Development of a Precision Tilt Sensor for a Cryogenic Torsion Balance Experiment

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The cryogenic torsion pendulum experiment at the University of Washington is the latest in the attempt by the Eöt-Wash group to observe interactions predicted by theories outside the standard model, detected as minute violations to Einstein's equivalence principle. A recently completed torsion pendulum experiment, conducted by the group at room temperature, provided the lowest upper bounds to date on the strength of new interactions coupled to baryon number across a wide distribution of interaction ranges[1]. Thermal noise has proven to be the greatest limitation to the sensitivity of such experiments to detect these weak interactions, motivating the development of a cryogenic experiment conducted at ∼4 K which could theoretically reduce noise and increase sensitivity by several orders of magnitude. This paper describes the challenges in the development of a precision tilt sensor which will measure the periodic tilts of the torsion pendulum apparatus itself, known to be a source of systematic error and false signals[2]. Sources of systematic noise in tilt measurements were identified, and a viable long-term calibration method was developed.

I. BACKGROUND: TORSION PENDULUM EXPERIMENTS

Torsion pendula have a long history dating back to the late 18th century with the determination of the electrostatic force by Coulomb and the measurement of Newton's gravitational constant (or the mass of the earth) by Cavendish. In recent years, the goal of producing a unified theory to describe the universe has renewed interest in this experimental apparatus because of its ability to precisely test Newton and Einstein's classical laws of gravity. These experiments could observe new theoretical interactions or differences in the behavior of gravity at very short length scales due to the presence of hidden dimensions.

A torsion pendulum is a relatively simple (in principle) apparatus consisting of a mass (pendulum) hanging from a long thin wire. The experiment is extremely sensitive to gravitational gradients across the pendulum itself. Figure 1 shows how forces on opposite sides of the pendulum with different horizontal components induce a twist in the fiber from which the pendulum is hanging. It is important to select a fiber which has little resistance to any small twist—one with an extremely high torsional oscillation quality factor. The most recent experiment used a 20 μm thick tungsten wire with a measured Q = 5000 ± 200[1]. Cooling to cryogenic temperatures is expected to significantly increase the Q-factor, allowing for greater sensitivity to small twists caused by force gradients. The source of these nonuniform gravity gradients can be caused by anything from a student standing in the lab to the gravitational field of the sun or the concentration of mass at the center of the galaxy.

In an experiment, the pendulum is designed with a specific geometry, mass distribution, and in the case of an equivalence principle test, composition distribution.

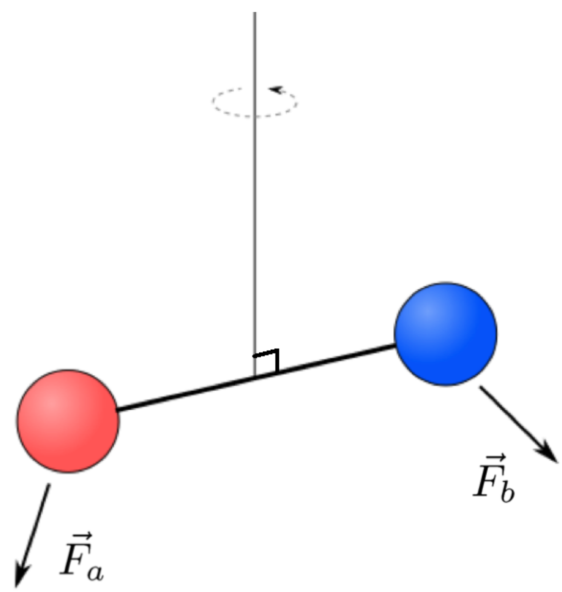

FIG. 1. An illustration of the principle of the torsion pendulum experiment. A pendulum hangs from a thin wire. A twist is induced when a field gradient exists across the pendulum, creating a different horizontal component of force on one side than on the other. The sensitivity of this device allows a well known nonuniform gravitational field to be studied in order to test classical theories of gravity.

A carefully designed or chosen attractor produces a well known gravitational field gradient across the pendulum. In order to produce a modulated signal, the pendulum or attractor may be smoothly rotated to create a changing field gradient. The same effect may also be achieved with a stationary pendulum due to the rotation of the earth in the gravitational field of the sun. The twists of the pendulum are measured with an autocollimator. As a simplified example, imagine the two colored spheres in Figure 1 represent equal masses but of different composition. For simplicity, the pendulum is influenced only by the mass of the earth which produces a downward pull, and the sun which produces a horizontal field gradient. If the pendulum is smoothly rotated, a periodic signal is produced as the horizontal component of gravity changes on the two spheres causing a small twist in the fiber. It is expected by the equivalence principle that the two spheres of equal mass experience the same gravitational forces over one full period of rotation. However, observation of a slight modulation to this signal could indicate the presence of a new interaction which creates a greater ”pull” on one mass than the other based on composition.

II. THE CRYOGENIC EXPERIMENT

A torsion pendulum experiment conducted at cryogenic liquid helium temperatures will theoretically increase sensitivity to small fiber twists by several orders of magnitude both by significantly lowering the thermal noise baseline in the fiber itself and by increasing the Q-factor of the fiber. The experiment, shown in the schematic in Figure 2 cools both the fiber and pendulum to around 4 K using a helium pulse tube cooler which repeatedly compresses and then adiabatically expands helium gas. Two of the greatest challenges in designing this experiment are controlling temperature fluctuations and eliminating vibrations. The temperature over the entire fiber and pendulum must remain constant and uniform. Any non-uniform thermal expansion or contraction will cause excess noise or false signals. For this reason, the entire experiment is conducted in a highly temperature controlled insulated box (not shown in Figure 2), and the pendulum is surrounded by thermal shields which prevent heat exchange via thermal radiation. The sensitive pendulum must also be well isolated from any external vibrations. For this reason, care has been taken to eliminate any rigid connection between the vibrating cold head and the rest of the experiment. The cold head rests atop the experiment on compressible bellows, and thermal heat links are made of thick flexible copper wire which allows for thermal conduction between the experiment and the cooler, while significantly reducing the transfer of vibrations. In order to further reduce vibrations, the experiment (not including the cold head) is rigidly attached to the substantially thick wall of the underground laboratory.

Due to the complicated and sensitive nature of such an experiment, the pendulum is designed to hang fixed, unlike the previous experiment which used a uniformly rotating pendulum[1]. The signal will be modulated by the rotation of the earth in the gravitational field of the sun (one solar day period), or the gravitational field of the center of the galaxy (one sidereal day period).

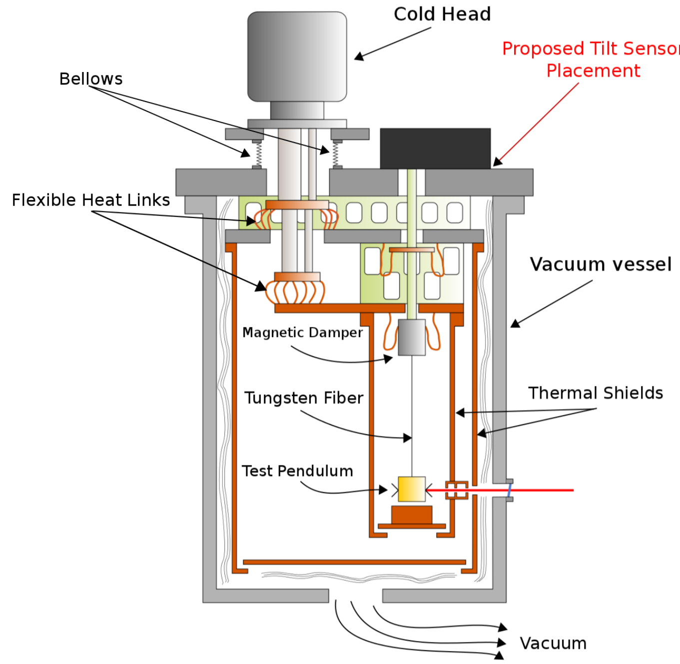

FIG. 2. A schematic of the cryogenic torsion pendulum experiment. The entire experiment is approximately 1 m in height, with a mechanical cold head mounted atop the vacuum chamber that holds the pendulum. The pulse tube cooler cools the pendulum to liquid helium temperatures and remains vibrationally isolated from the rest of the experiment using compressible bellows and flexible thermal links. A tilt sensor apparatus, in development, is proposed to be mounted to the top of the vacuum flange.

III. A PRECISION TILT SENSOR

Among the many possible sources of systematic error in such a sensitive experiment is that of tilt. Since the experiment is rigidly attached to the thick wall of the lab, it is subject to any small movements of the wall. These movements are likely caused by thermal expansion due to the heating of the building by the sun, the heating of the earth surrounding the wall, or shifting of the earth from other causes. As the experiment itself tilts, the freely hanging pendulum will continue to hang down towards the center of the earth. The fiber would then be at a slight angle with respect to the rest of the experiment, which, because of the way the fiber is crimped to the anchor point at the top of the experiment can induce small measurable twists, or because of imperfections in the mirror on the pendulum, could cause a change in deflection of the autocollimator beam without an actual twist[2]. Since these tilts are likely due to solar heating on a daily period and may therefore interfere with the signal of interest caused by the earth's rotation in the sun's gravitational field, they must be measured and accounted for.

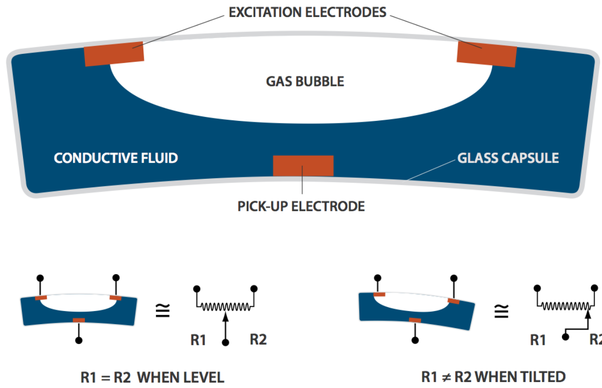

FIG. 3. The principle of operation of the commercial sensor used to measure tilt. A gas bubble is contained along with a conductive fluid. As the sensor is tilted, the bubble moves from side to side changing the resistance between the excitation electrodes and pickup, which changes the voltage output. *(Source: Applied Geomechanics)*

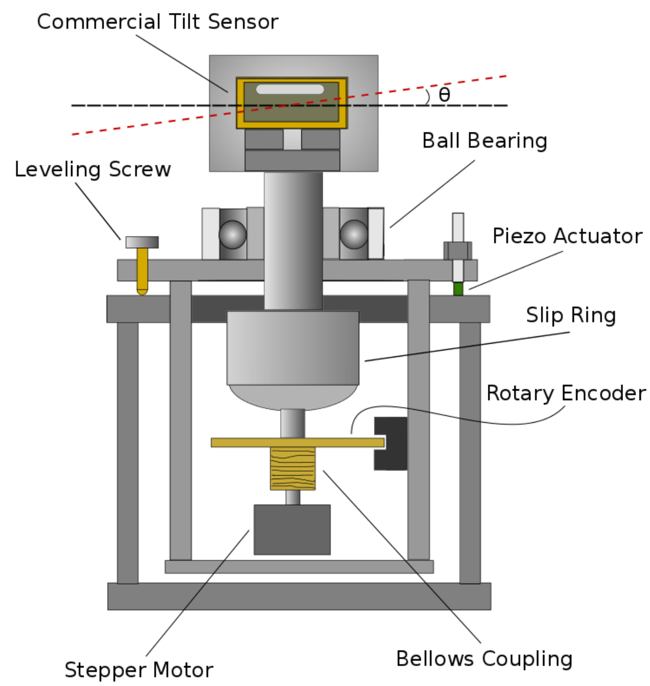

FIG. 4. The prototype tilt sensor apparatus which rotates the sensor about a vertical shaft to eliminate the problem of zero-point drift. Tilt measurements are made in one axis by rotating the sensor precisely 180° using a stepper motor. Subtracting two measurements in different directions along an axis eliminates the zero-point entirely. A gain calibration system has been incorporated by replacing one of the three leveling screws with a piezoelectric actuator, which expands creating a known tilt. The prototype stands at approximately 35 cm tall.

A commercially available electronic tilt sensor shown as a diagram in Figure 3 is used for this purpose. The tilt sensor works on the same principle as any inexpensive bubble level, wherein a gas bubble is contained with some liquid. As the device tilts, the buoyancy of the gas bubble in the higher density liquid causes it to shift from one side to the other. In the case of an electronic sensor, the liquid is conductive to electricity and two electrodes are located on either side of the bubble. As the bubble shifts, the resistance between one of these electrodes and a third pick-up electrode at the bottom increases, while the resistance between the other electrode and the pick-up decreases. This change in the ratio of resistances results in a change in voltage output. The tilt sensor used in the lab has an advertised resolution of 0.1 μrad, or the tilt induced by sliding a sheet of paper under one end of a rod the length of the University of Washington campus.

Several considerations must be made in order to incorporate this tilt sensor into the torsion balance experiment. First, both zero-point drift and gain drift (change in sensitivity) that occur over long timescales must be dealt with. The measurement must be stable and reliable in order to measure tilts that occur on daily periods. Noise introduced into tilt measurements must be kept at a minimum, and any noise should be as repeatable as possible. Random noise will simply decrease sensitivity. Finally, an apparatus must be designed that can be integrated into the existing torsion balance experiment.

A summer's worth of research was dedicated to figuring out the operation of a previous prototype apparatus, and then testing a new method to calibrate for a possible long-term gain drift. The prototype is shown schematically in Figure 4. The prototype apparatus fixes the tilt sensor to the end of a rotating shaft. The shaft is rotated with a small DC stepper motor and held by a ball bearing. The apparatus rests on a platform on three leveling screws, two of which are fine threaded micrometer screws for leveling purposes. A slip ring allows the wires from the tilt sensor electronics, rotating along with the shaft, to be mounted below. In order to eliminate unwanted vibrations during testing, the apparatus was placed atop the unused 220 ton cyclotron magnet[3] which provides a highly stable platform.

A. Zero-Point Drift

The purpose of rotation is to eliminate the problem of zero-point drift—that the signal from the tilt sensor kept perfectly level may drift over time. To accomplish this, a tilt measurement is made with the sensor stationary. Then, the sensor is rotated 180° and another measurement is taken. Subtracting these two measurements and dividing by two gives a measurement for the tilt along that axis while eliminating the zero-point all together. A stepper motor is employed to ensure that the sensor is rotated precisely 180° between measurements.

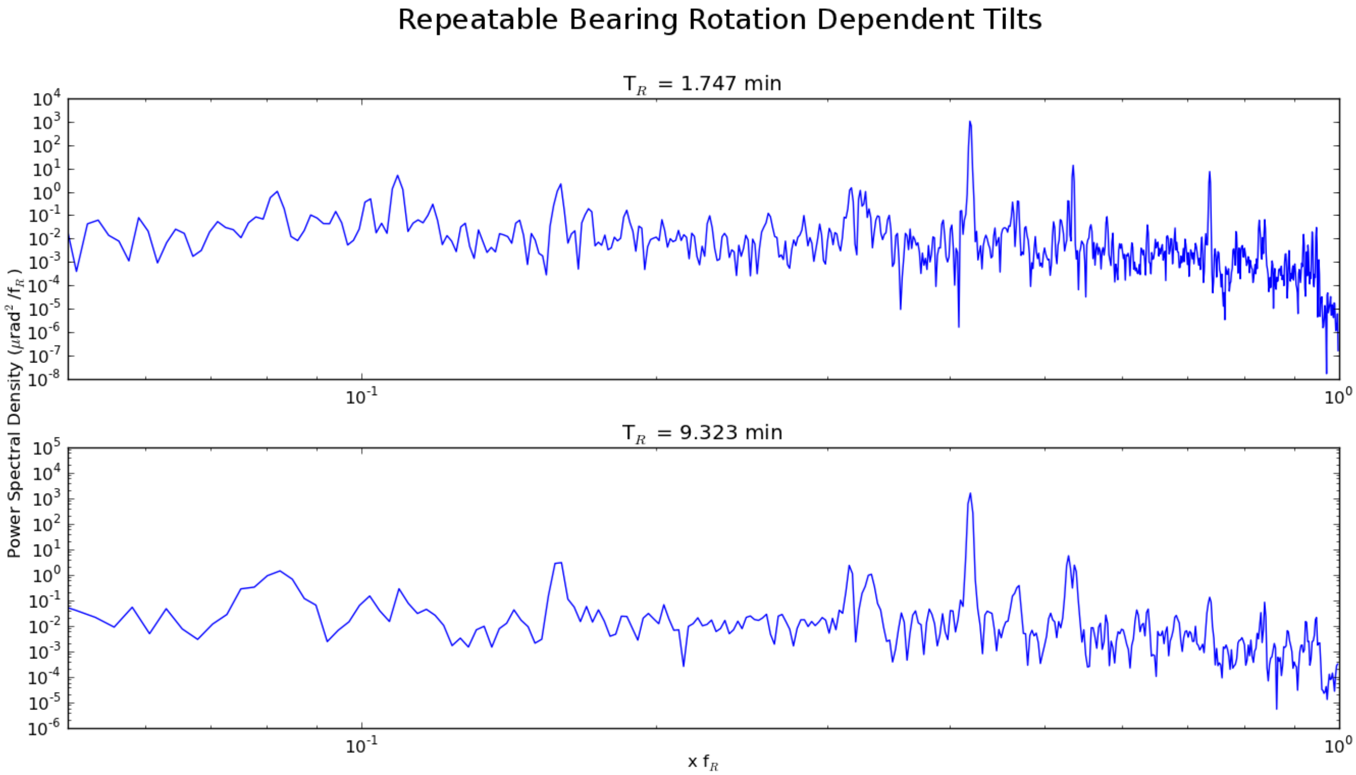

FIG. 5. Two frequency spectra from tilt data measured along one axis with shaft rotation periods of 1.747 minutes and 9.323 minutes. Each spectrum encompasses approximately 16 continuous hours of data, collected over a week apart. Both spectra are in terms of the shaft revolution frequency, revealing several notable ball bearing rotation dependent periodic tilts.

The stepper motor is a type of DC motor that contains a gear-shaped permanent magnet surrounded by four coils. The current is switched on in each coil successively, attracting the next tooth of the magnet, causing it to turn, and dividing the rotation into steps. An inexpensive controller chip can further divide the rotation by discretely ramping the voltage between the coils instead of switching them completely on and off successively. A circuit was built to divide the rotation into 3600 steps per revolution, which reduces noise and vibrations due to jerking between steps. It was discovered that the jerk produced when the motor stops causes an oscillation in the tilt measurement that lasts approximately 2.5 seconds, meaning the motor must be stopped for several more seconds to record an averaged tilt measurement.

B. Noise Sources

Rotating a sensitive tilt sensor with a motor is bound to introduce noise into the tilt measurements. The ball bearing holds the shaft and attached components and is designed to the specified precision for axial runout, or amount of up and down motion during rotation that would cause tilts. A ball bearing consists of balls squeezed between two rings, or races. The inner race is attached to the shaft and rotates while the outer race is stationary. Asymmetries in the races, or imperfections in the roundness of the balls can cause this unwanted up and down motion. However, if these ball bearing related tilts are repeatable, they can easily be dealt with later in analysis. Two tilt measurements were made with different shaft rotation frequencies, f_R, each over several hours, to produce the frequency spectra in Figure 5. Both spectra are in terms of the rotation frequency of the shaft, illustrating how several periodic tilts at certain fractions of the rotation frequency are present. This is a promising result because it means that bearing dependent tilts are repeatable, and if the rotation frequency is on the order of minutes, will be well out of the way of a daily signal. However, long-term tests that reveal lower frequency bearing rotation dependent tilts are necessary to make sure they do not interfere with real daily tilt signals.

Another possible source of noise is the slip ring, which allows wires from the tilt sensor electronics affixed to the rotating shaft to be mounted to the platform below. The slip ring consists of inner rotating conducting rings that make continuous contact with fixed brushes as they rotate. Changes in the connection or resistance between ring and brush during rotation could introduce noise. To test this, a 9 V battery was connected through the slip

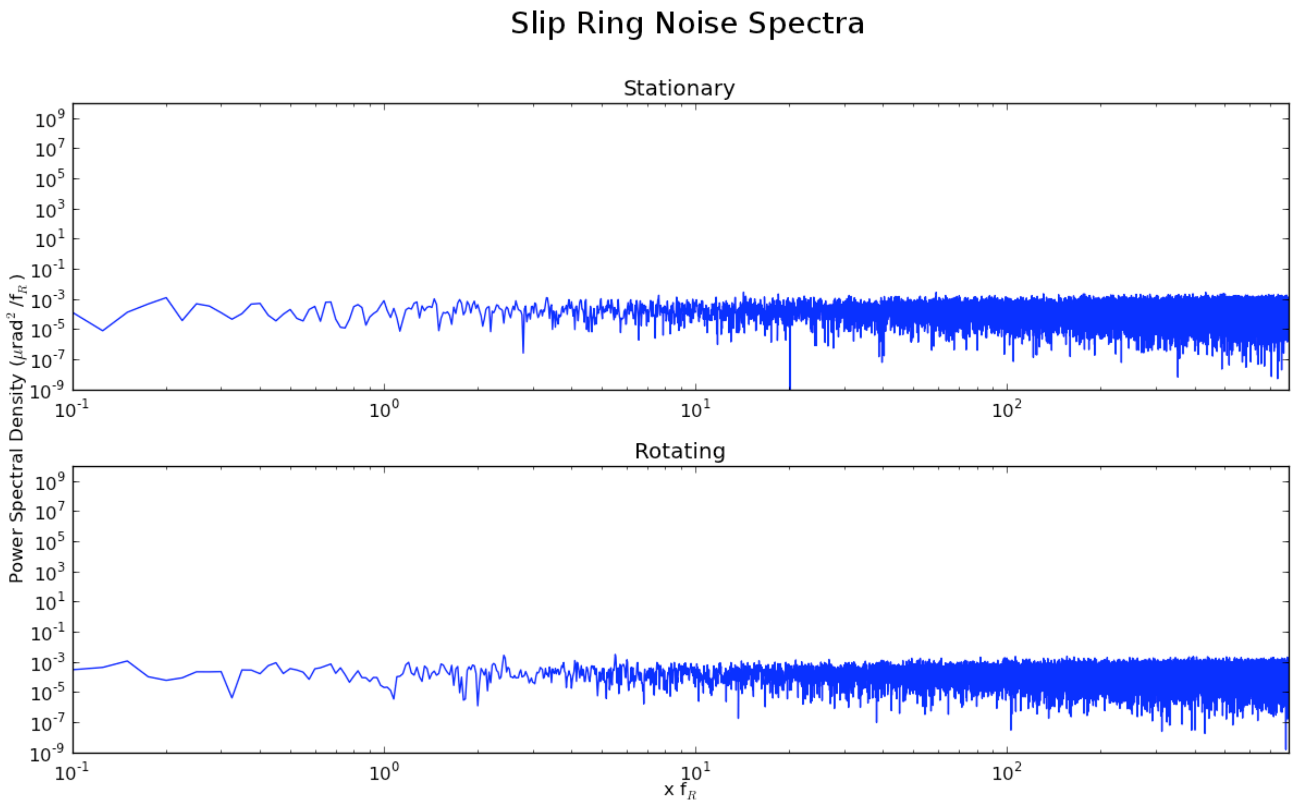

FIG. 6. Two frequency spectra produced by attaching a 9 V battery through the slip ring, a component that allows rotating wires to be connected to a stationary mounting. Data were taken both with the shaft stationary and rotating, revealing that no rotation dependent tilts are present, and that the overall noise level is well below that of the tilt sensor output.

ring both during rotation, and with the shaft stationary, producing the spectra in Figure 6. No periodic noise was introduced as a result of the slip ring rotation, and, the base noise level from the slip ring was well below that of the tilt measurements seen in Figure 5.

C. Gain Calibration

The next challenge is gain drift—that the sensitivity of the sensor to a given tilt may drift over the course of a long experiment. This drift may show up as a 1/f increase in noise at lower frequencies, reducing the sensitivity to lower frequency periodic tilts. To deal with this phenomenon, a calibration method must be developed which tilts the apparatus by a precise and repeatable amount on some time interval. A simple solution using an inexpensive piezoelectric actuator was designed, however, due to the nonlinearity and hysteresis exhibited by such actuators, much testing is required to determine the ability of the system to produce repeatable calibration tilts. Shown in Figure 4, one of the three feet of the apparatus was replaced by the small piezo actuator which has been glued to the end of a threaded rod. An external digital trigger circuit was designed and used to apply up to 100 V to the actuator, causing it to expand by up to 6 μm, and tilting the apparatus up to $\sim$30 μrad. It was observed that after voltage was applied to the actuator, a slow drift of the tilt signal occurred over approximately 1 minute after the initial jump in tilt. However, there is currently no method to measure the displacement of the piezoelectric actuator independently of the tilt measurement. In any case, the slow drift possibly indicates unwanted instability for calibration. Further experiments showed that any sudden change in tilt can cause the slow drift observed during calibration. Calibration tilts of 30 μrad took twice as long to stabilize as those of just 15 μrad. The future development of a circuit that can slowly ramp the voltage applied to the actuator over a couple seconds is expected to solve this problem.

A calibration repeatability experiment was conducted in which tilt was measured on one axis for 10 minutes both before and after 100 V was applied to the piezoelectric actuator. The change in tilt after applying the tilting voltage was recorded over a period of 8 hours, with results shown in Figure 7. The figure shows how the cali-

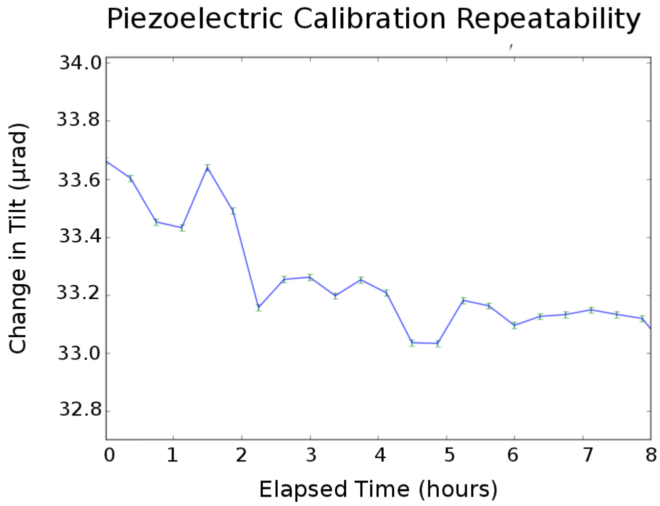

FIG. 7. The measured change in tilt after 100 V was applied to the piezoelectric actuator repeatedly over the course of 8 hours. These results showed only very small fluctuations of no more than 0.5 μrad, and seemed to stabilize after the first few hours. For reference, 0.5 μrad would correspond to a $\sim$100 nm displacement of the actuator, half the size of the smallest known bacterium. However, it is unclear whether fluctuations were caused by changing actuator displacements or an actual gain drift in the tilt measurement.

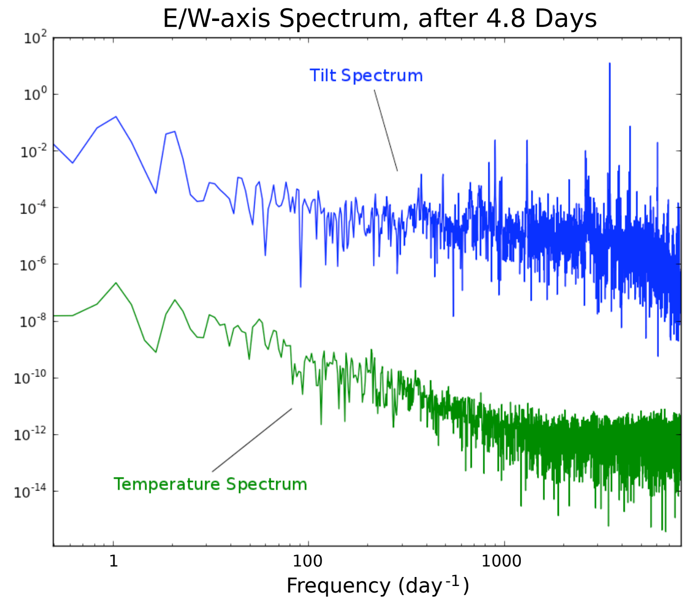

FIG. 8. Spectra created from 4.8 days of tilt and temperature data, revealing the higher frequency rotation dependent periodic tilts, as well as a possible daily and twice daily signal tied to temperature fluctuations.

bration tilt fluctuated by no more than 0.5 μrad at most, and seemed to stabilize after the first few hours. Several factors could be responsible for the fluctuations. First, is an instability of the power supply output voltage, which could be tested in the future by simultaneously measuring the output voltage and calibration tilt. Next, is an actual measured gain drift of the tilt sensor, and finally, an inherent non-repeatability of the actuator. Unfortunately it is difficult to decouple the tilt measurement and the actual displacement of the actuator, and testing this would be complicated and time consuming. More testing of calibration repeatability is required, especially over longer timescales—weeks or months. Overall, the results are extremely promising with such a simple and inexpensive solution using a piezoelectric actuator operating without expensive closed-loop feedback electronics.

D. Results

With a very limited time frame, nearly 5 days of tilt data were collected, along with measurements from the built-in temperature sensor. Figure 8 shows the spectrum of one of the two measured axes in the east/west direction. At higher frequencies, the large bearing dependent tilts were present. At lower frequencies, a daily and twice daily tilt signal that corresponded to periodic temperature changes began to emerge. However, with so few data, these peaks are hardly significant. An increase in the noise level also became evident at lower frequencies which may be an indication of gain drift. Of course, an experiment that collects tilt data for several weeks or months is necessary to observe the lower frequency phenomena.

E. Future Modifications

After the addition of the piezoelectric calibration system, few other modifications to the prototype apparatus are necessary. However, one possible addition is that of a precision rotary encoder. Currently, the apparatus makes use of a simple encoder which produces a digital signal once per revolution (see Figure 4). However, an encoder which produces several hundred equally spaced signals per revolution could be implemented to increase the certainty that the stepper motor rotates exactly 180° between measurements. The system currently uses a trigger that relies on the inexpensive stepper motor controller to make exactly 3600 steps per revolution. A better system would measure the actual physical rotation of the shaft using a commercial rotary encoder.

IV. CONCLUSION

After a summer of working to make the tilt sensor prototype operational and doing testing and modifications, a very useful apparatus was developed to measure the tilt of a cryogenic torsion balance experiment. The biggest challenge, that of gain drift, seems to have a viable solution, and the sensor tentatively seems sensitive enough to measure real daily tilts of the laboratory. The next step is to rebuild the apparatus in order to integrate it into the torsion balance experiment, as the prototype could not be mounted due to its geometry. Figure 2 shows the proposed placement of the new apparatus, which would be securely bolted to the top of the vacuum flange. Once integrated into the experiment, intentional tilts will be applied in order to find the threshold for tilting that will create a measurable systematic effect in the signal from the torsion pendulum. Then, real tilts will be measured over the long-term torsion balance test in order to measure whether or not they will produce systematic effects.

V. ACKNOWLEDGEMENTS

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