# Gravitational Waves: LISA Project

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## Introduction

The detection of gravitational waves within our universe has been a topic of interest since its prediction by Einstein's theory of General Relativity. General Relativity addresses the concern that there is no difference between a homogeneous gravitational field and an accelerated reference frame. One of the best analogies for this is Einstein's elevator in which a man on earth in a non accelerating elevator drops a ball and sees no difference in the ball's motion to that of his friend. His friend is in an elevator in space, with no gravitational field, that is accelerating upward such that he also sees the ball appear to drop. This is known as the equivalence theory where in one case gravity is causing the ball to drop to the ground, but in the other case of space, an accelerating reference frame causes this same motion. By introducing the notion of space time curvature, which in fluencies the motion of objects by a homogeneous gravitational field, Einstein is able to account for this equivalence problem.

The more massive an object is the more the curvature of space time distorts. As objects accelerate in space gravitational waves are created. The metric of our universe is mostly Minkowskian, which in simple terms means that the influences of space time curvature are very small, and in particular for gravitational waves are 1 part in $10^{-20}$.[1]

LISA which stands for Laser Interferometer Space Antenna is a constellation of three spacecrafts which will orbit the sun. A schematic of LISA can be seen in figure 1. LISA will follow earth's orbit 50 million km away. Each of the three arms of LISA will be 5 million km apart and will have masses on the ends. Each mass will compose of a mass in an enclosure where the gap between the two may vary.

To measure the effects of gravitational waves LISA will use a system of lasers at each arm to measure the time it takes for light to travel between masses. The light travel time is influenced by the presence of gravitational waves. When the gravitational waves are present then space time is distorted and the time for light to travel between each arm will change.

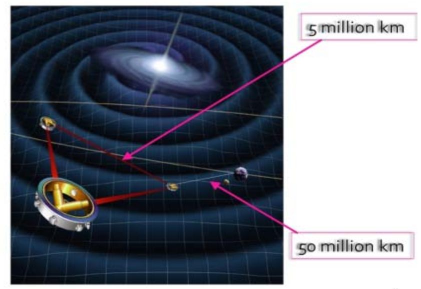


Figure 1: LISA Schematic which shows the layout of LISA relative to the earth and sun. Lasers are reflected off of test masses that are housed in three different spacecrafts.

Currently the Gravitational group at CENPA here at the University of Washington is characterizing and refining the torsion pendulums and autocollimator in hopes investigate noise sources for LISA. This paper describes the various components of LISA I have been involved in measuring and refining and the results and conclusions that can be drawn from the data that has been accumulated during this INT-REU experience.

## Torsion Pendulum

In our research we simulate the effects of our masses in LISA with a torsion pendulum, figure 2, because geometrically they are equivalent. The pendulum comprises of a gold plated pendulum that is suspended by a thin fiber and allowed to hang freely. One major problem facing LISA is the charge accumulation on the test masses due to cosmic ray impacts and solar particle collisions. Because the masses suspended freely, any interaction with charges or electric fields can cause unwanted forces on the pendulum that will affect the data. These forces introduce noise and degrade the sensitivity of the system.

The apparatus also encompasses a split copper plate that can move relative to the pendulum and therefore cause the pendulum to react to this change. It also has two electrodes on the other side of the pendulum. The charge on the pendulum can be inferred by switching the polarity of the feedback electrodes. We are then able to measure the changes in theta of the pendulum by using a laser that is reflected off the pendulum.[3]

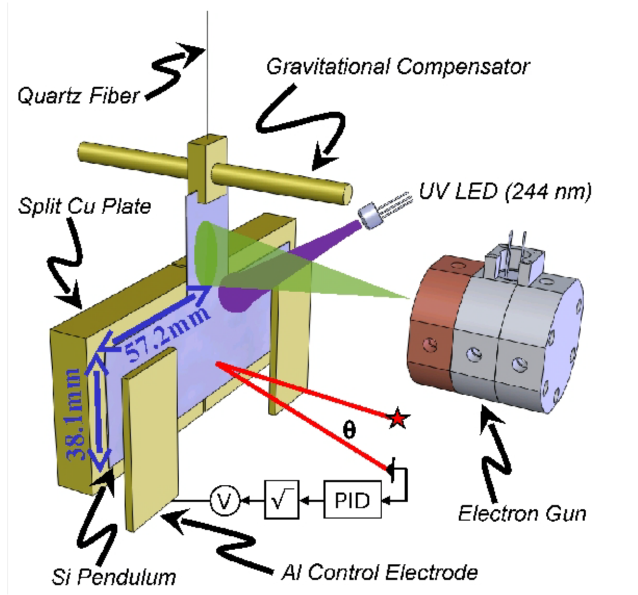


Figure 2: Torsion pendulum that makes up the test masses on either arm of LISA.

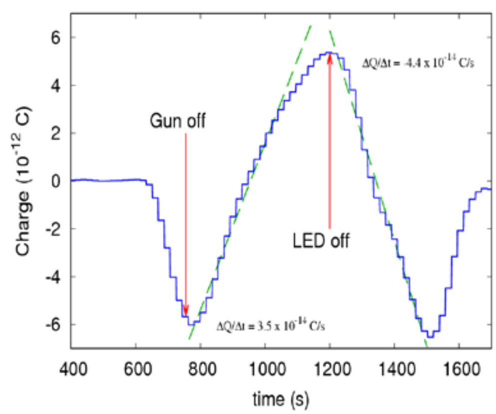


Figure 3: Demonstration of charge control. As the electron gun and UV LED are turned on and off we are able to control the change in charge of the pendulum which is on the order of 0.01 amps.

To charge the pendulum negatively an electron gun is used. The electron gun comprises of a copper and aluminum cylinder. Inside the aluminum magnesium is evaporated onto the surface which creates the cathode for electrons to be ejected from. This evaporation is done inside a vacuum evaporator here at CENPA. The electrons are ejected using the photo electric effect. To charge the pendulum positively a 330nm UV LED is used.

## Charge Control and Distance Measurements

I began my research on LISA by first demonstrating charge control of the torsion pendulum. To demonstrate this control I first had to lock the pendulum in a feedback loop using a DAQ system which locks the pendulum on the autocollimator detector so that data can be taken. This is referred to as “catching the pendulum”. Then using the DAQ system I turn on and control the electron gun and thereby negatively charging the pendulum. Once demonstrating that it can be negatively charged I then turn on the UV LED to charge the pendulum to the same magnitude that it was negatively charged. I then repeat this procedure to demonstrate that I can control the charge at any point in time. Figure 3 shows a charge control measurement that was taken.

The data is fairly smooth, and as it can be seen, I was able to control the charge on the pendulum and create a nice sinusoidal trace of the charge. Each step of this data corresponds to a 30 second time interval. Every 30 seconds the polarity of the feedback electrodes switches. This switching is essential to infer the charge on the pendulum.

Some issues that I faced in obtaining this data were problems associated with temperature fluctuations in the experiment room, and timing of the charging of the pendulum. When I initially took this data I was seeing abnormal waves in the linear parts of figure 3 which corresponded to temperature fluctuations in the room as the summer days became warmer. Because the temperature was not held constant the pendulum was not stable and this could be seen in the data. As for the charge, I had to experiment with the correct amount of exposure time of the electron gun and UV LED so that both the negative and positive charging occurred under the same time scales. This was not particularly hard to overcome, but it involved becoming more familiar with the software and at what settings the pendulum needed to be set to accomplish my measurement goals.

The next set of data that I took with the torsion pendulum was distance dependence measurements of the copper plates from the pendulum. We wanted to investigate whether the distance of the plates had a significant effect on our pendulum and we did this by measuring the pendulum on 8 separate nights as we were taking noise runs at 0V. Figure 4 is the data collected over these nights at distances from 2mm to 9mm.

As it can be seen, there seems to be more voltage noise at closer distances. Each measurement was taken at night while during the day charge control measurements were taken. This accounts for the discrepancies in charge because these small deviations from 0V are most likely due to human error. The error in particular being that I had to set the initial charge back to 0V after taking the other data.

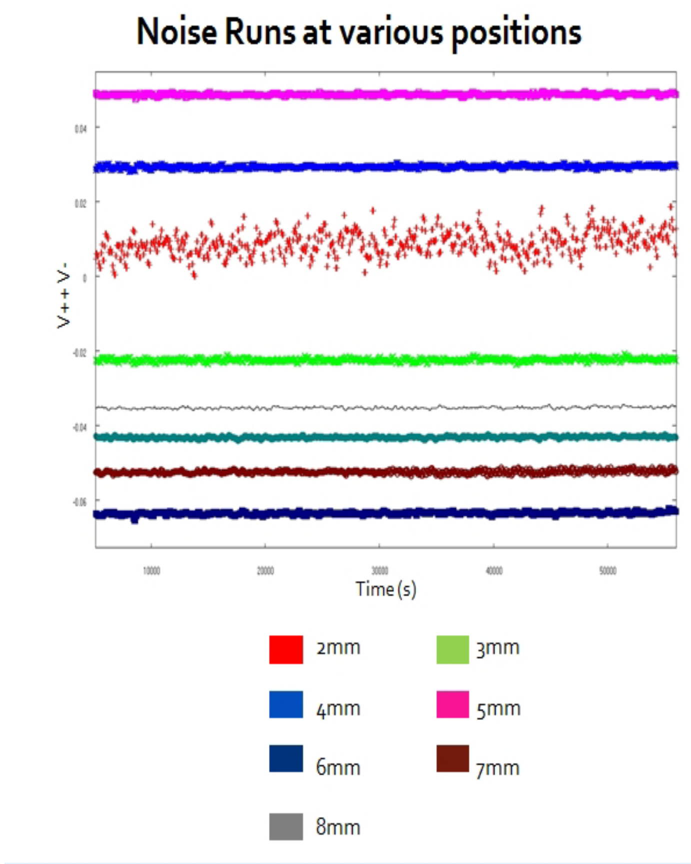


Figure 4: Distance measurements of noise run of LISA taken on 8 separate nights at distances from 2mm-9mm.

It is important to note that this is only initial data and power spectrum density analysis still needs to be conducted. Also a more controlled run of the data will be needed to see if there are smaller affects due to distance on the pendulum. This data should be conducted all at once with no other data taken in the middle so as to change the initial starting point of each run.

## Stepper Motor

The next improvement to LISA was to replace the broken stepper motor that can be used to rotate the pendulum. The motor is a bipolar motor and is used to do coarse rotations of the pendulum such that the pendulum is in a position to be locked into the feedback loop and be measured on the detector. The problem with replacing this motor was that there was no documentation that could be found on the previous motor. Therefore researched was done to find a motor that was compatible with the Pontech stepper motor controller already incorporated into the set up. Table 1 shows the specifications needed from the motor and what our 23D- standard stepper motor provides.

| | Bipolar | Current | Voltage | Size |
|---|---|---|---|---|
| Pontech Controller | ✓ | 2.0A | 5.0V | 4mm |
| 23D motor | ✓ | 1.47A | 4.2V | 2mm |

Table 1: Specifications for a new stepper motor.

The 23D motor fit our specifications needed for the controller. The next step was to mount the motor onto our vacuum system. Therefore I designed the mounting mechanism and built it in the shop at CENPA. Figure 5 is a picture of the finished product. The motor works as expected and LISA is again ready to run more experiments.

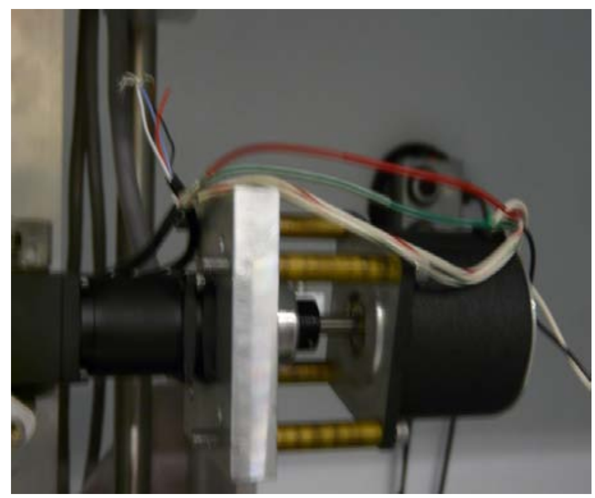

Figure 5: 23D- standard stepper motor replacement. Mounting devices was designed and built at CENPA.

## Electron Gun and Photo Current Measurements

One goal of the LISA project is to measure the photocurrent produced by our UV LED so that we can characterize it and know more about our set up. To do this I designed an electron gun which will measure the amount of photocurrent produced by the UV LED. It is important to note that the changes in current that we expect to see are on the order of Pico amps, therefore photo current maybe hard to detect. The electron gun uses a magnesium plate as the cathode which is connected with insulation to an aluminum cylinder. The cylinder is placed at a different potential then the magnesium such that the ejected electrons from the magnesium will travel through the electric field and deposit on the aluminum lid were the photocurrent will be measured. Figure 6 is a picture of the electron gun that I designed and fabricated in the machine shop.

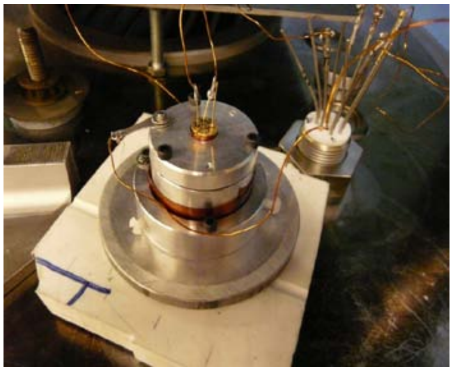

Figure 6: Electron gun to measure photocurrent of our UV LED. The bottom plate is the magnesium cathode while the LED sits on the aluminum cylinder. Different potentials are applied to each component and the photocurrent is measured at the lid.

After having built the electron gun the system was placed inside a vacuum chamber and photocurrent measurements were taken with the UV LED on and off. Figure 7 shows the initial data that was obtained from our measurements.

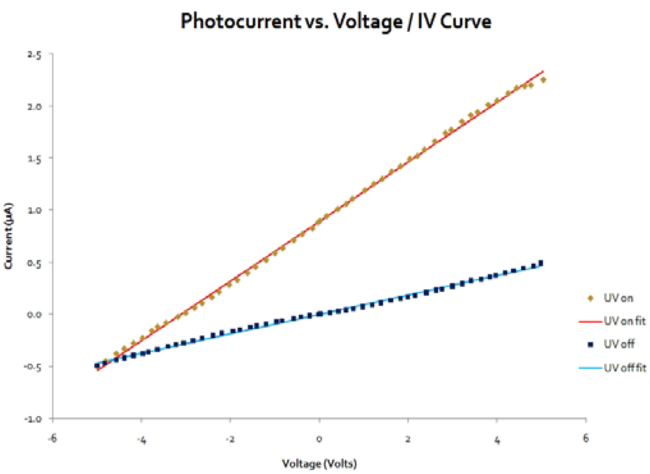


Figure 7: Photocurrent measurement from my electron gun design (see figure 6).

By observing this data it seems to indicate that when the LED is on that we can measure photo current. However measurements after this could not replicate this result. After debugging our system we found that the current that we saw was not photo current, but a huge leakage current coming from the bread board we were using to power all our circuitry. To fix this problem I designed a battery system to separately power the UV LED and eliminate the leakage current.

We simultaneously proceeded in a better design of our system. Therefore I designed a new electron gun which incorporated and Einzel lens, and it was our hope to draw more current from our system. Figure 8 shows the new system design and was created on Solid Works.

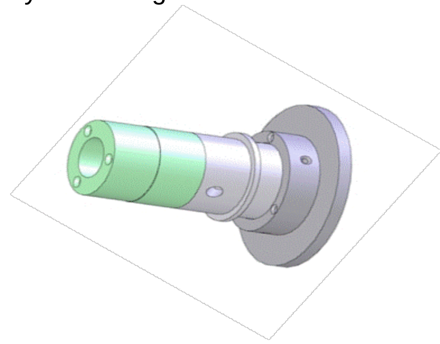

Figure 8: New electron gun design made on

Our first consideration from this new design was if we should replace magnesium as our cathode with a better candidate with a lower work function. Table 2 lists the possible candidates for our electron gun. These metals were taken into consideration after doing research on other electron gun assemblies and what materials they used.

| Element | Work Function |
|---|---|
| Cesium | 2.10 eV |
| Rubidium | 2.16 eV |
| Sodium | 2.28 eV |
| Potassium | 2.30 eV |
| Calcium | 2.90 eV |
| Lithium | 2.90 eV |
| Magnesium | 3.66 eV |

Table 2: Cathode Candidates.

Upon farther investigation, even though all the other candidates had lower work functions, we disregarded them based on their reactivity. Therefore we chose our initial model to keep magnesium since it had a relatively low work function, but was safe to use in our vacuum system.

The next consideration of the design was how to improve the amount of current that we could measure. It was decided to incorporate an Einzel lens into our system.

An Einzel lens is a system of metal cylinders that take advantage of applied voltages to create an electric field which can pull the ejected electrons through the gun. Figure 9 is a diagram of the Einzel lens design I chose. The source potential and the middle lens are placed at the same voltage, and the first and third lenses share the same voltage. By applying a higher voltage to the middle and source lenses we are able to create an electric field and pull our ejected electrons from our magnesium plate to the aluminum plate we wish to measure from.[2]

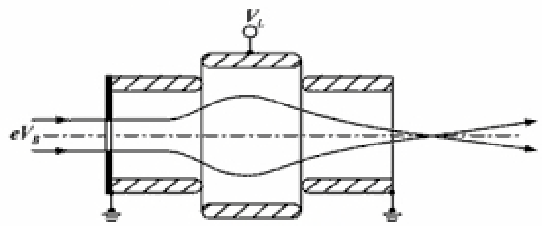


Figure 9: Einzel lens. If $V_L = V_b$ then the focal length is twice the diameter of the lens. Our design allows the electrons to travel up the gun at the same speed that they were ejected from the magnesium. Figure from *Applied Charged Particle Optics pg. 42.*

The design in figure 8 we incorporates this new feature. Figure 10 is a cross sectional diagram of our electron gun. As the UV LED emits photons at the magnesium the mesh source and Einzel lens pull the ejected electrons through the gun and onto a aluminum plate to measure the current.

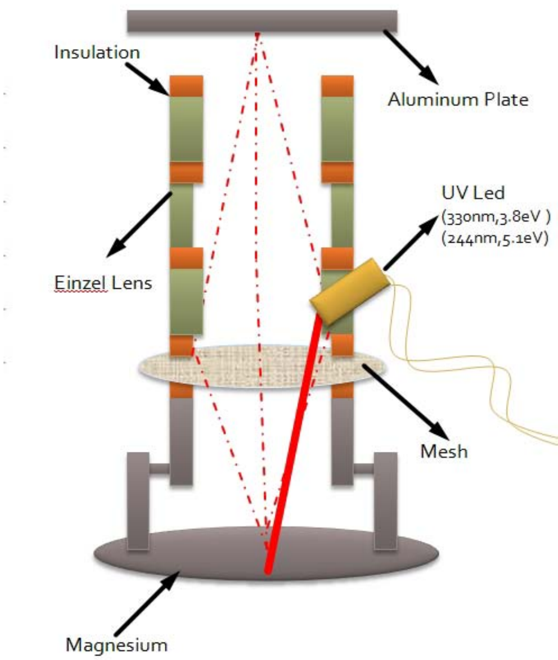


Figure 10: Cross sectional diagram of new electron gun design. Path of photons and electrons are indicated and it can be seen that by incorporating an Einzel lens we can control the flow of electrons to our aluminum measurement plate.

After fabricating the new design we took photocurrent measurements of the device. We did this with both a 240nm and 330nm UV LED. Figure 11 shows the results of our measurements. It can be seen that there is no measured change in photocurrent when the UV LED is changed. This made us realize that our initial data was just huge leakage currents and that we needed to debug our system. One other important note is that while taking data if someone were in the room then their proximity to the experiment greatly affected the current measured.

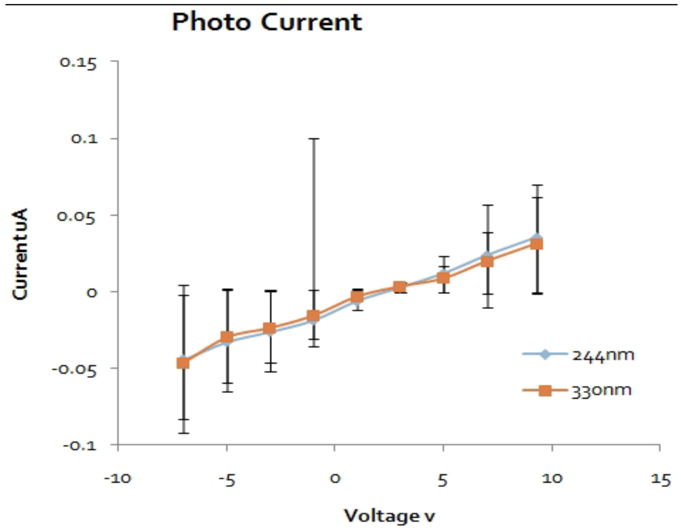


Figure 11: Photocurrent measurement taken with both 240nm and 330 nm UV LEDs on the new electron gun design.

After confirming that there were huge leakage currents and other issues in our system I designed the battery system. Figure 12a is the circuit diagram of the system and figure 12b is the actual system. The system uses a LM317 to regulate the amount of voltage that goes into the UV LED. We are then able to use a variable resistor to change the intensity of the light emitted. By replacing the set up with this power supply we should have significantly cut down on the amount of current leakage.

(a) (b)

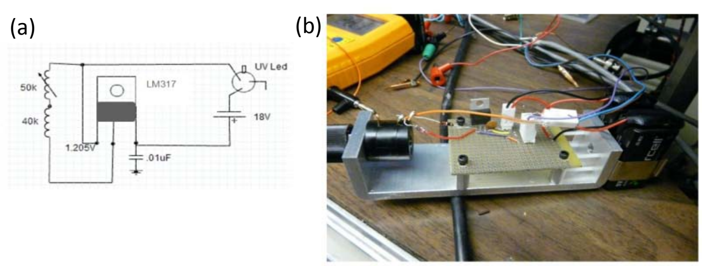


Figure 12: (a) Circuit diagram of battery system. (b) Actual battery system.

Before taking more data two other changes were also made to our experiment. The first was to go back to our simple electron design (see figure 6) and to replace our amp meter with a DAQ on a computer. This gave us an advantage that not only could we take more precise data with time, but we also incorporated into our DAQ program a function that could control when our UV LED turned on and off. Figure 13 shows a data run of our simple electron gun using our DAQ system.

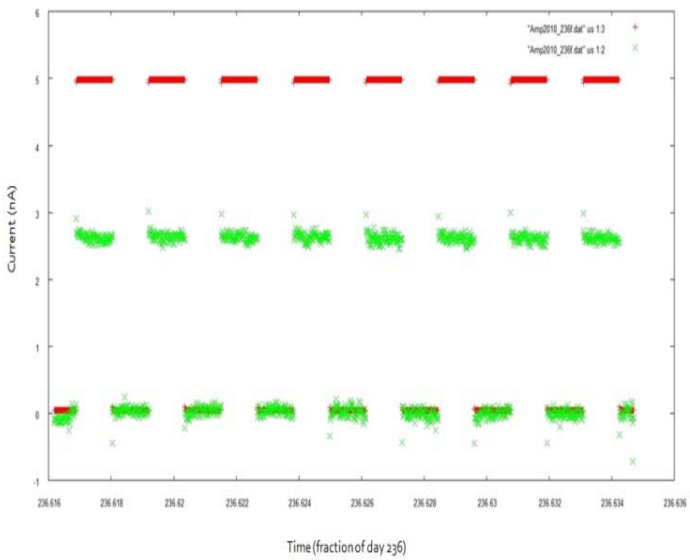


Figure 11: Photocurrent measurement taken with both 240nm and 330 nm UV LEDs on the new electron gun design.

The red data represents the program turning our UV LED on and off. Just as expected we see that when the LED is on there is a jump in current. This is very promising because now we have data to show and confirm that the current does change when the LED is on and off.

The next step was to take data at various voltage differences between our aluminum and magnesium and see if we can detect any changes in the photo current. Figure 14 shows the photo current measurements taken from -5V to 5V. We expect the shape to be that of a typical photo electric curve. We do see that at -5V the photocurrent seems to change dramatically, and therefore it is promising that we may be measuring photocurrent.

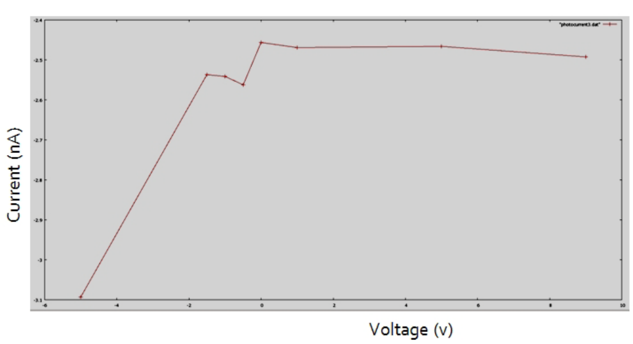


Figure 14: Photocurrent measurement taken from -5V to 5V potential difference from the electron gun using the new DAQ system. Both represent the same data, however the second graph is easier to read with the lines.

Although this data seems to indicate photocurrent changes, it is hard to conclude that that is what we are seeing. The issue is that because this data was taken at the end of my REU I have yet had the opportunity to measure data points in-between -5V and -1V to conclude that this is what we see. More data needs to be taken to confirm if this is photocurrent, and until this is done we cannot conclude that we are detecting changes in photocurrent, however good our data looks.

**Autocollimator and Temperature**

I also spent time working on improving LISA's autocollimator. Figure 15 shows the autocollimator that the previous REU student Jenna Walrath built last year as a REU participant (please see Jenna's paper in the 2009 REU class papers for more information).

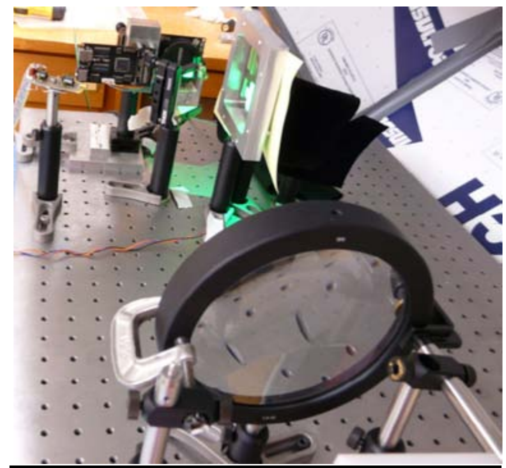

Figure 15: LISA autocollimator designed by Jenna Walrath during her 2009 INT-REU.

Using her set up I took some data that measures the sensitivity in angle of the autocollimator. Figure 16 shows one data run that I have taken with this set up. It is hard to tell from the first graph, but as you zoom in on the end tail of the data it can be seen that the data is sensitive to about $10^{-8}$ rad/ $Hz^{-1/2}$. The goal of this set up is to have $10^{-9}$ rad/ $Hz^{-1/2}$ sensitivity. It can also be seen that the data taken is very noisy, and so my hope was to try and build a device which could measure the temperature in the room and determine if there is any thermal noise in the signal. By subtracting the thermal noise it is our hope that we can increase our sensitivity and reach the $10^{-9}$ rad/ $Hz^{-1/2}$ goal.

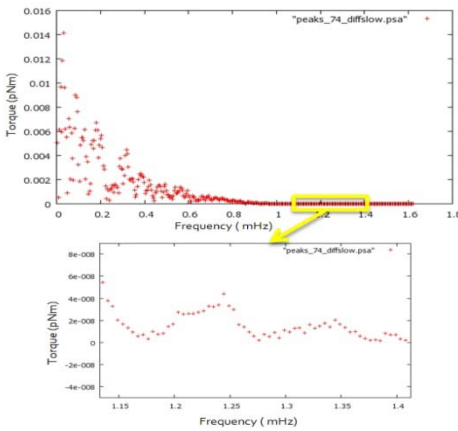


Figure 16: LISA autocollimator data. We observed that the sensitivity is only ~$10^{-8}$ rad/ $Hz^{-1/2}$ where our goal is $10^{-9}$ rad/ $Hz^{-1/2}$.

To measure the temperature and noise of the system I designed a system of two thermometers to measure the temperature inside and outside the autocollimator. Figure 17 (a) shows the circuit diagram and (b) the actual thermometer design. The circuit is a simple amplifying circuit which takes in the data from our probes and returns the temperature as voltage.

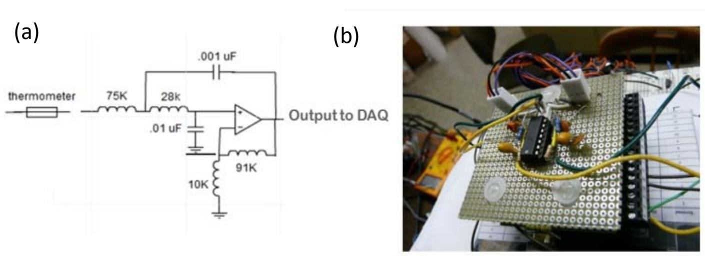


Figure 17: (a) Circuit diagram of thermometer system. (b) Actual thermometer system.

Using a DAQ system I was able to calibrate the system. I was then able to take temperature data of the experiment. Figure 18 represents a data run of the temperature outside of the autocollimator.

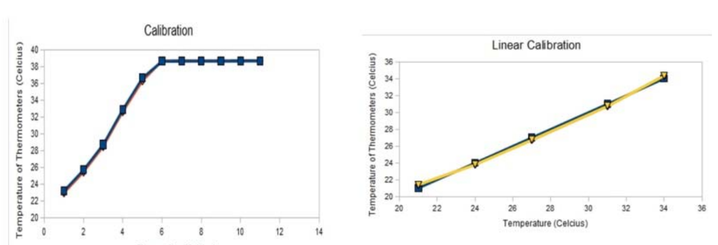


Figure 18: Temperature run outside of the autocollimator using the thermometer system I designed.

This data demonstrates that my design does work. I have not been able to try and smooth out the data or extract the thermal noise from this it, however I was able to make a device that someone can easily use when I leave. The other important modification that will need to be made in the future will be to integrate the autocollimator and thermometer DAQ so that they are on the same time scales. That way when noise is extracted we can correlate that with the autocollimator data.

## Conclusion

Many improvements on the LISA project have been made this summer. I was able to demonstrate charge control of the torsion pendulum and this data was taken to the LISA Symposium at Stanford this summer by my advisor Stephan Schlamminger. I was also able to add a new motor to LISA and design a electron gun to measure the photo current of our UV LED. I was also able to make improvements on the autocollimator by adding a thermometer system. Much has been done this summer but much more needs to be done before LISA will be ready to launch behind the earth. The most important work to be done at this time will be to vary the voltage between the magnesium and aluminum of the electron gun and take photo current measurements to show that we are in fact measuring photocurrent and for what voltages. Then the Einzel lens should be reincorporated into the design and characterization of the photo current of our UV LED needs to be closely measured. The autocollimator and thermometer DAQ's need to be integrated and then more data needs to be taken to increase the autocollimator's sensitivity. After this it is our hope to redesign the autocollimator and make a more functional prototype that could be used inside of the final LISA design.

## Acknowledgments

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## References

[1] Peter R. Saulson, *Fundamentals of Interferometric Gravitational Wave Detectors* (World Scientific Publishing Co., River Edge, New Jersey) 1994.

[2] Helmut Liebel, *Applied Charged Particle Optics* **39-43** (Springer, Verlag Berlin Heidelberg New York), 2008.

[3] S. E. Pollack *et al*., Phys. Rev. D **81**, 02110(R) (2010).