Precision Tilt Measurements for a Cryogenic Torsion Balance

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Abstract

Torsion balances allow for high-precision tests of the equivalence principle, gravitational inverse square law, and certain weak theoretical forces coupled to properties such as spin. A cryogenic torsion balance is able to achieve even higher precision than a room temperature setup by lowering noise levels, both by decreasing the temperature and by increasing the quality factor of the pendulum. While instrument tilt is a significant systematic in general for this type of experiments, the lower noise floor and the fact that this cryogenic pendulum does not rotate make precision tilt measurements even more important since periodic changes in tilt with the same frequency the experiment searches for are present when the pendulum doesn't rotate. We present the results of a rotating tiltmeter prototype with sub-microradian accuracy, which can be modified to be mounted on the cryogenic torsion balance assembly near the upper fiber attachment in order to accurately monitor changes in tilt.

1 Introduction

The torsion pendulum in its simplest form is a mass suspended from a fiber, all in the field of an attractor. The mass has a force on it due to the attractor, and we assume the force on the fiber is negligible. We are only concerned with twisting motion, so we also ignore any forces that may cause the pendulum to swing; we damp them out until they are too small to cause any measurable effect. To better detect rotational motion, either the test mass or the attractor is rotated. This makes any torque caused by the attractor periodic so that it is detectable above any background signals that may be present. Figure 1 shows a basic torsion balance setup with the attractor very close to the test mass. With an appropriately designed pendulum, this type of close proximity arrangement could be used to test the gravitational inverse square law at small distances. This is possible because torsion balances are sensitive to very small torques, which is further helped by the fact that small asymmetries in the test mass automatically cancel out because they cause the mass to tilt slightly, balancing the pendulum and eliminating any torques that could have been produced by the asymmetry.

The angular displacement of the pendulum is measured by an autocollimator, which bounces laser light off of a mirror on the test mass and collects the reflected light using either a split photodiode or a position sensitive detector. These devices are highly sensitive to displacements in the plane of rotation of the pendulum. The next generation of autocollimators used in the Eöt-Wash group will provide precision down to about a nanoradian [1].

Torsion balances have a long and successful history as scientific instruments. Experiments using torsion balances were first carried out by Coulomb in 1777, and independently by John Michell in the early 1780s [2]. Coulomb used the devices to measure the force between two charged bodies, leading to the discovery of Coulombs law. Cavendish used a torsion pendulum to calculate the gravitational constant in 1798 [3].

Today,torsion balances are used to test the equivalence principle, which asserts that gravitational mass and inertial mass are identical. For these experiments, test masses that are composition dipoles

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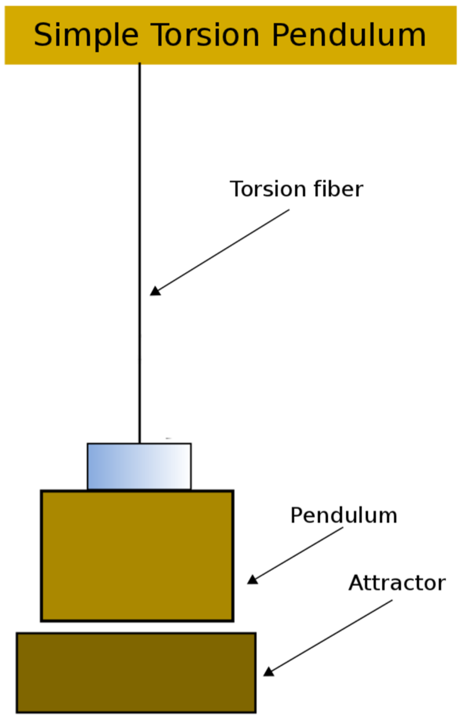

Figure 1: A simple torsion pendulum with an attractor.

are used to maximize any torques that would be present due to composition-based equivalence principle violations [4].

Torsion pendulums can also be used to test the gravitational inverse square law at small separations, using specially designed pendulums and attractors which are disks with patterns of holes cut out of them [5]. A search for theorized but unobserved forces coupled to properties such as spin also uses torsion pendulums [1].

The reason torsion balances are so useful is that, unlike experiments that use single particles, a torsion balance uses an ensemble of roughly 10^{23} particles to magnify the effects of any force on the test mass and yield more precise results. The difficult part is to only magnify the signal of interest and not any other types of forces. When testing gravity, this means electromagnetic forces must be eliminated by shielding the pendulum, and forces from collisions with gas particles in the air must be removed by performing the experiment in vacuum [4].

Thermal noise introduces a torque signal whose power follows the proportion

$$\tau^2 \propto \frac{4kT}{\kappa Q \omega} \tag{1}$$

with k Boltzmanns constant, T temperature in Kelvin, Q the quality factor of the torsion balance, ω the frequency, and κ the spring constant of the fiber. Lowering the temperature reduces noise in itself, but it has the added benefit of also increasing Q [6].

Certain factors such as tides and thermal expansion due to solar heating and the day-night cycle cause the pendulum's tilt to change by small amounts. While it is true that the pendulum hangs down no matter which direction down may be, tilt is of concern because the upper portion of the fiber is crimped to a screw. Crimps are not symmetrical, so when the angle between the fiber and the screw to which it is crimped changes, a slight rotation is induced in the torsion balance. If tilt occurs periodically on a timescale similar to that of the signal the experiment is looking for, the rotations due to tilt mimic the sought-after signal. To compensate for this, tilt must be measured and accounted for. Commercial tiltmeters are able to achieve nanoradian precision, and are useful for this application. One of the experimental setups actively corrects for tilt using feedback to drive the thermal expansion of feet supporting the balance.

Gravity gradients provide a significant challenge to performing rotating torsion balance experiments. Local fields are not perfectly uniform down to the level of sensitivity of a torsion balance experiment, and nonuniformities cause the gravitational force to point in slightly different directions at different points. This is a problem for a rotating pendulum since torsion balance experiments are highly sensitive to torques, which are caused by slight differences in the direction of forces between two ends of the pendulum. For a non-rotating pendulum, gravitational gradients present a constant torque, which does not effect the modulated signal. For rotating pendulums, the torque due to gradients is modulated by the pendulum's rotation, so it appears to be an extra-gravitational force. To account for this, gravity gradients around the pendulum are measured and then compensated by arranging masses, usually lead bricks, around the torsion balance to flatten the field immediately around the test mass. Designing highly symmetric test masses also helps reduce this problem by reducing the pendulum's response to gravity gradients.

2 The Cryogenic Torsion Balance

The cryogenic torsion balance is designed to take advantage of the significant noise reduction that comes with lower temperature. As explained after equation (1), lowering the temperature of the experiment has a twofold effect on lowering the noise because the

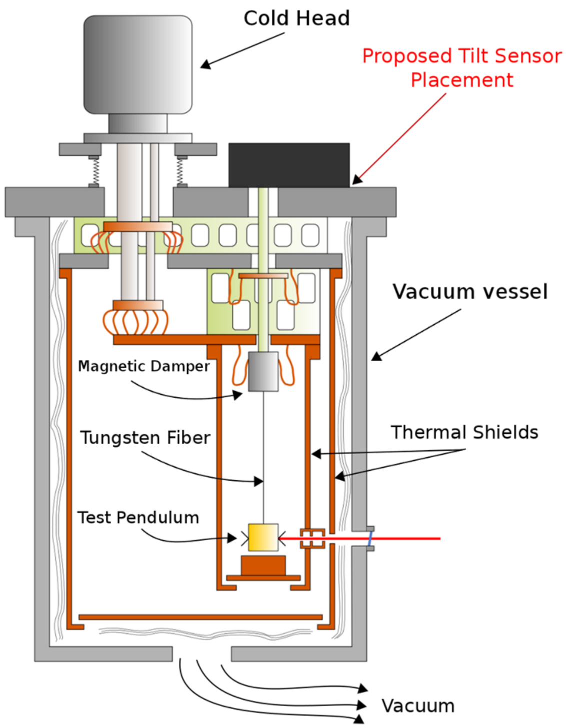

Figure 2: The cryogenic torsion balance, with the location of the wall at the left of the figure. The proposed location of the rotating tiltmeter apparatus is shown at the top right.

quality factor increases as temperature decreases.

Figure 2 shows the design of the cryogenic torsion balance. At the heart of the assembly is the fiber, hanging with the test mass suspended from it. Near the top of the fiber is a magnetic damper, which damps the swinging modes of the pendulum but does not affect the twisting modes that are necessary for the experiments. The test mass and fiber are surrounded by two thermal shields, each connected to the cold head by flexible heat links to minimize vibration. The cold head works by adiabatically expanding high pressure helium gas pulses. The two layers of thermal shielding allow the pendulum to be cooled to just above 4 Kelvin while the outer layer stays at roughly 50 Kelvin. The thermal shields are isolated from the warmer parts of the setup by supports made of G10, which has very low thermal conductivity. The design of the supports removes unnecessary material to further insulate the thermal shields. The outer shield is also surrounded by superinsulation, and the entire inside of the apparatus is isolated from electromagnetic fields by a magnetic shield. Air is pumped out of the cryostat through the bottom to keep the experiment at vacuum. The entire setup is mounted to the wall in two vibrationally isolated segments to further reduce noise.

A small viewport on the front, with cold filters to block infrared light from getting through and heating the pendulum, allows laser light from the autocollimator to shine into the vacuum chamber and reflect off the mirrors on the test mass. The autocollimator is mounted securely to the outside of the vacuum chamber for stability.

A "parking brake" is located directly under the pendulum. The test mass can be lowered into the parking brake, which clamps onto the mass in order to more efficiently cool it. Without this device, the only available modes of cooling would be radiation and conduction along the fiber, neither of which is effective.

The first experiment to be done using the cryogenic torsion balance is a test of the equivalence principle using the sun as a source mass and the Earths rotation to modulate the signal. In the future, tests of short-range gravitational interaction could also benefit greatly from running at cryogenic temperatures. These tests would be able to improve current limits by an order of magnitude.

3 Tilt Measurement for the Cryogenic Torsion Balance

3.1 Rotating Tilt Sensor Setup

Figure 3 shows the tilt sensor apparatus, designed several years ago and used last summer in a configuration very similar to its present setup. It consists of two separate parts. The bottom support is purely structural and made of aluminum. It sits on the ground and supports the top section, which contains all the sensors and moving parts arranged in a column, supported by three feet which rest on the bottom support. Two of the feet are fine-threaded screws with ball-shaped ends that guarantee they sit stably. The third foot is a piezo-electric actuator, which allows for the introduction of a known tilt to measure and correct for gain drift in the tiltmeter. One of the screws is constrained to sitting in a hole on the surface of the support, and the other screw is constrained to a slot. These two constraints are exactly enough to determine the relative positions of the two pieces of the tilt sensor setup without allowing for extra movement and without overdetermining the system. The piezo-actuator rests on the surface of the support with its position completely determined by the positions of the two screws.

The tiltmeter, located underneath its signal conditioner in the top part of the apparatus, is the component that actually measures the tilt. Underneath it is a shaft that runs through a bearing to a slip

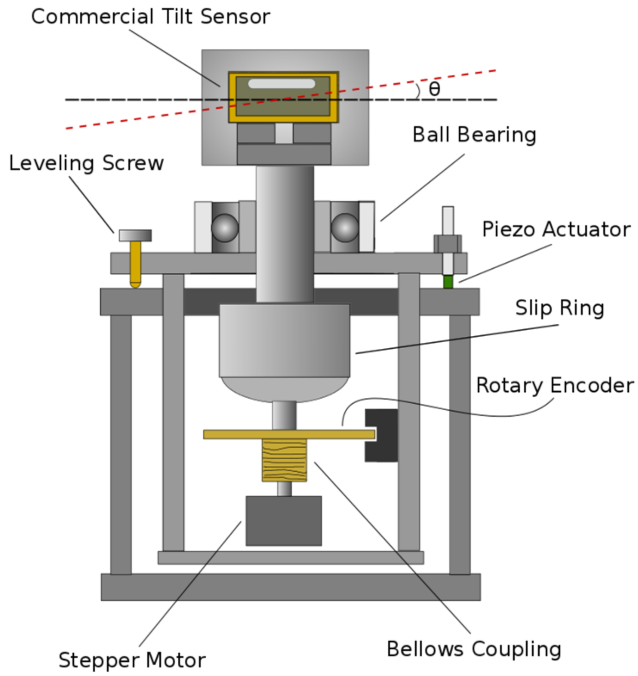

Figure 3: The prototype rotating tiltmeter device.

ring. The slip ring allows the rotating tiltmeter electronics to remain connected to the rest of the electronics, which do not rotate. Below the slip ring is a rotary encoder, which is used to verify the behavior of the stepper motor. A bellows coupling connects the shaft to the stepper motor, allowing for slight misalignments between the rotation axes of the shaft and stepper motor. This is necessary because perfect alignment is impossible to achieve, and imperfect alignment without the bellows coupling would likely cause the whole apparatus to bind and not turn at all. Finally, at the bottom is the stepper motor, which is driven by a microcontroller. The microcontroller drives the stepper motor for a quarter revolution, then stops it in order for the tilt to be measured. The quarter revolutions are repeated constantly with approximately one full revolution per minute.

3.2 Tiltmeter

The tiltmeter itself, an Applied Geomechanics miniature single-axis electrolytic tiltmeter, is housed in the upper part of the apparatus, inside a cylindrical aluminum container. The electronics that run it are located in a box directly above it. The inside of the tiltmeter, shown in figure 4, is a curved glass chamber filled with an electrolytic fluid and a bubble of gas. As one would expect, the bubble always floats to the top. Two electrode are located on the top of the tiltmeter so that as the bubble moves, different amounts of the fluid contact them. A third

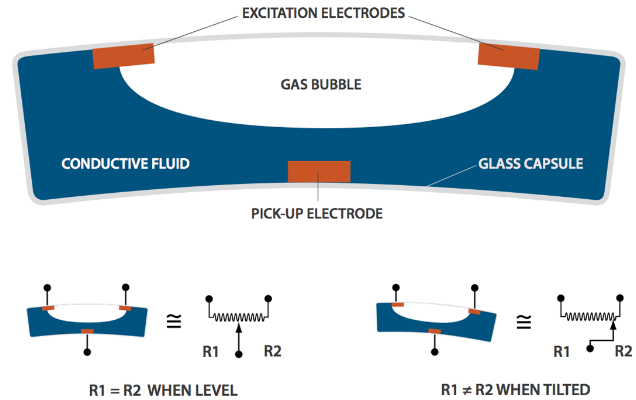

Figure 4: The commercial electrolytic tiltmeter used in the rotating tiltmeter device.

electrode, the pick-up electrode, is completely submerged in the fluid and equidistant from the other two electrodes. The amount of fluid touching an excitation electrode changes the resistance of the path from the pick-up electrode to that excitation electrode, so different amounts of tilt induce different amounts of resistance across the contacts. When an AC voltage is applied across the fluid, the voltage difference between the two paths from pick-up electrode to excitation electrode is proportional to the inclination of the tiltmeter. Alternating current must be used because direct current would cause the electrodes to be plated by the electrolytic fluid.

3.3 Piezo-Electric Actuator

The piezo actuator used in the tiltmeter setup is a Thorlabs PZS001 piezo-electric actuator, which is fitted with a strain gauge. When a voltage is applied across the actuator, its length changes. Since the length change is so small (microns) the response is approximately linear over the voltage range used (0-100V). The displacement is calculated by converting a strain gauge reading in volts to a displacement in micrometers.

The strain gauge is a wheatstone bridge, with two active and two dummy resistors. The active resistors change resistance as the length of the piezo stack changes, while the dummy resistors do not. The dummy resistors are present in order to cancel out changes in resistance due to temperature changes in the piezo. The resistors that make up the strain gauge are zig-zagging patterns of conductive material attached to the surface of the piezo stack. The dummy resistors are arranged so that their resistance doesnt change appreciably when the length of the stack changes, while the active resistors are arranged so that they are stretched when the piezo's length in-

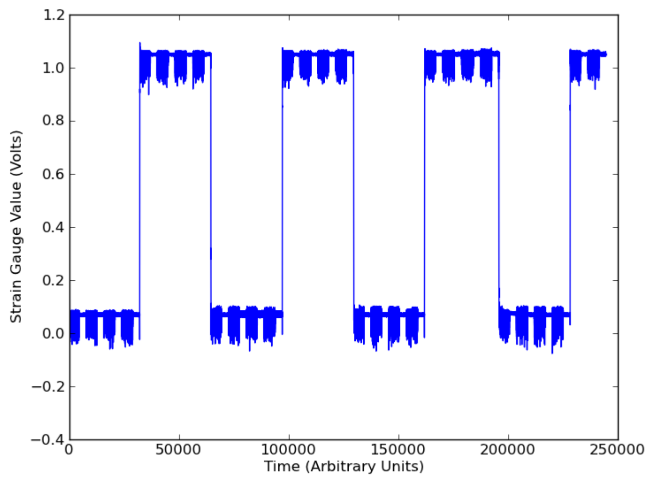

Figure 5: A plot of the piezo strain gauge reading for several revolutions, with about 1.1 minutes per revolution. Each revolution, the set point was alternated between 0.07 volts and 1.05 volts. The noisier segments occur when the tiltmeter setup rotates.

creases, decreasing their conductivity. The change in conductivity results in a change in voltage measured across the wheatstone bridge. This change is very small, so it must be amplified electronically. The amplified signal is then read into the DAQ device and converted to a displacement.

The datasheet for the piezo stack gives an approximate scaling of the length change in terms of the strain gauge reading, but we found that this information was inaccurate. In order to more accurately measure the behavior of the piezo stack, we assembled a Michelson interferometer on a small optics bench and set it up so that the piezo pushed one of the mirrors, changing the path length of one arm of the interferometer. We then connected the leads of the piezo to a variable voltage power supply. Since we knew the wavelength of the laser light in the interferometer, we were able to tell how far the piezo was displaced for a given strain gauge reading by looking at changes in the fringe pattern of the interferometer. Recording the change in number of fringes along with the strain gauge voltage at that displacement allowed for a fit of the displacement as a function of strain gauge reading. We found that the linear approximation was not acceptably accurate for the precision we wanted, so a quadratic fit was used, with much better results.

Knowing the behavior of the piezo, we can control it via a feedback loop. As shown in figure 5, we are able to accurately keep it at strain gauge voltages between 0.07 and 1.05 volts, corresponding to a range of displacement of about 6 μm, significantly less than the advertised 10+/-2 μm.

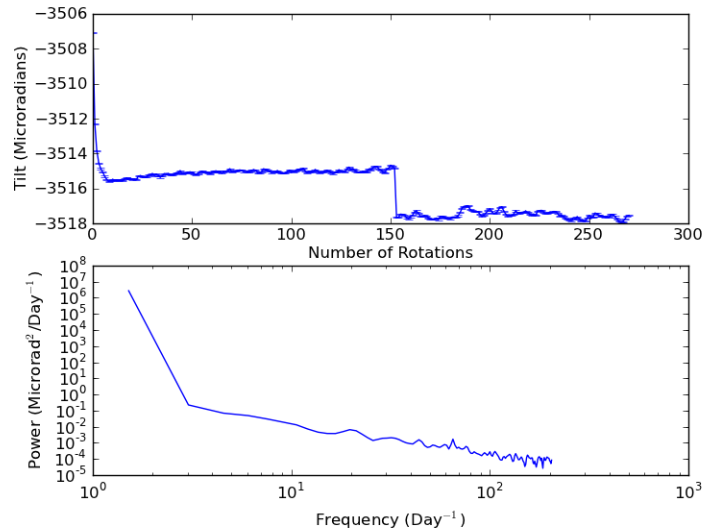

Figure 6: Top: A plot of tilt along one axis over approximately 16 hours. Notice the jump near rotation 150. Bottom: Power spectral density for the tilt. The noise is low for all but the lowest frequencies.

3.4 Results

Tests on the rotating tiltmeter were conducted on top of the 220 ton cyclotron magnet at CENPA which provides a stable platform isolated from vibrations, reducing noise in the tilt readings.

Once the new piezo actuator was installed and the software to run the device was written and set up, the first round of data was taken. It was significantly noisier than measurements from last summer. We had already corrected for zero point drift and gain drift in the data analysis software, so those were not an issue. There were, however, other problems: large drift in the signal at the beginning, aperiodic jumps in the tilt value, and periodic signals probably due to a combination of the stepper motor and the bearings.

Whatever the cause of the periodic signal, it turned out to be fairly easy to deal with because it occurs regularly. A low pass filter was implemented in software to mute the signal, which was far above the frequencies of interest, like the once per day frequency that would be expected of an actual signal due to Earth's rotation. Upon further investigation, we found that reducing power to the stepper motor greatly reduced this noise, and our suspicions were confirmed that the noise was due to the rotating elements of the device. This reduction made using the filter unnecessary, but still useful in some cases. Fig-

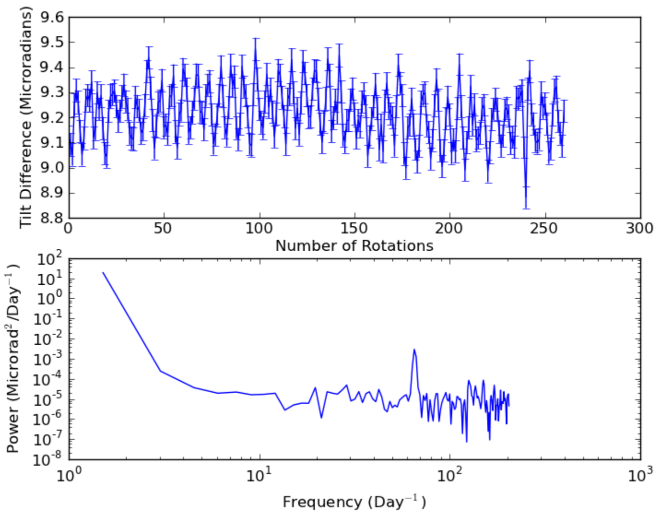

Figure 7: Top: A plot of difference in tilt between two different tilt configurations of the rotating tiltmeter for the same conditions as figure 6. On top of a short-period trend, a weaker, longer period (about one day) trend is also visible. Bottom: Power spectral density for the difference in tilt. Note the spike in noise near 65 Day^{-1}, which is likely due to the stepper motor or bearings.

ure 6 shows the initial drift and an aperiodic jump in tilt. Figure 7 shows that gain drift is not significant on short timescales.

The drift that occurs at the beginning of each measurement, while not desirable, is not of much concern because of its transient nature and short (about half an hour) duration. We believe that this drift is caused by changes in the electrolytic fluid inside the tiltmeter when voltage is first applied. Because the drift only affects the very beginning of a data set and does not appear to be easily removable, nothing is implemented to remove the drift and the initial data is thrown out.

The largest problem with the data is the aperiodic jumps of irregular magnitude in the value of the tilt measurement. This feature of the tilt data presents the biggest problem because it most likely represents an actual change in the orientation of the tiltmeter with respect to the gravitational field. Since the jumps are not periodic and do not always have the same magnitude or a predictable direction, they cannot be filtered using software. To get rid of them, the source must be found and eliminated.

After testing, it seems most likely that the source of this unwanted change in signal is the piezo slipping across the surface it rests on when it is jerked by the stepper motor starting or stopping its motion. Reducing the power to the stepper motor so that it has just enough power helps reduce this problem, as well as reducing the periodic noise. Unfortunately this change was not enough to completely remove these jumps.

We also reattached the piezo after finding that the epoxy had not properly bonded it to the platform it supported. This seems to have made the aperiodic jumps come closer together, which is the opposite of the effect we had hoped for. This effect may have been due to the epoxy continuing to set, so in the future the jumps may decrease in frequency. If the jumps do not go away, an alternate method of eliminating slipping between the piezo and the surface must be found. Of course, this problem could resolve itself when the new rotating tiltsensor is built and mounted on the cryostat.

3.5 Future Work

Since it appears that everything is now repeatable and in working order except for the signal jumps, the next step is to make the circuitry driving the tiltmeter assembly more permanent. The microcontroller and stepper driver, currently on breadboards, will be soldered onto a board together, where the wires won't free themselves.

Following that, the prototype has served its purpose, and a new device will need to be designed with dimensions that allow it to be mounted on the cryostat. I have come up with a preliminary design that may work, but I will not have time to properly draw it up and test it this summer. Because the prototype design is so much larger than the space available on the cryostat (see figure 2), significant changes will need to be made. The space is so limited that it is most likely that the new tiltmeter assembly will be mounted on a thick aluminum plate that partially hangs off the top of the cryostat.

The new tiltmeter device will not need some of the parts present in the prototype, which will allow it to better fit within the space constraints. The rotary encoder is no longer necessary, as we now know the behavior of the stepper motor. The size of the tiltmeter housing can also be reduced, and its electronics box can be moved to further reduce the height.

Once this new design is complete, the only work remaining to completely integrate the tiltmeter into the cryogenic torsion balance setup is to integrate the software that drives the feedback loop and data acquisition into the rest of the cryogenic balances software. This should be simple because all of the current programs, for the tiltmeter and the cyrogenic torsion balance, are written in C♯ using Microsoft Visual Studio with the National Instruments DAQmx package.

4 Conclusions

We have presented a working prototype of a rotating tilt sensor for use on a cryogenic torsion balance. The cryogenic experiment will allow for improvement in precision over previous tests of the gravitational equivalence principle, and the addition of the rotating tilt sensor will allow us to control this important source of systematic error.

Improvements to the tilt sensor setup include a new piezo actuator with a strain gauge, driven by a feedback loop which tilts the apparatus by a known amount in order to correct for gain drift, achieving long term signal stability.

Due to space constraints, in the future a more compact version of this same basic design will be constructed. It will then be attached to the outside of the cryogenic torsion balance near the upper fiber attachment in order to measure the tilt as close to that point as possible. Once completed, the cryogenic torsion balance with its rotating tiltmeter will allow for improvements of an order of magnitude over current limits of violations of the equivalence principle for ranges greater than one astronomical unit. Future uses of this technology may also be able to improve limits on violations of the grvitational inverse square law, and look for forces caused by hypothetical particles.

5 Acknowledgments

I would like to thank Frank Fleischer for his help and patience in teaching me everything related to torsion balance experiments. Little did I know coming into this summer that I would learn not just about torsion balances, but also machining, electronics, and digital signal processing. I also want to thank Deep Gupta and Alejandro Garcia for their encouragement and for giving all the REU students the opportunity to come to Seattle to do physics research for a summer.

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