3$ mHz, and by acceleration noise for lower frequencies. In order not to spoil this sensitivity with the noise reintroduced by the GRS through the Drag Free and Attitude Control System (DFACS), the required sensitivities for the capacitive readout are $2\cdot10^{-9}$ m/Hz$^{1/2}$ for translational DOFs and $2\cdot10^{-7}$ rad/Hz$^{1/2}$ for angular DOFs. These requirements are based on the very stringent assumption that the coupling of transverse movements to the main interferometer axis is $\leq 0.1\%$. It is worth of noting that this tight requirement holds in the frequency interval where LISA is limited by position noise, while it can be relaxed as $1/f^2$ below 3 mHz. It is clear that any reduction of the readout noise below the specifications would give a corresponding relaxation of the requirement for the cross-couplings. For the capacitive sensor, the sensitivity can only be further improved by reducing the free gap between test mass and electrodes, but this would give an unacceptable increase of back action due, for example, to net charges. On the other side, an ORO system can potentially give a significant noise reduction with negligible back action.

## PROPOSED OPTICAL LEVER SENSOR

We are studying an ORO system based on optical levers and quadrant photo-diodes (QPD) or position sensing devices (PSD) as light detectors. The general idea is that light beams are sent to the surface of the LISA proof mass and the position of the reflected beams is sensed by the QPDs. A translation or rotation of the proof mass results in movements of the light spots across the sensors. With a suitable combination of beam and sensors, all the six DOFs can be detected. In previous papers, we have already described in detail the principle of operation with the main limiting noise sources [2] and the scheme proposed for the actual implementation in LISA [3].

### Sensitivity Measurements

To study the sensitivity of our ORO system, we used a rigid set-up. The bench is machined from a single block of stainless-steel and has interfaces for fiber couplers and sensors. The dummy "test mass" mounts some mirrors and can be moved for calibration. Furthermore, the system is symmetric for differential measurements. The whole set-up is closed in a box to reduce thermal variations and prevent effect of air flows etc. Since the beginning of the experimental activity, several efforts have been devoted to the improvement the of thermal isolation of our system. Also the optical set-up has been improved by using polarization maintaining single mode optical fibers for injecting the light beam and Faraday-isolators for preventing back reflections that could spoil the stability of the laser sources. A further improvement has been the usage of window-less QPDs in order to remove the effect of stray fringes due to multiple reflections inside the window. All these efforts have permitted to achieve the sensitivity reported in figure 1, which gives significant improvements with respect to previous results [3]. The measurement (actually the residual beam motion across the sensor) is performed with a single beam, in different frequency intervals, and is compared with the expected noise model [2] and the measured sensitivity for the capacitive sensor. As we can see, the ORO sensitivity is already below the requirement for frequencies above 1 mHz. It is worth of noting that the measured sensitivity is still about a factor 5 higher than the expected one; this extra noise has not yet been explained and it is still under investigation. Nevertheless, the present noise level would already allow a relaxation of the requirement on cross-couplings by a factor of ten at 10 mHz and even more at higher frequencies. The angular sensitivity can be evaluated by considering the length of our optical lever (L = 10 cm), so that the measured residual displacement can be converted in angular jitter (upper limit). It turns out that the angular noise is well below the specification ($2\cdot 10^{-7}$ rad/Hz$^{1/2}$) in the whole frequency interval.

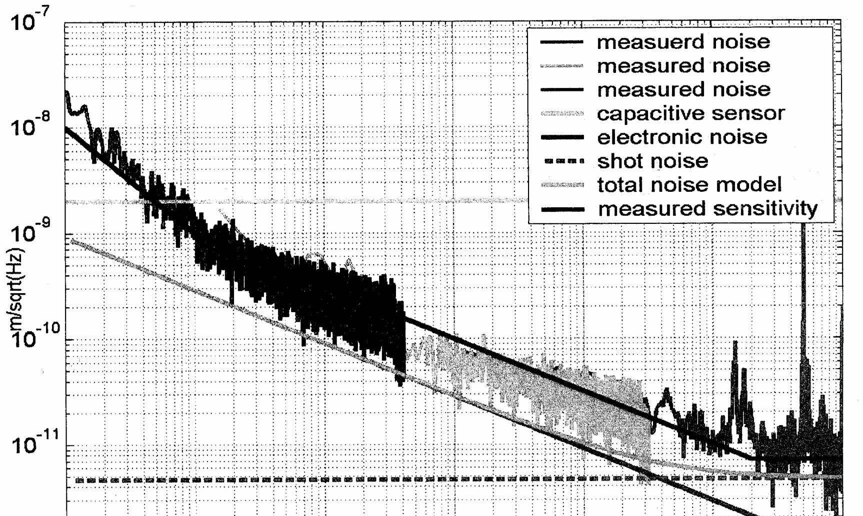
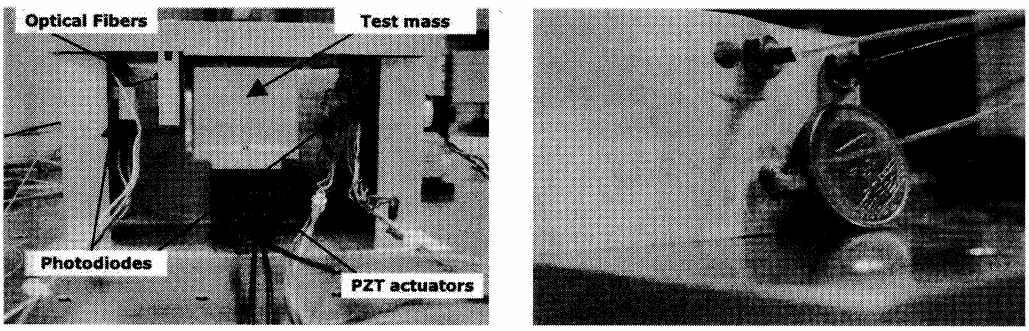



**FIGURE 1.** ORO sensitivity measured with the rigid set-up (incidence angle 45°) compared with electronic noise and shot noise computed for a power of 0.3 mW and capacitive sensor sensitivity.

## Real scale prototype for integration in LISA

In order to study an ORO set-up compatible with the LISA GRS, we used, as a starting point, the Test-Flight Package (LTP) model for the electrode housing (EH), since we don't have yet a final design of the LISA layout. In the proposed solution, three fiber output couplers are directly mounted on the external part of the EH and some of the electrodes are used as mirrors for sending the beams to the surface of the test mass. The reflected beams exit from the EH through small holes in the electrode guard-rings and are collected by photo-detectors placed on the internal walls of the vacuum chamber. Laser sources and photodiode electronics should be placed outside the vacuum chamber. A detailed description of the opto-mechanical set-up can be found in reference [3]. In order to test the effectiveness of this design, we realized a real scale prototype that reproduces exactly the overall dimensions of the EH from the point of view of the light paths, without including the features that are not relevant for the test of the ORO. The prototype is shown in figure 2, together with a detail of the plate supporting the fiber output couplers. The dummy test mass (TM), hosting the mirrors that reflect the light beams, is mounted on a three dimensional PZT actuator, with capacitive readout, used for calibration and for measuring the optical matrix that links the photodiode signals to the test mass displacements.




(a) (b)

**FIGURE 2.** (a) The ORO prototype. (b) A detail of the angled interfaces for the output of the optical fibers.

The tests performed with this device allowed to validate the optical layout, since the light beams come out in the right position on the detectors within few hundreds microns (compatible with machining tolerances).

We also measured the (six by six) sensing matrix $B_{ij}$, which relates the TM displacement to the QPDs signals. What we can actually measure, is the inverse matrix $A_{ij} = B_{ij}^{-1}$ that links the output signals to the mass displacement. This matrix is measured by moving by a known amount the TM on one single degree of freedom, using the PZT actuation system. In this way, the six matrix elements of a given column can be measured as direct ratio of the six photo-detector signals over the input test mass displacement as measured by the capacitive sensor of the PZTs. In the practice, it is better to excite the system sinusoidally so that the matrix element can be measured with higher precision as the ratio of the FFTs of the output and input signals (this gives modulus and phase, and then also the sign is known). Once the matrix is filled, we can invert it, in order to obtain the matrix **B**. Presently, in our set-up we can only move the TM in the three longitudinal DOFs so that only 18 of the 36 matrix elements can be measured. In the future we plan to add rotation actuators for measuring all the 6 DOFs. The measured matrix elements are in good agreement (within 1 %) with the analytical model, that is then also validated and can be used for inverting the matrix **B** in order to get the direct matrix **A**.

## DISCUSSION

We have analysed an optical readout system, based on optical levers, to be integrated as a back-up solution in the LISA GRS. The device is very simple and then cheap and reliable. This makes it interesting also in comparison with other ORO systems [4,5] that are potentially more sensitive but with higher cost and complexity (some kind of interferometers for example).

The measured sensitivity is better than the one of the capacitive sensor in a wide frequency range (> 1 mHz). The improvement in sensitivity would permit a relaxation on specifications for cross-couplings, if such a sensor was adopted as the main one for drag-free control loops.

A layout compatible with the LTP present design has been also developed and successfully tested on a real scale bench-top prototype.

Next step will be the integration and testing of our ORO system on a torsion pendulum, to be performed in collaboration with the group of Trento University. This test will allow to check the performances with an independent measurement device and to verify that the back action is within the specification.

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