Thermal Noise in Non-Equilibrium

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Abstract

Gravitational wave detectors have evolved into the interferometers at LIGO/VIRGO that we know today. Still, their biggest obstacle is reducing the level noise in order to see varying gravitational wave signals. One type of thermal noise that exists in these detectors still have not been fully explored; thermal noise in non-equilibrium. This occurs whenever a heat gradient is introduced to an environment. This noise will be explored using a combination of an oscillator and two interferometers. The system will be exposed to varying temperatures and the data will be collected through photodiodes at the end of the interferometers. Thus far, the sensitivity is two orders of magnitudes away from seeing the thermal noise. Several measures are taking place in order to increase our range. This noise must be understand in order to further improve upon the methods we have now.

Contents

1 Introduction

This paper will begin with a brief overview of gravitational waves and the general theory behind it. The next subsection will then go on about detecting gravitational waves and the method as to which we currently detect them. Section two will discuss our reasoning behind the experiment and the steps to take in achieving it. Section 3 will show the results that was attained so far. Section 4 and 5 will summarize the thoughts, future questions, and the experiment. The work was conducted at the Instituto Nazionale di Fisica Nucleare (INFN) in Legnaro, Italy. This lab works in conjunction with the Universita di Padova.

1.1 Gravitational Waves

The source of gravity itself has been an elusive topic to the science community. We are able to express gravity through equations and theorize about it, but any further experimental clues to its physical form has been hard to find. That is, until the concept of gravitational waves came to officially existing in the universe.

As of today, gravity is described as curvatures in space due to a mass and can be generally expressed with the equation shown below. With the mass of the object and the curve that it creates being directly proportional. If the mass is to accelerate through this space then it creates waves that propagate from it at the speed of light. These waves are extremely small, as small as 10^{-20} meters, and are known as gravitational waves[5]. That gravitational waves that we have seen are only from sources of huge mass, like a black hole. Gravitational waves were first theorized by Henri Poincare in 1905 and was later predicted by Albert Einstein in 1916. Einstein was able to use his general theory of relativity to argue his claim.

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \tag{1}$$

He claimed that space and time would be disturbed by massive objects and would create something similar to a shock wave. This equation was then formulated to describe how space and time relate. Gravitational waves carry what we call gravitational radiation that can go in areas where even electromagnetic waves cannot[2]. Using these waves, we can take the next step in understating space and even the origin of the universe.

1.2 Wave Detection

It is theorized that gravitational waves are running throughout our solar system at every frequency. In the 1960's, Joseph Weber, an American physicist, began his search for gravitational waves. He developed an experiment, now known as Weber bars, which involves the movement of two aluminum cylinders. These cylinders were suspended on steel cables. They were made to be massive in order to carry a resonance frequency of 1660 hertz. When the disturbances in space pass through this, the oscillator moves in resonance. Piezoelectric crystals are attached around the cylinder allowing its movement be converted to an electrical signal that we can analyze[1]. This method was used for many years but yielded no significant results.

Interferometry was then developed with the capability of having a much higher sensitivity. Interferometry is widely used among scientists today for detecting things on the nanoscale. This method also proved to be easy to reproduce as seen in figure 2. It features one laser that is passed through a

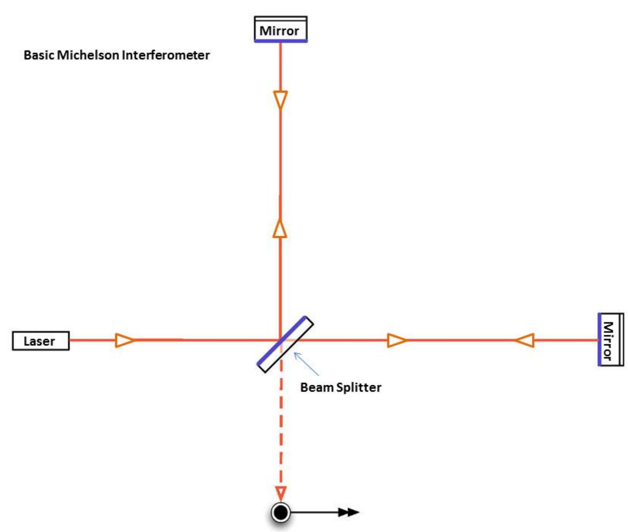


Figure 2: Layout of a basic interferometer. The black circle is a photodiode that is accepting the created output signal

50/50 beam-splitter. These two beams then are reflected back to the beam-splitter creating a mixed output beam. The output beam's interference is measured using a photodiode. The fringe pattern created by that interference is what describes the displacement experienced from the mirrors. It can be described through trigonometry and other means, i.e. Fourier transforms, making it easy to express mathematically [1]. In 2002, the Laser Interferometer Gravitational-Wave Observatory (LIGO) was built in the United States of America as the first full-scale interferomrty project for gravitational waves. They currently have two campuses in Livingston and Hanford with a current project to build another in India. There are two other main ground-based interferometers, VIRGO in Italy and GEO600 in Germany. These two also work hand in hand with LIGO hunting for the next wave.

(a) LIGO Hanford, Washington.

(b) GEO600 in Hannover, Germany.

(c) VIRGO in Cascina, Italy

Figure 3: The current areal view of these locations.

September 14, 2014, The first "chirp" came through at LIGO in Livingston, Louisiana, marking the official discovery of Gravitational Waves. LIGO later received two more confirmed signals solidifying their ability to detect gravitational waves. The next step for these groups is to improve their instruments where they can pick up waves on even more frequencies letting us actually see further into space. One of the biggest obstacles, still, is the presence of thermal noise.

Scientists have completed several experiments on how thermal noise behaves in equilibrium[3]. This allowed us to map out where the noise occurs, so we won't mistake it as a gravitation wave in future readings. The results

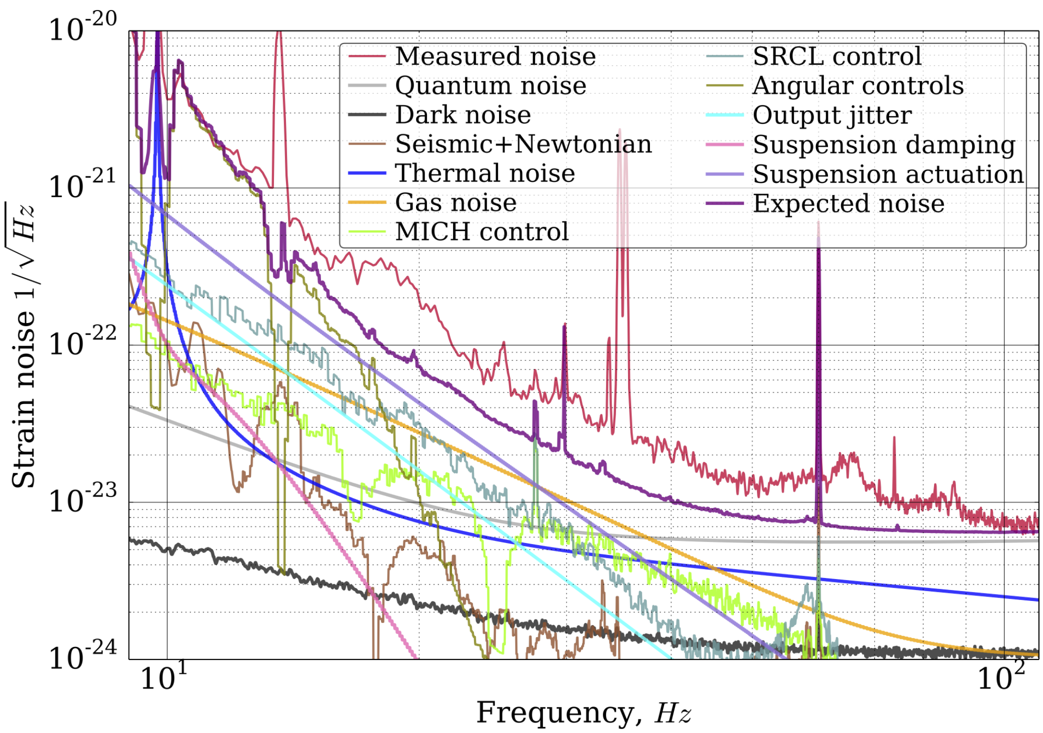


Figure 4: The current power spectral density of LIGO. Here you can see the thermal noise resting in about the middle of the graph.

were used in helping to improve the interferometers' sensitivity. Although, it has been shown that ground-based interferometers also have non-equilibrium thermal noise to consider. Today, there a very few experiments done to study the behavior of thermal noise in non-equilibrium. Some groups are beginning this new search and are raising interest for others to follow.

2 The Experiment

2.1 Purpose

It has been shown that ground based gravitational wave detectors are non-equilibrium instruments due to their thermal compensation schemes and laser power absorption [6]. So far, there has been research in the thermal noise produced from systems that are in equilibrium. However, ground based gravitational wave detectors, like LIGO, encounter thermal noise not in equilibrium as well. The aim of this experiment is to examine the thermal noise produced from a macroscopic oscillator in non-equilibrium. Not only will this help improve all interferometers, but we will better understand the noise from anything else that experiences a heat gradient.

2.2 Methodology

For something to be out of thermal equilibrium, there must be a thermal gradient of some kind along that mass. In the case of this experiment, the mass in question is the aluminum oscillator inside the vacuum chamber. When one part of the oscillator is heated, a thermal gradient is formed, and the aluminum starts to contract and elongate. The thermal noise produced from this process is exactly what we are measuring.

2.2.1 Interferometry

This experiment utilizes two interferometers that have been superimposed and was placed on an optical table as seen in Figure 5. The beam is first sent through a MODE1 fibereeeee And then a vertical polarizer. The $\lambda/2$ waveplate is set to offset the polarization by 45^0 making the power equal in S and P. There are two interferometers due to the several reflecting mirrors that we are using on our interferometer bench (see Appendix). The exact layout is as follows in figure 4.

We have one central beam that goes through the first 50/50 beam splitter. The reflected half is sent to a photodiode and will be read as our incoming power. The other half is sent to the bench where it is reflected on the oscillator surface and a 0^0 mirror. The two outputs are measured using the four photodiodes. As the bar inside the oscillator expands and contracts from the heat gradient, this slightly moves the mass on the bottom of the oscillator and hence the surface. These small movements are picked up through the two interferometers in the photodiodes allowing us to measure the thermal noise.

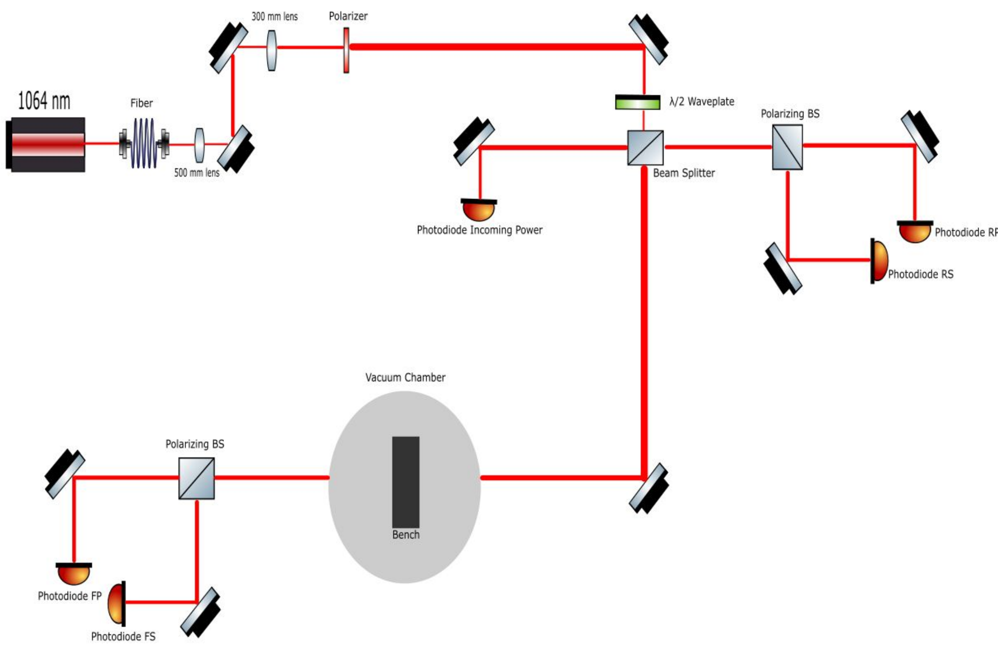


Figure 5: This is a reconstruction of the optical table. It is a simplified version for the sake of showing how the two interferometers are set out on the table.

2.2.2 Vacuum System

Reducing all other possible sources of noise for this experiment is crucial. One of the many factors is the noise made by the various particles that exist in the air. In order to funnel this out, a vacuum system was put into place. Our threshold of minimal vacuum was 10^{-4} mbar. The system included two main stages that led up to the chamber itself. The first stage is standard pump that operates using pistons and electrical power to drive the air out of where ever is connected to. The second stage is called a TURBO vacuum. This was operated more as like a filter between the higher and lower pressures that can exist inside the tubing. To keep everything monitored, three vacuum gauges were placed after each main section. This was used in powering up certain instruments at certain times in order to keep the pressure levels constant throughout. A sandbox was later installed around the tubing closest to the chamber in order to reduce the vibrations caused by the pumps.

2.2.3 Data Analysis

The analysis of this experiment was done through Matlab's basic command line. We used its graphing and averaging functions to produce PSD, frequency versus time, and ASD graphs.

The power spectral density (PSD) is what gives us the noise curves that we analyze. What it really is defines is the average power across a given wave frequency. The output that the photodiodes gives are in volts. This is converted to watts and then expressed through this averaging equation.

$$P = \lim_{T\to\infty} \frac{1}{T} \int_0^T |x(t)|^2 \, dt. \tag{2}$$

With x(t) representing the signal and T representing the time variable. T also allows us to specify a certain interval to calculate the integration. This interval is used when dealing with the frequency component of this operation. A truncated Fourier transform is needed since the normal transform cannot be easily used when dealing with these frequencies[4]. This transform can be expressed as:

$$\hat{x}(\omega) = \frac{1}{\sqrt{T}} \int_0^T x(t) e^{-i\omega t} \, dt. \tag{3}$$

After integrating through, the power spectral density can be formed. Although, a different way to show this is through a summation instead.

$$\tilde{S}_{xx}(\omega) = \frac{(\Delta t)^2}{T} \left| \sum_{n=1}^{N} x_n e^{-i\omega n \Delta t} \right|^2. \tag{4}$$

This summation can express a single estimate of the PSD. It is formally reached once T has approached infinity. This summation is what the Matlab program is running in order to produce the graphs that we want.

3 Results

The project is currently ongoing and is only at the stage of collecting initial samples. I am not able to continue with this project due to personal time constraints. The total visibility from the photodiodes that we achieved was 94% in the s-polarization and 90% in the p-polarization. The output that we received from them is shown in Figure 6.

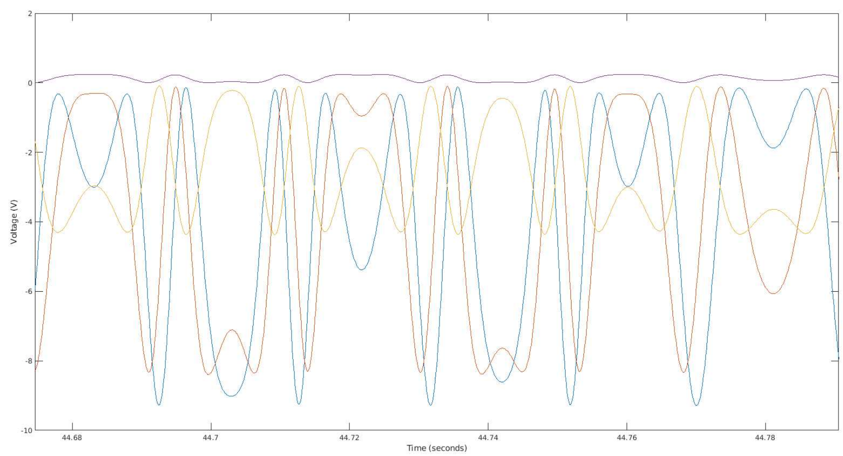


Figure 6: Here are the four signals received from the photodiodes that are receiving the ends of the interferometers. The fifth photodiode, that is receiving the incoming power, is not included.

The interference from the two interferometers makes the sinusoidal path that the four signals exhibit. Below is the current noise curve for our experiment made from Figure 6. From it, we see that noise up to 10^{-13} $m/hz^{.5}$ can be reached. This plot was made with the parameters of having the lights off and the vacuum tubing going through a vibration-damping sandbox.

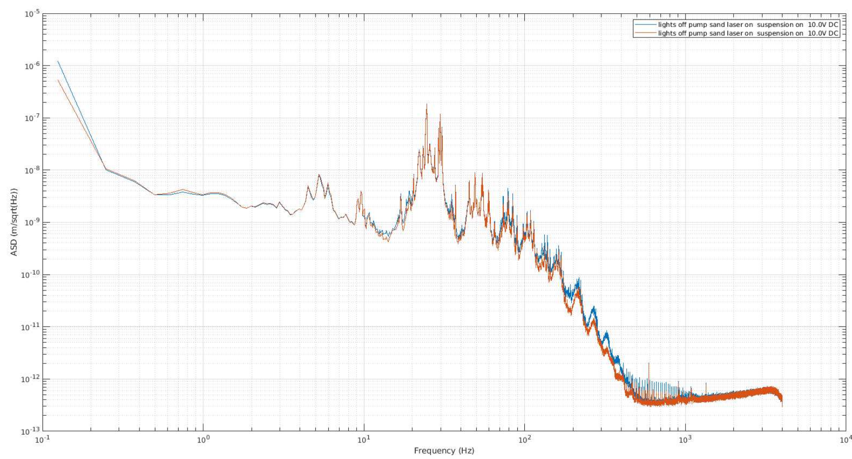


Figure 7: This graph is attained after taking the square root of a PSD graph.

4 Discussion

The noise curve that we obtained shows promise for improvement. We need to reach a sensitivity of about 10^{-15} $m/hz^{.5}$ in order to see the thermal noise. The result that we saw in our experiment is primarily dependent on acoustical and electrical sources. The 1st stage vacuum pump produces a relatively loud noise on the macroscopic level. Measures are being done to establish a connection outside of the room itself so that the pump can be used out there. This will greatly decrease our total acoustic noise. Another obstacle the vacuum system brings is the small vibrations both pumps produce in the tubing. To get around this, a section of the tubing closest to the chamber was funneled through a box of sand. The sand was put in place to absorb the vibrations running through the tube. However, with it having to go through that box, our pumping speed was greatly decreased. A bigger sandbox was then designed and will be built so that the pumping speed can increase back to its original capacity. While obtaining our results, the vacuum pressure was at about $5e^{-4}$ mbar versus the $7e^{-6}$ mbar that could attain before in a reasonable amount of time. Having our vacuum pressure back down to those levels should increase our sensitivity as well.

Another phenomenon that we found was the signal's dependence on any incoming laser fluctuations. A frequency regulator was used to change the frequency of the laser while keeping the amplitude the same. After doing this, a spike was formed with an amplitude of about 10^{-3} $m/hz^{.5}$ on the ASD plot where the plateau occurs. Once this event is explored further, any more limitations or possible configuration improvements can be found to aid in this project. When an interferometer or vacuum system is being built at high-end labs the utmost security towards outside obstructions is given. During this experiment, we were careful in isolating everything in a clean room along with cleaning things while we could, although, it was not done in the strictest of manors which will cause an unknown amount of error. However, with this in mind and the fact that we still have a the thermal noise in our grasp shows how reproducible this project is.

5 Conclusion

The end conclusion is still in development since the project is still ongoing. This needs to be studied further by not only this project but by others as well. Not only for the improvement of interferometers, but for anything else that has a thermal gradient. Once this can be applied to LIGO/VIRGO, new areas of space will become available to us in being able to now detect waves of different frequencies. Objects in space never discovered before or even a better look at the past before electromagnetic waves were able to travel. This same idea could be experimented again except without using an oscillator as the source of the gradient. This could possibly cause a different range in where the thermal noise would appear.

6 Acknowledgments

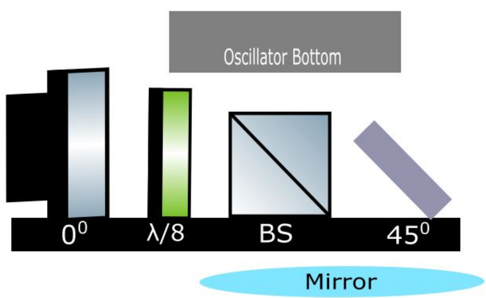
I would like to thank everyone working with INFN, Universita di Padova, VIRGO, and Alvise for teaching me not only gravitational wave physics but how to be a logical scientist. Thank you to the University of Florida for providing this International Research Experience for Undergraduates and allowing me to take part. Thank you to the National Science Foundation for funding this experience.

7 Appendix

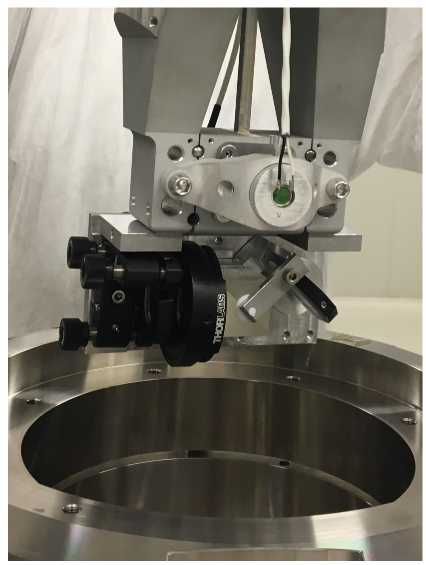
Here is a brief classification of certain instruments or objects used in the experiment.

7.1 Appendix A: Interferometer Bench

The bench that was attached along the bottom of the oscillator is what held the components necessary in creating the interferometry. This object was cleaned and screwed into the oscillator which was in whole inside the vacuum chamber.



(a) This is a simplified depiction of the bench that was placed under the oscillator.



(b) This picture shows what the bench looks like in real life. This is while it is attached to the oscillator but outside the vacuum chamber.

Figure 8: Visuals of the bench.

8 References

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