The UF Torsion Pendulum, a LISA Technology Testbed: Sensing System and Initial Results

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Abstract. The upcoming LISA Pathfinder mission will test the Gravitational Reference Sensor and the Disturbance Reduction System for a future LISA-like space mission. While LISA Pathfinder is expected to show that the technology for LISA exists and meets the LISA requirements, it is likely that LISA Pathfinder will also reveal areas where future improvements can be made and might be necessary. Some of these are already well known (such as the discharging system). After all, the technology for LISA Pathfinder was frozen about 10 years ago or about 30 years before a LISA-like mission will be launched. The case for continued testing and development of the technology is clear. The University of Florida is currently building a torsion pendulum-based test facility to explore new techniques and also to develop a base in the United States for state-of-the-art Gravitational Reference Sensor technologies.

1. Introduction

LISA [1][2] is the most mature concept for detecting gravitational waves from space and has the potential to both open up a new realm of astronomy and provide a probe of fundamental physics. To do this it must measure gravitational wave strains of $\approx 10^{-23}$ over a ten day integration time, and thus must be sensitive to length strains on the order of $\frac{\text{pm}}{\sqrt{\text{Hz}}}$ in the measurement band of 0.1 mHz to 100 mHz. One obstacle to this ambitious goal is residual acceleration noise on the test masses, which limits the sensitivity of LISA-like missions below a few mHz. LISA-like missions typically use the following requirement for the residual acceleration noise on each test mass:

$$s_a^{1/2} < 3 \times 10^{-15} \left( 1 + \left( \frac{f}{3 \text{ mHz}} \right)^2 \right)^{1/2} \frac{\text{m}}{s^2 \sqrt{\text{Hz}}}$$  \hspace{1cm} (1)

The UF Torsion Pendulum is a LISA technology development facility which will build on the work done at the University of Trento and is aimed at testing the performance of new technologies for the LISA Gravitational Reference Sensor (GRS) that enable this requirement to be met.

2. Concept and Motivation

The LISA spacecraft (SC) ensure the purity of free fall of their test masses using the Drag-Free Attitude Control System (DFACS). The GRS continually senses the position and orientation of the TMs. These signals are used by the DFACS to maneuver the SC around the TMs with $\mu$N thrusters. Conceptually, the GRS consists of a set of electrodes which surround the TM. These electrodes are mounted inside the electrode housing (EH) and are connected to the GRS electronic. Two of the electrodes are used as injection electrodes where an AC signal is injected to polarize the TM. This polarization is measured with the sensing electrodes. Furthermore, the electrodes are also used for electrostatic actuation of the TMs. The GRS completely encloses the TM and is ideally the only device which interacts with it. Most spurious forces on the
TM will depend on these interactions and need to be minimized to meet the acceleration noise requirements in Eq. 1.

Ground-testing is critical to develop noise models for these interactions and to investigate different designs and operational modes of the GRS. The University of Trento has previously constructed a torsion pendulum [3] to decouple form the Earth’s gravitational field. Their experimental results still set the standard in this field and our design is similar. We attached hollow mock-ups of LISA TMs to the ends of the arms of a cross-shaped structure which serves as the pendulum’s inertial member. This entire structure is suspended from a torsion fiber. The rotational or torsional degree of freedom of the pendulum is then decoupled from Earth’s gravitational field and in ‘free fall’ above its mHz resonance frequency. The lever arm of the pendulum allows us to treat its rotation as a simple translation of the TM inside the GRS. Hollow TMs are used to reduce the mass of the pendulum. The reduced mass allows to reduce the thickness of the suspension fiber which reduces the thermal noise. The reduced mass also increases the accelerations and displacements caused by all surface forces which enables us to study these least understood forces in greater detail [4] while accelerations caused by bulk forces are typically independent of the mass. Two of the four TMs are then encased in separate GRSs to study their interactions with the TMs.

3. Mechanical Design

3.1. Torsion Pendulum

The inertial member structure is comprised of four cubic test masses which are mounted on four 22 cm long struts. Each 46 mm, 480 g test mass is hollow and fabricated from aluminum to minimize mass. The aluminum surfaces are gold-coated to minimize stray surface potentials. Each test mass is constructed from five individual parts that are bonded together with EPO-TEK H20E conductive epoxy. Two of the TMs are surrounded by simplified electrode housings (EHs). These two TMs are fixed to the main pendulum structure via quartz rings to electrically isolate them. The inertial member is shown in Figure 1, and the full system in Figure 2.

The suspension fiber is fixed to a shaft that elevates the attachment point to a position 10 cm above the center of mass of the pendulum. This maximizes the natural frequency of the pendulum in the tilting mode so that it is well above the measurement band and the rotational mode frequency. The suspension fiber itself is a 1 m long tungsten fiber with a diameter of 50 µm. The fiber thickness was minimized for the given weight of 480 g (with a safety factor of roughly 2) to minimize fiber thermal noise. This fiber is glued to a custom fiber attachment cap at each end such that a standard screw can be attached. A magnetic damper is located above the main fiber to damp out the swinging mode of the pendulum. The damper consists of two sets of neodymium magnets fixed to the vacuum chamber. An aluminum disc-shaped conductor is fixed to the suspension fiber within their magnetic field so that any swing in the pendulum is damped by eddy currents formed in the conductor. The magnetic damper is shown in Figure 3b. A thicker (250 µm diameter) tungsten fiber is located above the magnetic damper. This fiber preserves all degrees of freedom of the pendulum, while experiencing a negligible amount of deformation during torsional oscillation. Using similar custom caps, the thick fiber is fixed to the top of the vacuum chamber.

Figure 1: Inertial Member. The hollow TM mockups are mounted at the ends of four rods, each in turn attached to a central assembly.
Figure 2: Complete UF Torsion Pendulum assembly. Various features are pointed out.

3.2. Simplified Electrode Housing

The current electrode housing is a simplified version of the LISA Pathfinder GRS, and includes a total of 6 electrodes: 1 located on each of the interior faces. In the future, we will replace this EH with potential flight models that include electrodes to sense all degrees of freedom. The inertial member of the pendulum hangs from the suspension fiber such that two of the test masses remain enclosed in electrode housings for capacitive readout. The structure of the housing is also gold-coated aluminum.

The electrodes are electrically isolated from the structure of the housing with ceramic bushings. In the sensitive direction (in which the pendulum rotates about its axis), the gaps between the electrodes and test mass surface are 8 mm. This gap size was chosen (in contrast to the 4 mm gap size in the LPF GRS) to minimize interactions between the GRS and the TM while we improve our facility as a whole.

UV optical fibers connect directly to the structure of the electrode housing so that UV light can be used to control the charge of the test mass. There are 3 available optical fiber ports located on each electrode housing: one that illuminates the test mass, one that illuminates the housing, and one that illuminates both. The electrode housing is shown in Figure 3a.

Figure 3: Photographs of the (a) electrode housing and (b) eddy current damper, both prior to integration with the pendulum.

All of the abovementioned components are located inside a vacuum chamber. The vacuum chamber is 60 cm in diameter. It includes a tall
Table 1: Natural frequencies of pendulum, both as computed from theory and as measured (see Fig. 7). Damping terms have been left out as they only negligibly influence the frequencies. The measured values are the average of three separate overnight measurements.

| Mode       | Rotating | Swinging | Tilting | Bouncing |
|------------|----------|----------|---------|----------|
| Parameters | $\Gamma = \frac{\pi^4}{2L} \left( E_r + \frac{mg}{\pi r^2} \right)$ | $L = 1\text{m}$ | $I_t = 8.37 \times 10^{-3}$ | $k = \frac{E_b \pi r^4}{L}$ |
|            | $E_r = 161 \text{ GPa}$ | $g = 9.81 \text{ m/s}^2$ | $m = 477 \text{ g}$ | $r = 25 \mu\text{m}$ |
|            | $I_r = 1.65 \times 10^{-2}$ | $h = 98.8 \text{ mm}$ | $E_b = 411 \text{ GPa}$ | $E_b = 411 \text{ GPa}$ |
| Equation   | $f_r = \frac{1}{2\pi} \sqrt{\Gamma I_r}$ | $f_s = \frac{1}{2\pi} \sqrt{g L}$ | $f_t = \frac{1}{2\pi} \sqrt{g h I_t + I_r}$ | $f_b = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$ |
| Predicted Value | $f_r = 393 \mu\text{Hz}$ | $f_s = 455 \text{mHz}$ | $f_t = 948 \text{mHz}$ | $f_b = 6.55 \text{Hz}$ |
| Measured Value  | $f_r = 310 \pm 8 \mu\text{Hz}$ | $f_s = 434.2 \pm 0.1 \text{mHz}$ | $f_t = 1.27 \pm 0.03 \text{Hz}$ | $f_b = 6.08 \pm 0.04 \text{Hz}$ |

4. Electronic Design

4.1. Analog Electronics

The GRS measures the position of the TM by measuring the position-dependent capacitance of a set of electrodes towards the TM. Our electronics function by polarizing the TM at 100 kHz, converting the current flowing through the TM/electrode capacitors to a voltage with a transimpedance amplifier, and digitizing the result. The transimpedance amplifiers hold the sensing electrodes at virtual ground with respect to the TM, which guarantees that the voltage drop between the TM and electrodes is only due to (discounting noise sources) to the injection voltage. This is important not only to maintain purity of the 100 kHz signal, but also to avoid unintentional forces on the TM.

Figure 4: Block diagram of signal flow in the UF Torsion Pendulum readout scheme.
In more detail, the injection voltage $V_{inj}$ is applied directly to a pair of electrodes on a given GRS prototype as shown in Fig. 3a, so the resultant TM voltage at 100 kHz (the frequency to be assumed throughout the text) is

$$V_{TM} = \frac{2C_{inj}}{C_{tot}} V_{inj} \equiv \alpha V_{inj},$$  \hspace{1cm} (2)

where $C_{inj}$ is the capacitance of one injection electrode towards the TM, and $C_{tot}$ is the total capacitance of the TM towards the EH and electrodes (all held at ground). Further consider the position dependence of both capacitances in the “soft” DOF in the parallel plate model:

$$C_{\pm}(x) = \frac{\epsilon_0 A_{elec}}{d \mp x}$$ \hspace{1cm} (3)

$$\approx \frac{\epsilon_0 A_{elec}}{d} \left( 1 \mp \frac{x}{d} + \left( \frac{x}{d} \right)^2 \pm O \left( \frac{x^3}{d^3} \right) \right)$$ \hspace{1cm} (4)

$$\rightarrow \Delta C = C_+ - C_- = -\frac{2\epsilon_0 A_{elec}}{d} \frac{x}{d} + O \left( \frac{x^3}{d^3} \right)$$ \hspace{1cm} (5)

$d$ is the gap between the TM and electrode when the TM is centered, and $A_{elec}$ is the area of that electrode. For small displacements ($\frac{x}{d} \ll 1$) the difference between two opposing capacitances is close to linear in the TM displacement. Hence, a measurement of the differential capacitance is a measurement of the position of the TM with respect to the center of the housing. The electronics shown in Fig. 5 shows the sensor circuit. The 100 kHz signal passes through the initial high-pass filter to the transimpedance amplifiers and finally to the differential amplifier. The total transfer function is

$$V_{out} = -\frac{R_2}{R_1} \frac{\Delta C}{C_{fb}} \alpha V_{inj} = -\frac{R_2}{R_1} \alpha V_{inj} \frac{2\epsilon_0 A_{elec}}{d} \frac{x}{d}$$ \hspace{1cm} (6)

Therefore, the amplitude of the readout electronics output at 100 kHz, which is the desired readout signal, is linear in the TM displacement. The expected limiting noise source is shot noise in $R_{fb}$ at an equivalent displacement noise level of 10nm/√Hz.
4.2. Digital Electronics

The signal is a 100 kHz signal with an amplitude which is proportional to the displacement and which changes phase by 180° at the lock point. This signal is then demodulated digitally on board the DAQ card. The 100 kHz signal from the readout electronics is passed through a single-pole antialiasing filter with a corner frequency of 350 kHz before it is digitized with a 700 kHz sampling rate. The digitized signal is then multiplied with both the 100 kHz signal which was used to polarize the TM and that same signal phaseshifted by 90°. We use cascaded integrator-comb (CIC) filters to integrate and downsample these products by a factor of 8192, for a final data rate of 85.6 Hz. These demodulated signals are passed to the host computer for storage. By observing the In-phase/Quadrature vector swept out by the pendulum’s motion, we can rotate the demodulation phase such that all of the information is in one quadrature to maximize signal-to-noise ratio. The dataflow for this scheme is shown in Fig. 6.

![Figure 6: Block diagram of the digital side of the readout electronics. Here \( \phi \) is the Numerically-Controlled Oscillator (NCO) angle and \( \Theta \) is the demodulation angle.](image)

The DAQ is also used to apply actuation signals to the pendulum. The force between two capacitor plates (in an idealized infinite-parallel-plate model) is given by

\[
F_{\text{cap}}(x) = -\frac{1}{2} \frac{\partial C}{\partial x} (V_1 - V_2)^2
\]

where \( V_1 \) and \( V_2 \) are the voltages on the capacitor plates. Therefore, we can apply a force on the TM by applying a voltage on the appropriate electrode and pull the TM in that direction. We currently have monopolar DC amplifiers (which we will upgrade to bipolar AC amplifiers shortly) which can amplify up to 1000 V for initially stabilizing the pendulum. For precision actuation, we use the 10 V output of the DAQ directly. These signals are first sent through a low-pass filter to avoid interference with the readout, and thereafter directly applied to the electrodes.

5. Current Noise Performance

We present here a measurement of the noise performance of the facility at its current state of development and a plot of the theoretical limit on the performance of the pendulum. After allowing the chamber to pump down to its base pressure of \( 2 \times 10^{-5} \) torr, both sensors (referred to as “Gamma” and “Delta”) were calibrated using the micrometer translation stage shown in Fig. 2. The equilibrium point of the system was moved to the center of the sensor using the rotation stage, and the pendulum’s rotational mode was damped using the electrostatic actuation. The actuation was then shut off and the pendulum was allowed to freely oscillate over a weekend for nearly 59 hours. During this period, the positions of the TMs in both the Gamma and Delta sensors were recorded. The motion is dominated by the swinging motion which is correlated in both degrees of freedom. We are more interested in the differential motion which is directly associated with the torsional rotation of the pendulum. Fig. 7 shows the linear spectral density (LSD) from the Gamma sensor signal; the LSD of the Delta sensor signal looks identical, and the differential signal \( \phi_{\text{LSD}} \). The signal has been scaled by the lever arm of 22 cm while the
differential signal is scaled by the distance between both test masses to express them as angles. The LISA requirement and the breakdown of the pendulum performance limit is shown in Fig. 8.

Note firstly that the rotational mode peak is somewhat less than what it should be from theory (see Table 1). This reduction in resonant frequency is due to the presence of charge on one of the TMs, which we measure to be on the order of $10^{-10}$ C. Our charge control system (see [6]) has thus far been unable to remove it completely. As mentioned above, charge on the TMs adds (to first order) a negative stiffness which counteracts the natural stiffness of the fiber and lowers the resonant frequency. All other resonances were close to theory.

A large amount of common-mode noise between the sensors in the 1 to 100 mHz band is taken out in the Phi LSD; this implies that it resides in the swing mode. Our ability to remove this noise in the Phi spectrum depends strongly on the accuracy of our relative calibration between the sensors, so investigating this flat, non-electronic noise between 10 mHz and the swing resonance is a prime concern. We are also limited around 1 mHz by an unknown noise source that goes as $1/f$, here partly obscured by the rotational resonance. At the lowest frequencies (below the resonance), the cross-coherence between Phi and temperature (measured but not shown here) is nearly 1; while this is currently below our measurement band, it will likely become important as we improve the
performance of the pendulum at higher frequencies, and as such we will build a thermal room around the pendulum to stabilize the thermal environment.

Finally, analysis of the prototype readout electronics suggests the noise floor at higher frequencies (above the swing mode resonance) should be around $10\, \text{nm}\sqrt{\text{Hz}}$, but in reality it is several times higher than this; the noise is definitely electronic in origin as it appears at the same level when the GRS is replaced by two static capacitors. Since there is actually a strong cross-coherence between the two sensors above 100 mHz, we suspect this higher noise level may be due to either insufficient shielding or a common ground loop. We will continue to investigate the cause of this excess and improve the design of the readout electronics to bring them in line with the LISA GRS performance requirement.

6. Future Work
The ongoing mission of the UF Torsion Pendulum group is to measure the performance of various GRS designs and test new technologies with which we can improve that performance. Practically speaking, this means we will be measuring the transfer function of various physical parameters related to the GRS into external torque. With appropriate models of the LISA environment, this will allow us to assert that a given GRS model would perform at a certain level during the actual mission. For example, we will integrate heating elements to vary the temperature of different parts of the GRS (both net and differentially) or the pressure inside the chamber. Investigations into these transfer functions will begin as soon as we finish the commissioning phase for the facility and produce a first prototype of a LISA-like GRS, both of which are currently in progress. We will also use the facility to test alternative hardware and techniques for the Charge Management System. Another broader goal is to reduce sources of noise in the pendulum as much as possible - not only to be able to make more sensitive transfer function measurements, but also to be able to make statements about the level of excess noise from unmodeled sources present in the system. As a simple example of this procedure, insulating styrofoam will be added around the vacuum chamber to improve thermal stability. To further improve thermal stability, the entire vacuum chamber will be placed in a two-meter-deep concrete pit, which should provide some isolation against building vibrations as well.

Furthermore, we will implement an interferometric readout for the pendulum. A potential design is shown in Fig. 9. It is a polarization-multiplexed heterodyne interferometer, wherein (in Fig. 9) the red and blue lasers are orthogonally polarized, and offset by the heterodyning frequency. A reference beat signal between the two lasers is taken on the reference PD-bench before BS1. The blue laser then gathers phase information from the test mass, while the red laser gathers a constant amount of phase from a reference mirror (M1). The beat between these signals is then measured on the main PD-bench. The advantage of this scheme is a minimization of the space on the whole bench which needs to be ultrastable. Finally, we will be able to do wavefront sensing with the Guoy telescope on each PD-bench to also measure the tilt of the TM.

7. References
[1] Stebbins R et al. (2009). Astro2010 RFI Response.
[2] Amaro-Seoane P et al., (2012), arXiv:1201.3621
[3] Carbone L et al. (2007) Phys. Rev. D 75, 042001
[4] Ciani G (2008) Ph.D. Thesis, University of Trento.
[5] Hewitson M et al. (2009) Class. Quantum Grav. 26 094003
[6] Olatunde T et al. (2014) LISA Symposium X Proceedings This Issue.