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Optimization of an Active Leveling Scheme for a Short-Range Gravity Experiment

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Abstract. At Cal Poly Humboldt, undergraduate researchers and faculty have constructed a torsion-pendulum experiment that seeks to measure gravitational interactions below test mass separations of 100 microns. The aim of this experiment is to look for deviations in the weak equivalence principle (WEP) and inverse-square law (ISL). The scale at which this experiment operates is within an untested range at the submillimeter scale. This apparatus's torsion pendulum consists of equal masses with differing materials arranged as a composition dipole. The twist of this configuration is measured as an attractor mass oscillates in a parallel-plate arrangement nearby. The oscillation creates a time-dependent torque on the pendulum which can be studied for deviations in the WEP and ISL. At present, an active leveling scheme has been implemented to mediate the apparatus's long-term tilt variations. This scheme has been optimized through the use of a power supply and proportional-integral-derivative (PID) loop that mitigates the variations in tilt by applying a voltage to a resistor attached to one of the apparatus legs. The applied voltage causes thermal expansion of the apparatus leg support structure, thus correcting and modulating the tilt of this experiment.

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INTRODUCTION

What is gravity? Gravity is one of the four fundamental interactions—it binds us to the earth and causes objects to fall. Although gravity was the first fundamental interaction to be discovered, it remains at the forefront of current physics and astronomy research. The behavior of gravity at short range is of particular interest in the effort to unify general relativity (GR) and the standard model of particle physics (SM). General relativity has passed all experimental tests to date but is still fundamentally inconsistent with the standard model.

Cal Poly Humboldt's experiment works to test gravity within a short range. The focus of this research is dedicated to submillimeter-scale tests of the gravitational inverse-square law (ISL) and weak equivalence principle (WEP). These tests could reveal evidence of string theory, through the effects of its extra dimensions, or new fundamental particles and forces [1]. Such experiments could also find an explanation for dark energy and why it seems to be causing the universe's expansion to accelerate [2]. This work could even shed light on potential new forces mediated through undiscovered particles [3].

THE EXPERIMENT

Torsion-Pendulum Experiment

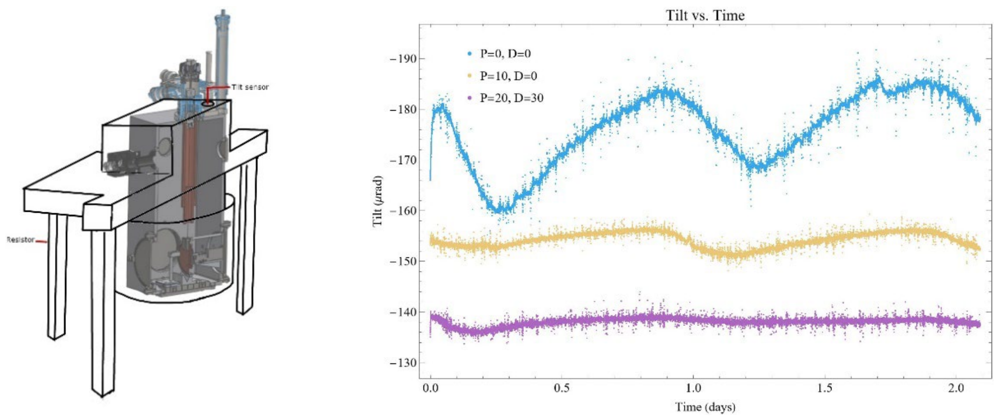
A detailed description of the experiment can be found in [4]. The main apparatus consists of a torsion pendulum with equal masses of two different materials arranged as a composition dipole. The twist of the torsion pendulum is measured as a copper attractor mass in a parallel-plate configuration is oscillated nearby. The oscillation of the attractor mass creates a time-dependent torque on the pendulum. The motion of the pendulum is recorded using an optical autocollimator system. The magnitude and size of this torque may be studied to test for deviations in the WEP or ISL at untested distance scales. The pendulum is suspended using a 20-μm-diameter tungsten fiber. Other major components of the experiment include various pendulum and attractor positioning mechanisms, an electrostatic pendulum control, and diverse environmental monitors.

EXPERIMENTAL CHALLENGES AND TECHNIQUES

Progress in the gravity lab evolved as we addressed several experimental challenges. In addition to the experiment's vulnerability to interference from electrostatic, magnetic, and thermal factors in the laboratory environment, the laboratory is in an old building on unstable soil. This produces tilt variations. To address them, a control system has been built to actively level the experiment throughout the course of the day along the axis that most affects our experimental measurements.

Tilt Sensor

As seen in Fig. 1(b), daily tilt changes the angle of the apparatus by around 30 microradians (μrad) every day. These tilt variations affect the measurement of the pendulum and attractor separation, a key parameter in the analysis of data required for ISL tests. Since the torsion fiber is roughly 0.5 m in length, these daily variations cause the separation to change by tens of microns—a substantial amount for our experimental tests.



(a) (b)

FIGURE 1. (a) Cross section of the vacuum chamber in a diagram of the supporting table structure. (b) Apparatus tilt results with and without the PID loop applied.

An active leveling scheme was implemented to account for the experiment's sensitivity to environmental factors. This scheme utilizes a proportional-integral-derivative (PID) feedback loop implemented in LabVIEW that allows for correction of the apparatus's tilt. PID loops hold a setpoint value by calculating the error based on a previous measurement value and changing their output accordingly. In this experiment, the initial tilt is read into the PID loop which then outputs a correction for the tilt. The voltage output is applied via a resistor to the leg of the main apparatus, thus modulating and correcting the tilt of the experiment. See Eq. (1) for implementation of the PID feedback loop. In this expression, V_i is the voltage output from each PID loop iteration. P, I, and D are constants chosen to optimize the process of the feedback loop. T_i is the current reading of the tilt sensor and T_s is the setpoint value. This system is similar to one developed in [6], although our system directly heats the leg of the support structure rather than a separate foot attached to the table leg and is designed to compensate for much larger daily tilt changes.

$$V_i^2 = P\,(T_i - T_s) + D\,(T_i - T_{i-1}) + I \sum_{n=0}^{i} (T_i - T_s) \qquad (1)$$

The power dissipated by a resistor depends on the square of the voltage applied over the resistor. Since the power that the resistor in the tilt control system dissipates is the source of heat used to expand the table leg to adjust the tilt, the tilt correction depends on V^2 rather than depending directly on V.

RESULTS

Figure 1(b) illustrates the implementation of the PID loop over the course of a day. The top run (blue) was taken when the PID loop was inactive. The middle run (yellow) was taken when only the proportional term P was implemented, and it had a value of 10. The bottom run (purple) was taken when the P and D terms were set to 50 and 10, respectively. The I term of the PID loop can be included, but is not generally used because the overall constant tilt offset does not affect the sensitivity of our study. In Fig. 1(b) the effectiveness of the PID loop can be observed, not only as a reduction in the tilt of the main apparatus but also as a reduction in the scattering of measured tilt values. The tilt control system is not fast enough to respond to the frequent spikes we see or to transients like earthquakes. However, the experimental signal is in the millihertz regime, so these more frequent spikes do not impact the measurements at relevant frequencies.

Data and Calibration

Before the PID loop can successfully be relied upon, calibration of the output voltage must first be determined. Calibration involves stepping through a range of voltages, changing the output over long runs (1–2 days), and then observing the height the apparatus settles upon (Fig. 2). The calibration process found the extent of the applied voltage to be around 250 μrad, leaving ample range to compensate for the daily tilt variations of around 30 μrad. The tilt depends quadratically on the voltage and we see this relationship confirmed in Fig. 2 where the tilt = constant * V^2.

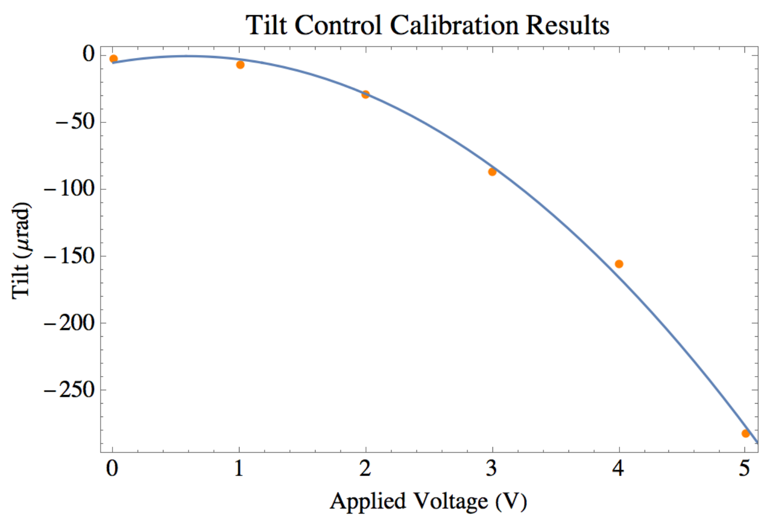


FIGURE 2. Tilt control calibration results.

Measurement of Pendulum Response to Apparatus Tilt

The tilt control system has also been used to deliberately modulate the tilt of the apparatus. The pendulum's response to the tilt of the apparatus was measured by adding a term to the PID output that causes a sinusoidal variation of the applied voltage at an amplitude and frequency determined at the beginning of a data collection run. Since the frequency of variation of the applied voltage is known, the amplitude of the pendulum's response at that same frequency can easily be determined using Fourier techniques. Initial results indicate that the pendulum twist is altered by about 2 μrad per microradian of tilt (Fig. 3). This allows for correction from the effects of the known tilt on the motion of the pendulum in experimental measurements.

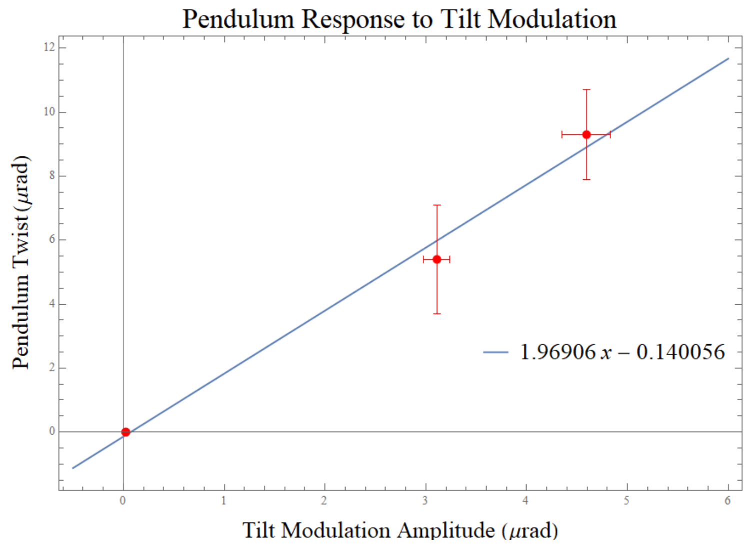


FIGURE 3. The response of the pendulum twist to modulations in tilt.

Conclusion

For additional gains, modulation of the tilt control is being optimized with a power supply that allows for finer control of the correction voltage. It's also worth noting that this system controls tilt only in the direction that affects the pendulum-attractor mass separation; a future improvement would be to also control tilt on the perpendicular axis. To measure gravity at untested distance scales, our experiment has to be tuned with a full understanding of the environmental impacts it will experience during short-range gravity tests.

At Cal Poly Humboldt we have designed an apparatus that can measure the interactions between a torsion pendulum and an attractor mass. Through measuring and controlling environmental disturbances, this apparatus has the promise to measure gravity at unprecedented length scales. It will soon enter the stage at which gravitational effects can be separated from other interactions.

Acknowledgments

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