Temporal Extent of Surface Potentials between Closely Spaced Metals

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Variations in the electrostatic surface potential between the proof mass and electrode housing in the space-based gravitational wave mission LISA is one of the largest contributors of noise at frequencies below a few mHz. Torsion balances provide an ideal testbed for investigating these effects in conditions emulative of LISA. Our apparatus consists of a Au coated Cu plate brought near a Au coated Si plate pendulum suspended from a thin W wire. We have measured a white noise level of $30\,\mu\mathrm{V}/\sqrt{\mathrm{Hz}}$ above approximately 0.1 mHz, rising at lower frequencies, for the surface potential variations between these two closely spaced metals.

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The low frequency sensitivity of the ESA/NASA gravitational wave mission LISA is limited by spurious accelerations of its enclosed proof masses [1, 2]. Above 0.1 mHz one of the largest contributors of spurious accelerations are forces due to electrostatic patch field fluctuations [3]. Each of the proof masses (PM) in LISA are contained within an electrode housing, together known as the gravitational reference sensor (GRS). The electrodes and the PM form a collection of capacitors used in position determination and proof mass actuation for the drag-free operation of each spacecraft. Fluctuations in the electric potential between the PM and each of the electrodes will lead to acceleration disturbances of the PM. The current LISA requirement on surface potential fluctuations, based on a noise budget flowdown, is that they do not exceed $50\,\mu\mathrm{V}/\sqrt{\mathrm{Hz}}$ above 0.1 mHz [4]. Previous measurements of surface potential variations, using a Kelvin probe [5] or a mock-up of the proposed LISA GRS which has finished engineering testing for the LISA Pathfinder mission [6], are believed to be measurement limited at $\sim 1\,\mathrm{mV}/\sqrt{\mathrm{Hz}}$ above 0.1 mHz.

Our torsion balance apparatus has been specifically designed to investigate parasitic voltage fluctuations and thermal gradient related effects [7, 8]. The pendulum is a mostly rectangular wafer of Si suspended by a 53 cm long, 13 μm diameter, W fiber. The Si was coated with an adhesion layer of ~ 20 nm TiW and then ~ 225 nm layer of Au. A movable Cu plate of slightly larger size is split into two halves, left and right. It is coated with ~ 30 nm TiW then ~ 100 nm Au, A schematic of our setup is shown in Figure 1. The separation between the pendulum and Cu plate can be adjusted between 0 and 10 mm to within $\approx 10\,\mu$m reproducibility.

Four Au coated control electrodes made of Al are mounted on the side of the pendulum opposite that of the Cu plate, two smaller in size and closer to the pendulum rotation axis. The distance between the control electrodes and the pendulum is 7 ± 1 mm. Optical readout of the pendulum rotational angle is done by an autocollimator, which is also located on this side of the pendulum. The autocollimator combined with the control electrodes provide a feedback mechanism for fixing the pendulum angular position. The torque due to thermal and other forces on the pendulum can be measured through the control voltage supplied to the control electrodes, typically the larger electrodes. As detailed in [8], running the system in the feedback mode does not increase the noise or degrade the performance of our torsion balance. The residual motion of our pendulum is at the level of $2\,\mathrm{nrad}/\sqrt{\mathrm{Hz}}$, which is equivalent to a cold damped temperature of about 0.3 K. Thermal noise at 297 K is nearly

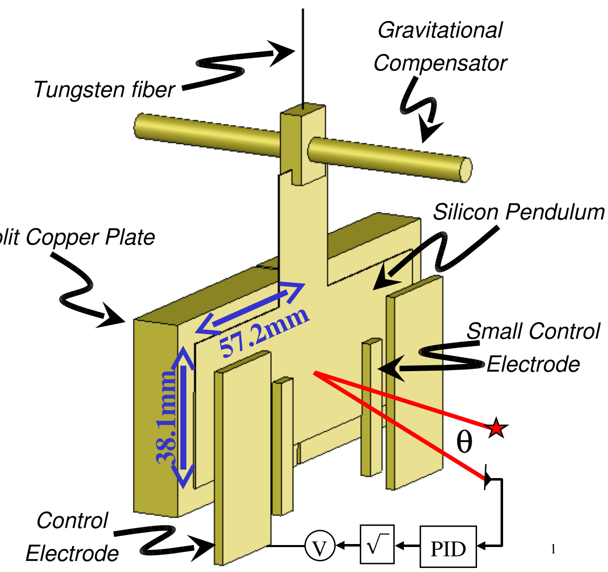

FIG. 1: Schematic showing the Si pendulum suspended from the W fiber with the split Cu plate and control electrodes. The autocollimator for optical readout of the pendulum angle is shown along with the feedback control loop mentioned in the text.

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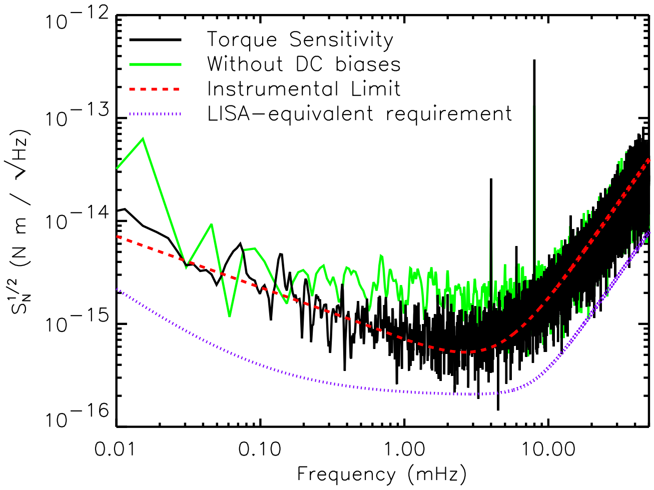

FIG. 2: (color online) Torque sensitivity of our apparatus in feedback with a plate-pendulum separation of 1 mm with (dark) and without DC biases applied (green/grey). Our instrumental limit (dashed) and the LISA-equivalent requirement (dotted) are also shown. The quadrupole and hexadecapole gravitational couplings, along with an off-axis coupling, of our external calibration source can be seen at 4, 8, and 6 mHz respectively [8].

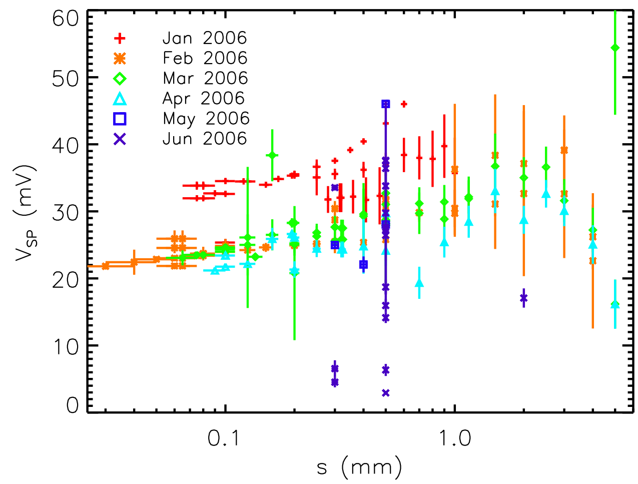

FIG. 3: (color online) Measurements of the surface potential between the pendulum and the right half of the Cu plate as a function of the plate-pendulum separation. Both halves of the Cu plate have similar separation and temporal characteristics. Variation with separation may be explained by spatial variations in the surface potential.

$1\,\mu\mathrm{rad}/\sqrt{\mathrm{Hz}}$ at 1 mHz.

The entire assembly is housed within a vacuum chamber with a base pressure $\approx 10^{-5}$ Pa. A polystyrene enclosure around the vacuum chamber assists in passive thermal control of the apparatus. The chamber rests on a large Al plate which is supported on a block of concrete.

The free torsional oscillation period of our pendulum, with the Cu plate ≈ 1 cm away, is 830 s. The calculated moment of inertia of our Si pendulum is $I = 135\,\mathrm{g\,cm}^2$. Four masses rotate around the vacuum chamber act as a gravitational calibration source for converting angular deflections into torques [8]. Figure 2 shows typical torque noise data for our pendulum when under electrostatic feedback. Also shown is the instrumental limit given by the sum of the pendulum thermal noise, with a quality factor $Q = 4000$, and the autocollimator noise converted into torque. The LISA-equivalent requirement is the goal acceleration noise sensitivity [9] converted into torque assuming a proof mass of $M = 1.96$ kg and a moment arm $l = 33$ mm.

Variations in the electronic work function between the Au coated Si pendulum and Cu plate can be exaggerated in our apparatus by decreasing the separation between them. We measure the spatial average surface potential between our pendulum and one half of the Cu plate by finding the minimum of the voltage-torque curve given by the following expression:

$$N = \frac{1}{2}\frac{dC}{d\theta}\left(V - V_{SP}\right)^2, \tag{1}$$

where the capacitance is given by $C(\theta) \approx \epsilon_0 A/s$, with $A = 2.18 \times 10^{-3}\,\mathrm{m}^2$ the half-plate-pendulum area overlap, s is the plate-pendulum separation, V is the applied electric potential on the Cu plate (with the pendulum at instrumental ground), and V_{SP} is the derived surface potential difference. In practice, we measure the torque via the applied voltage on the control electrode required to keep the pendulum parallel to the Cu plate. By changing the voltage on the Cu plate we map out a parabola and fit for the surface potential value. We have consistently measured ≈ 120 mV on the left half of the Cu plate and ≈ 25 mV on the right half. The value we determine is the sum of all contact potential junctions as well as the physical surface potential difference between the two Au coated surfaces. Therefore our results represent an upper limit on the physical surface potential fluctuations between the two surfaces. The electrical paths to our DAC of both halves of the Cu plate are similar. The connections external to the vacuum chamber were verified of not causing this discrepancy by swapping them.

We have noticed that the derived surface potential appears to vary somewhat with the plate-pendulum separation. Figure 3 contains surface potential determinations against s over the course of the first half of the year 2006. We suspect that this effect is due to spatial variation of the patch fields across the Cu plate and pendulum. As the plate-pendulum separation is changed, different patches are averaged over resulting in slight differences in the surface potential value. Variations such as these have been observed with Kelvin probe measurements which determine patch fields on the order of 1 mm in size for similar materials [5]. The slow variation on the timescale of weeks indicates for LISA that the surface potentials will need to be periodically measured and corrected for by applying small DC biases on the control electrodes [4]. In our apparatus we apply DC biases to each half of the Cu plate to cancel the surface potential. When the appropriate potentials are not applied the torque noise measured from the pendulum is increased (see figure 2) we believe due to the amplification of voltage fluctuations via the variation of Equation 1 with $V = 0$ rather than $V \approx V_{SP}$:

$$\delta N = \left| \frac{dC}{d\theta}(V - V_{SP}) \right| \sqrt{\delta V^2 + \delta V_{SP}^2}. \qquad (2)$$

A faster determination of the surface potential comes by realizing that only two applied voltages need to be used. These two voltages are chosen to be symmetric about the surface potential and yield the same torque on the pendulum, e.g., $V_\pm = V_0 \pm V_a$, where V_0 is a guess for the surface potential value from previous measurements, and $V_a \approx 0.3\,\mathrm{V}$ is chosen to yield a suitable torque on the pendulum. We switch between these two potentials and record the torque on the pendulum, which remains relatively constant by construction. If the surface potential changes with time, then also will the measured torque difference when switching between the two voltages. Therefore the torque difference is a measure of the surface potential. Mathematically the relation is

$$V_{SP} = V_0 - \frac{(N_+ - N_-)}{2\frac{dC}{d\theta}V_a}, \qquad (3)$$

where $N_\pm$ is the measured torque when $V_\pm$ is applied. $dC/d\theta$ is determined before and after each measurement and is on the order of $1000\,\mathrm{pNm/V^2}$. Figure 4 contains a measurement of surface potential fluctuations using this technique. The spectrum is white at $\approx 30\,\mu\mathrm{V}/\sqrt{\mathrm{Hz}}$ for frequencies above about 0.1 mHz, and rises $\sim 1/f$ below. The voltage on the Cu plate is monitored by our ADC during these measurements. The electrically measured voltage noise on the Cu plate shows a similar spectral shape, with a level $\approx 10\,\mu\mathrm{V}/\sqrt{\mathrm{Hz}}$. The current LISA requirement for voltage fluctuations is $50\,\mu\mathrm{V}/\sqrt{\mathrm{Hz}}$ above 0.1 mHz, rising slowly at lower frequencies [4]. Our upper limit on the surface potential fluctuations meets the LISA requirement at frequencies above 0.1 mHz, with some excess at low frequencies.

The noise in the voltage applied to the Cu plate contributes to the measured surface potential value in Figure 4. However, the electrically measured value of the voltage noise ($\approx 10\,\mu\mathrm{V}/\sqrt{\mathrm{Hz}}$) is below that of the measured surface potential which implies that this is not the dominant source of noise. Using a slightly noisier source ($\approx 20\,\mu\mathrm{V}/\sqrt{\mathrm{Hz}}$) does not increase the measured surface potential fluctuations.

The voltage noise on the control electrode will also contribute to the measured surface potential fluctuations. By having a smaller area overlap with the pendulum, the smaller control electrodes provide a mechanism to reduce the effect of any control voltage noise. Given the difference in areas and lever armlengths of the smaller control electrodes, the noise level contribution from the smaller control electrodes should be a factor of ~ 3 less than that from the larger control electrodes. As shown in Figure 4 there does not appear to be any substantial change in the surface potential level when operating with the smaller control electrodes.

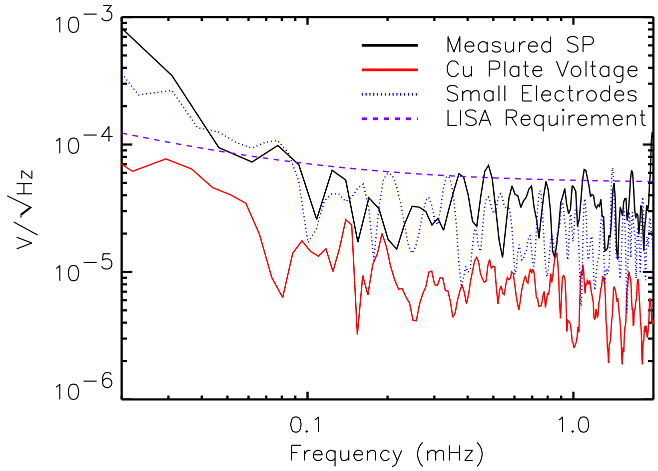

FIG. 4: (color online) Measured surface potential fluctuations (dark solid) using the method described in the text have a level of $30\,\mu\mathrm{V}/\sqrt{\mathrm{Hz}}$ rising as $1/f$ below 0.1 mHz. The LISA voltage fluctuation requirement (dashed) is $50\,\mu\mathrm{V}/\sqrt{\mathrm{Hz}}$ rising as $1/\sqrt{f}$ below 0.1 mHz [4]. The red (light solid) trace is the voltage noise on the split Cu plate measured electronically. Using the small control electrodes (blue, dotted) for control does not significantly reduce the measured noise level even though the contribution due to output voltage noise has been reduced by a factor ~ 3.

The white nature of the fluctuations is unusual, and should fall off at higher frequencies. Our measurements are limited in frequency by the response of our feedback loop when switching between V_+ and V_-. It is quite possible that by using a modified Kelvin probe, or a Kelvin probe style torsion pendulum, one can improve the frequency span we have presented here.

An estimation of the measurement sensitivity of our procedure is obtained by applying a constant voltage, i.e., $V_a = 0$, to the Cu plate and analyzing the data as described above (assuming $V_a = 0.1\,\mathrm{V}$). In this manner the fluctuations in the measured torque due to the surface potential are suppressed since $V_0 \approx V_{SP}$. We determine a measurement sensitivity level of $6\,\mu\mathrm{V}/\sqrt{\mathrm{Hz}}$ which does not rise at frequencies below 0.1 mHz. This is consistent with the result from Equation 3 using the noise level measured in Figure 2 at our switching frequency of 3 mHz with a switching amplitude of $V_a = 0.1\,\mathrm{V}$. This indicates that our measurement process is not limited at $30\,\mu\mathrm{V}/\sqrt{\mathrm{Hz}}$. It is possible that dielectric losses in the

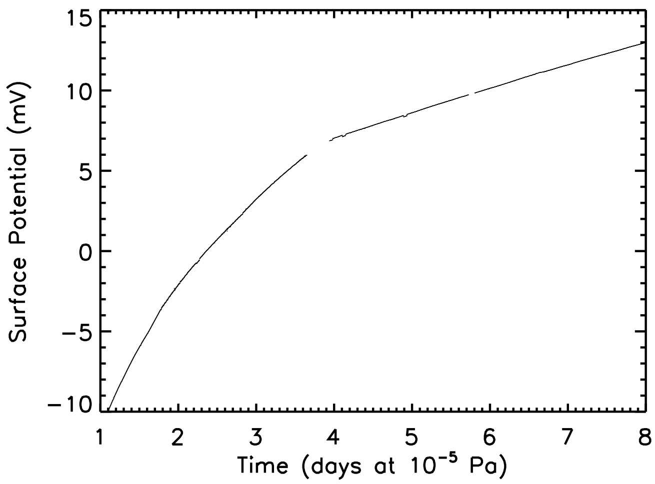

FIG. 5: Surface potential measurements after venting to nitrogen, atmosphere, and pumping back to $\approx 10^{-5}$ Pa, with a mild bake-out at 50°. An exponential fit to this data gives a time constant of about 2.5 days. The drift rate after 30 days at this pressure was measured to be ≈ 0.30 mV/day and after 50 days it was ≈ 0.15 mV/day. This slow drift of the surface potential is likely due to contamination located on our Au coated surfaces.

Cu-Si capacitor introduce noise at this level.

We have reason to believe that contamination, which may lead to dielectric losses, is a principal contributor to the measured surface potential fluctuations. After venting our system to nitrogen, then atmosphere, and then pumping back to $\approx 10^{-5}$ Pa, and a mild bake-out at 50°, we monitored the surface potential value for several days, shown in Figure 5. It is likely that adsorbed materials are outgassing from the surfaces, causing the surface potential value between the two surfaces to drift. In a previous bake, while under vacuum, we noticed a change in the surface potential of ≈ 80 mV before and after baking at $\sim 50°$. A recent study [10] has shown that force noise due to the outgassing of particles should be a small effect in LISA. However, outgassing related electrical effects, e.g., conveyed by thermal recrystallization or thermoelectricity, were not studied.

In Figure 5 we observe fast jumps in the surface potential as well as what appears to be a kink in the curve just before 4 days. The kink occurs after a period of time in which we took calibration data, e.g., determining $dC/d\theta$ and s. There also appear to be fast jumps in the data, some as large as 0.1 mV, for which we are uncertain of the source. We are now in the process of taking data with an electrically isolated pendulum and see similar steps in the deduced electrical charge on the pendulum, quite possibly occurring due to cosmic ray showers [11].

We have built a torsion balance to measure small forces between closely spaced surfaces. We have used this instrument to measure surface potential fluctuations between two gold coated surfaces. In our setup, we find an upper limit of $\approx 30\mu\mathrm{V}/\sqrt{\mathrm{Hz}}$ for these fluctuations at frequencies above 0.1 mHz. This result is relevant to the design of LISA and advanced LIGO.

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