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Tests of Short-Range Gravity with a Novel Parallel-Plate Torsion Pendulum

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Abstract

The incompatibility of the Standard Model and General Relativity has pushed gravitational measurements to the forefront of experimental physics. The general lack of short range gravity measurements has inspired students and faculty at Humboldt State University (HSU) to construct an apparatus that will measure the effects of gravity at submillimeter scale. This experiment will consist of a torsion pendulum in a parallel plate geometry with an attractor mass that will oscillate in close proximity. Since our previous report, [1] the apparatus has entered into the commissioning stage and has begun to take preliminary data.

Keywords: Gravity, Inverse-square Law, Weak Equivalence Principle, General Relativity

1. Introduction

1.1. Motivation

The incompatibility of the Standard Model and General Relativity has prompted many questions concerning the behavior of gravity at short range. A multitude of theoretical situations predict deviations from the inverse square law of gravity (ISL) and the weak equivalence principle (WEP) at short distance scales [3]. String theory predicts alterations of current gravitational laws resulting from the existence of extra dimensions [4, 6]. Additionally, the behavior of gravity at short distances may be affected by Dark Energy [2].

1.2. Parameterization

ISL deviations are parameterized with a Yukawa addition to the Newtonian gravitational potential energy [3]

$$V\,(r) = -\frac{G\, m_1 m_2\, (1+\alpha e^{-r/\lambda})}{r} \qquad (1)$$

Where α is the strength of the deviation and λ is the length scale at which these deviations would become relevant. The shaded region in Figure 1 is where previous experiments have concluded, within 95% confidence, that there are not deviations from the ISL. The black curves are the limits of previous experiments and the blue dashed lines are the expected limits from the HSU experiment. The other marked regions correspond various theoretical situations described in [3].

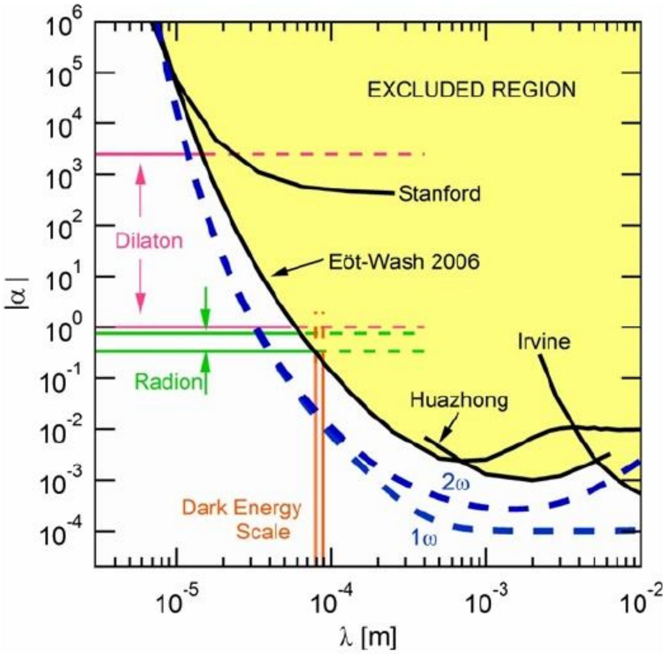

Figure 1: The ISL deviation $\alpha - \lambda$ parameter space.[3]

2. Experiment Overview

The experiment consists of a torsion pendulum in parallel plate configuration with a flat attractor mass placed in close proximity. The pendulum is made out of an aluminum step with two titanium blocks inserted into each side. The use of two separate materials allows for the test of the WEP because of the difference of atomic number and neutron number of the two materials, in this case aluminum and titanium [3]. This pendulum is hung inside a vacuum chamber using a 25μm tungsten fiber.

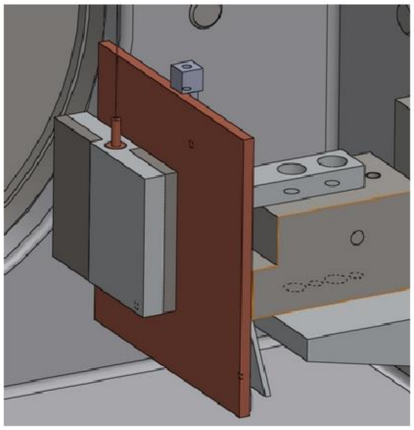

Figure 2: Pendulum-Attractor Geometry. The light gray is the aluminum step of the pendulum, the dark gray is the titanium blocks, and the copper colored plate is the copper attractor mass. Not shown is the electrostatic shield which is stretched in between the pendulum and attractor mass to reduce electrostatic interactions.

The pendulum's lateral movement is restricted by a magnetic damper but it is allowed to rotate freely. The copper attractor mass oscillates laterally toward and away from the pendulum. As described in Section 3.1, an electrostatic shield is installed in between the pendulum and attractor mass. The angular deflection of the torsion pendulum is then measured using an optical position sensitive device over a period of time [5]. From this, one can detect the torque applied to the pendulum from the attractor mass.

3. Experimental Progress

3.1. Installation of Thermal and Electrostatic Shielding

The weakness of gravity requires a very sensitive apparatus and thus substantial environmental controls are necessary [1]. The need for controls required students to design and build both electrostatic and thermal shielding. Although many thermal controls were already implemented, the need for a thermal shroud was evident.

This shroud surrounds the fiber to reduce radiative coupling between the walls and the fiber, which could cause false effects. Due to the shrouds mass, it has a long thermal equilibration time which shields the fiber from short term fluctuations. It is made of 1/8 inch thick copper tubing that is thermally isolated from the chamber and consists of two telescoping pieces which allows for easy adjustment. The electrostatic shielding consists of two assemblies, the attractor mass electrostatic shield and the electrostatic can. The electrostatic shield was a previous design that was altered to fit the updated assembly. It uses 25µm BeCu foil which is stretched flat, similar to a drumhead. This design allows for the least distance possible between the pendulum and the attractor mass, but still provides shielding. The electrostatic can is still in development, but it will be made from copper sheet metal and will surround the most vital parts of the experiment. Both of these parts will be gold plated to increase conductivity and will be grounded to the chamber, thus decreasing the possibility of patch charge build up. The installation of these shielding pieces is expected to reduce false effects and simultaneously decrease the noise in the system.

3.2. Improvement of Electrode Control System

Previous electrode designs [5] were found to be inadequate when a more precise pendulum was installed. As a result, students redesigned and built an improved electrode control system consisting of adjustable rectangular caps attached to cylindrical posts both made of aluminum. These were insulated from the rest of the apparatus by vacuum compatible plastic plates which were shielded by an aluminum cover. This design kept the parallel plate geometry of previous versions yet also increased adjustability. It also decreased the distance from the pendulum and electrodes thereby heightening their sensitivity. These electrodes are controlled by a PID LabVIEW code. This allows for highly controlled motion of the pendulum. Figure 3 is an example of the electrode's control ability.

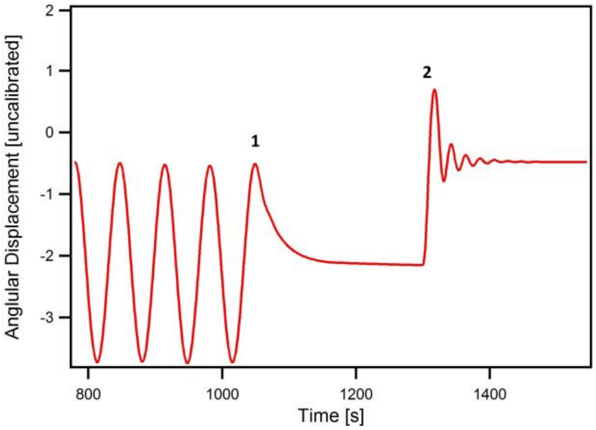

Figure 3: The original sinusoidal motion is due to the natural oscillation of the pendulum. At 1, the PID program was turned on thus damping out the pendulum's motion. At 2, the pendulum was rotated to a new equilibrium angle using a rotation stage at the connection point of the fiber. The feedback subsequently damped out the resultant motion.

3.3. Design and Implementation of Attractor Mass Assembly

With the installation of the improved pendulum, the next natural step was to design and implement an attractor mass assembly, show in Figure 4. This assembly had to move an attractor mass in a sinusoidal motion extremely accurately while allowing for fine adjustment of the attractor mass's parallelism to the pendulum while electrical shielding the pendulum from the attractor mass. The first step was to order a stepper motor that was capable of fine motion and had ultra-high vacuum compatibility. A mount, an attractor mounting arm, and an electrostatic shield were then designed to be combined into the attractor mass assembly. The attractor mounting arm was composed of two triangular plates attached to each other by finely threaded screws. These were then attached to the motor by a rectangular bar. The previously mentioned electrostatic shield was then inserted in front of the entire assembly. Subsequently, the motor was programmed to move in a highly controlled sinusoidal motion. With the implementation of micro stepping, continuous pseudo-sinusoidal motion was achieved as shown in Figure 5.

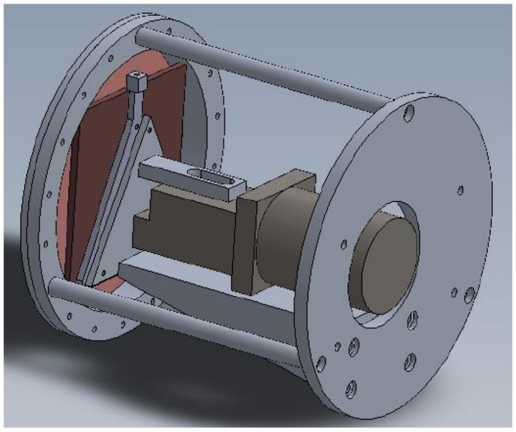

Figure 4: Attractor mass assembly viewed from the back. The dark copper colored is the attractor mass with the light gray support structure behind it. This attaches to the dark gray stepper motor. The light copper color behind the attractor is the electrostatic shield mentioned in Section 3.1.

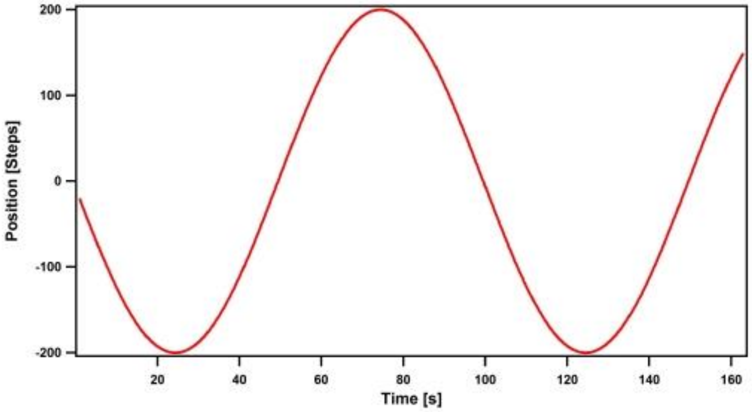

Figure 5: Attractor mass driving signal.

4. Preliminary Data

With the installation of the new controls and attractor mass assembly, the decision was made to take a noise run and an attractor test run. The noise run was conducted by recording the angle of the pendulum over time as it was free to oscillate while keeping the attractor mass stationary. This time series data was then turned into an amplitude spectral density to allow for frequency domain analysis. Figure 6 shows the amplitude spectral density of the noise run data. The large spike at about 3 mHz is the natural oscillation of the pendulum. The noise to the left of this spike has decreased with the installation of the thermal shrouding but is expected to decrease further with the other noise reduction efforts.

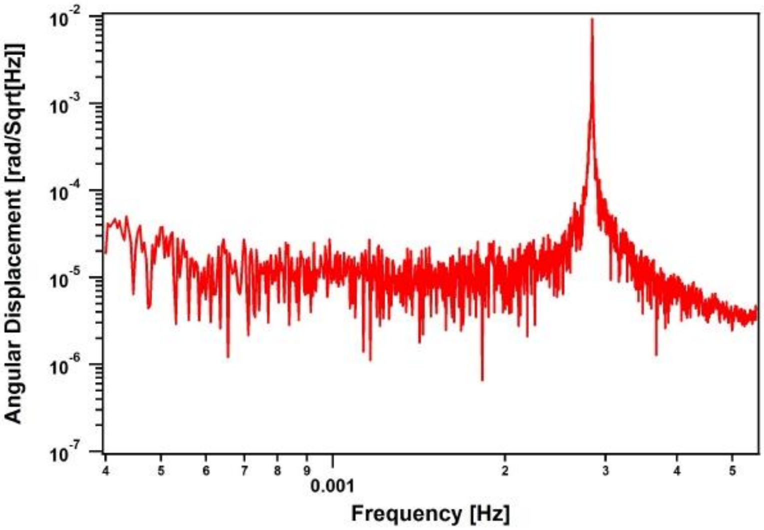

Figure 6: Noise Run

The attractor test run was conducted by oscillating the attractor mass at 1 mHz with an amplitude of 2 mm. The zero point of the oscillation corresponded to the distance between the attractor mass and pendulum being about 15 mm. The amplitude of the natural oscillation of the pendulum was decreased to allow for easy comparison with motion caused by the attractor mass. Figure 7 is the amplitude spectral density of the attractor test run data. The spike at 1 mHz is the motion that was caused by the attractor mass, high harmonics can easily be seen. The 3 mHz harmonic is overwhelmed by the natural oscillation of the pendulum, however both the 2 mHz and 4 mHz harmonic are clearly shown. This motion demonstrates interactions between the attractor mass and the pendulum, but no conclusions can be drawn from it. The apparatus is not yet at the stage to isolate gravitational interactions and the signal is an order of magnitude larger than any expected gravitational signal, therefore we assume that the motion is most likely due to a combination of interactions. Further analysis is currently underway to determine which forces are responsible for the measured motion.

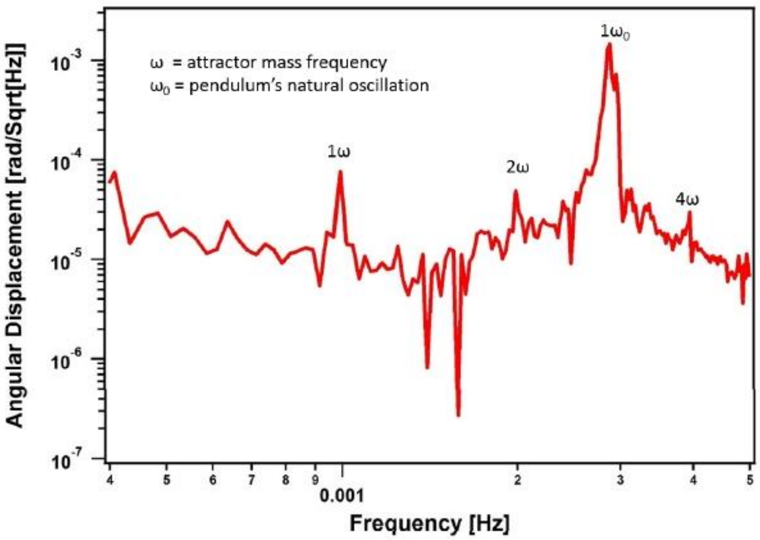

Figure 7: Attractor Mass Run. Attractor mass oscillating at a frequency of 1 mHz with an amplitude of 2 mm.

5. Future Work

There are many improvements to be made by future students. The attractor mass assembly was only constructed as a prototype thus some of the assembly parts will need to be carefully remachined to ensure flatness and parallelism. Many of the parts will need to be gold plated to maximize conductivity and decrease the probability of patch charges. Much of the data analysis Python code is still under construction and will need to be completed before measurements can be made and analyzed.

6. Conclusion

Students and faculty at HSU are constructing a short range gravitational experiment that has entered into a commissioning stage. The preliminary data has shown interactions between the attractor mass and pendulum; however, no conclusions can be drawn, as of yet, due to the lack of isolated gravitational interactions. With the installation of shielding and the remachining of many parts, science-quality data is not far off.

7. Acknowledgements

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