LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Characterization of the FROSTI next-generation adaptive optic

Sophia Arnold

California Institute of Technology
LIGO Project, MS 18-34
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project, Room NW22-295
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
Route 10, Mile Marker 2
Richland, WA 99352
Phone (509) 372-8106
Fax (509) 372-8137
E-mail: info@ligo.caltech.edu

LIGO Livingston Observatory
19100 LIGO Lane
Livingston, LA 70754
Phone (225) 686-3100
Fax (225) 686-7189
E-mail: info@ligo.caltech.edu

http://www.ligo.caltech.edu/

1 Introduction

The first prediction of gravitational waves was by Oliver Heaviside in 1893. Noting the symmetries between the behavior of the force of gravity and electric charges, he proposed that gravity may also have wave-like behavior as to match its electrical field partner. After Heaviside, the next major conjecture on gravitational waves came from Henri Poincaré, when he predicted that gravitational waves move at the speed of light. Without experimental proof, these hypotheses had some traction within the physics community, but the first real proponent of gravitational waves came from Einstein's theory of General Relativity. Gravitational waves are what we would consider to be ripples in space-time, with detectable ones being by-products of massive stellar events, like colliding black holes, or pulsars. Contrary to its electromagnetic counterpart, gravitational waves have a very weak interaction with matter, making them impossible to detect without the help of massive interstellar events [1]. While their weak interaction with matter makes gravitational waves impossible to detect without using astrophysical phenomena, this characteristic also allows them to be used to further understand the behaviour of their sources.

The first direct detection of gravitational waves was by aLIGO, the advanced Laser Interferometer Gravitational-wave Observatory in 2015. LIGO is effectively built as two massive Michelson interferometers, each which have two 4 km long perpendicular arms that form an L-shaped detector. An example of the basic premise of a Michelson interferometer is shown in Figure 1. The general premise, is that in this sterile environment, changes in the length of the arms will be a direct result of contortions and contractions that arise from very powerful gravitational radiation. These minute changes in length can be detected by phase differences in the laser beams, allowing us to directly measure the effect of a gravitational wave's path through the detectors.

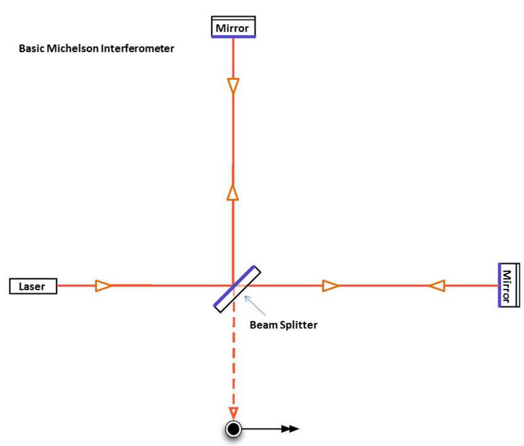


Figure 1: Diagram of basic Michelson Interferometer [2]

aLIGO is an advancement project for LIGO, which began in 2008, to upgrade the facilities of LIGO. In aLIGO and in future improvement initiatives to LIGO, minimizing noise and loss from the laser is central to improving LIGO's detection. In advancing the precision and accuracy of LIGO's detections, we are further able to understand both the behavior of gravitational waves and we can further understand the behavior of the interstellar phenomena which cause these detections. A diagram summarizing the aLIGO's improvments upon the initial design are shown below (Figure 2).

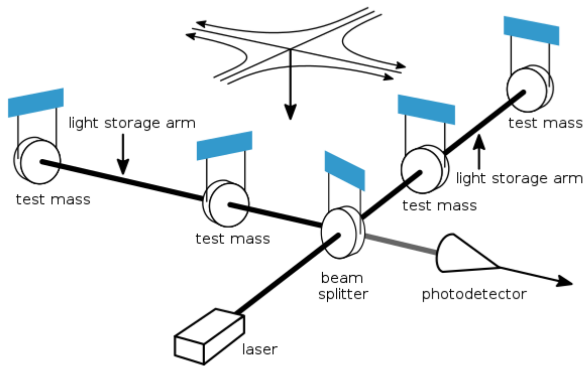


Figure 2: Diagram of aLIGO's updated interferometer [3]

A facet of aLIGO, and LIGO A+ which is the next improvement initiative for LIGO, is achieving higher laser power in order to get more precise measurements. Higher powered lasers introduce added potential for scattering and lensing from defects in the reflector's surface, which is already a major issue limiting the capabilities of aLIGO. A central source of this noise is from point absorbers and uniform coating absorption on the mirror sources scattering the beam that is central to LIGO's data collection [4]. To combat this noise, the FROSTI (Front Surface Type Irradiator), an annular ring heater, has been designed to apply a corrective heating pattern to the test mass to minimize scattering and power loss from the beam. The device has a diameter of 34 cm and will be placed 5 cm from the targeted test mass (Figure 3). There are eight heating elements which are placed along the circumference of the ring, which apply the incident radiation.

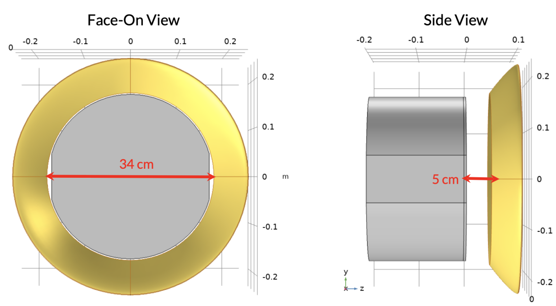


Figure 3: Model of the FROSTI prototype [4]

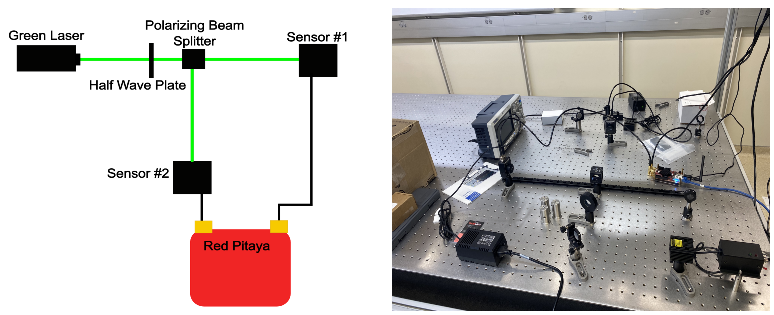
Theoretical models of the desired irradiance pattern have been produced, but experimental data has yet to be taken to confirm agreement with the expected profile. This SURF project will focus on reducing power loss from scattering within the LIGO arm cavities first by experimentally finding noise fluctuations in FROSTI's heater elements, and addressing them, and second by testing the irradiance profile of the FROSTI prototype and verifying its agreement with existing these theoretical models.

2 Objectives

1. Construct optical layout consisting of green laser and two photodetectors.
2. Compute the Power Spectral Densities (PSDs) of each channel along with the Cross Spectral Densities (CSDs) of the signals acquired from the optical setup using Python code.
3. Apply this framework to a sample heater element to measure the CSD of intensity noise.
4. Complete assembly of a clean-room optical layout to allow for collection of FROSTI data.
5. Determine agreement of experimental data in relation to existing theoretical models through the development of a Python package.
6. Examine the thermal patterns of individual heating elements within system.

3 Approach

There have been two primary objectives during the first two weeks of this project: the first to construct the optical setup for the experiment and the second to begin developing code which will dynamically generate the Cross Spectral Density (CSD) of the intensity noise of a green laser. The optical setup, as pictured in Figure 4(a), is a single green laser source, which is split into two beams by a polarizing beam splitter. Once the beam is split, the light is fed into two separate detectors connected to a Red Pitaya, which we use to collect data from the signals. The largest challenge with this setup is getting equal power sent to each detector, but by feeding the beam into a half wave plate before the spilt, we are able to adjust the power that is sent along each arm. An image of the physical, in-lab setup is pictured in 4(b). This setup will enable us to create Cross Spectral Density (CSD) graphs of the signals from the split beams from the green laser, helping us to accurately measure the noise produced by the green laser alone.



(a) (b)

Figure 4: (a) Model of the optical setup for noise analysis of the green laser. (b) Image of the physical optical setup for intensity noise analysis of the green laser.

After initial data collection from this system, the focus moved to performing the desired Fast Fourier Transform (FFT) analysis using Python. The goal of the code is to generate a dynamic plot based on Figure 5 as given in a Fermilab intensity noise analysis of interferometers [5]. This code's job will be to intercept the data, then continuously update a visible CSD plot.

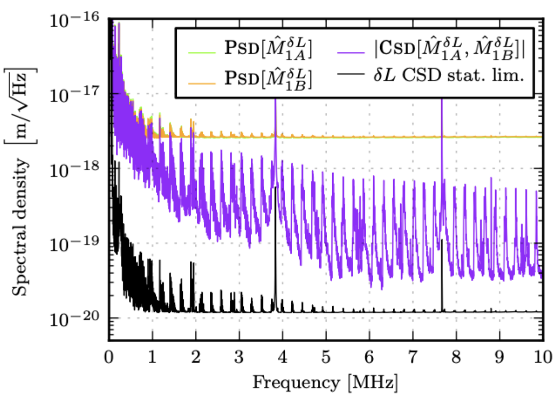


Figure 5: Plot from [5], which gives the thermal noise of one interferometer given by a CSD.

This code was built using the framework outlined in [6]. It works by partitioning the data set, applying a Hanning window function to one partitioned section, computing the FFT of this section, and finally taking the rolling averages of the result of the FFT [6, 5]. The Hanning window is defined by the equation:

$$w_j = \frac{1}{2}[1 - \cos(\frac{2\pi * j}{N})] : j = 0...N-1$$

Where the windows are symmetric by:

$$w_j = w_{N-j}$$

To compute the PSD and the CSD, first we must calculate the window sums defined by as:

$$S_1 = \sum_{j=0}^{N-1} w_j$$

$$S_2 = \sum_{j=0}^{N-1} w_j^2$$

Then, we put these computed values along with the values calculated in the FFT algorithm, through the following equations to compute the Power Spectra (PS) and the Power Spectral Density (PSD) based off of the Discrete Fourier Transformed data (y_m) [6]:

$$PS_{rms}(f_m = m * f_{res}) = \frac{2 * |y_m|^2}{S_1^2}$$

$$PSD_{rms}(f_m = m * f_{res}) = \frac{PS_{rms}(f_m)}{ENBW} = \frac{2 * |y_m|^2}{f_s * S_1}$$

To compute the Cross Spectral Density (CSD), we simply apply these same equations for the PSD to data which has been multiplied with a complex conjugate of the FFT of one of the two signal channels. The code to produce plots of the CSD is in its first running stages with initial plots already being produced. Next, we are looking to incorporate this analysis with a steady intake of data, to generate the dynamic intensity noise plots we are looking for.

4 Challenges and Next Steps

Our next step is determining the number of data points we should include in each section of our partitioned data set. Following the Nyquist theorem, the maximal useful frequency is $f_{Ny} = f_s/2$ where f_s is the sampling frequency [6]. Thus, we know that the optimal frequency resolution is between $\frac{f_s}{100}$ and $\frac{f_s}{100{,}000}$, so moving forward we can determine the best resolution for this situation.

Next, we want to begin communicating with the Red Pitaya outside of the Jupyter Notebook environment inside of the Red Pitaya's interface, and instead access it through the Red Pitaya's SCPI server. This will give greater freedom in our ability to collect data over longer stretches of time, helping us towards having this be a continuous read of noise information.

After the intial analysis is complete with the green laser, the next step is to test a sample heater element and perform the same analysis. At that point, we will use the FLIR camera for data collection.

Full prototype tests on the irradiance profiling and noise are expected to follow.

References

[1] Rana X. Adhikarli, *Gravitational radiation detection with laser interferometry*. American Physical Society (APS), LIGO P1200121, v3 (2014). x

[2] `https://www.ligo.caltech.edu/system/media_files/binaries/237/original/Basic_michelson_labeled.jpg?1435862648`

[3] Phoebe Zyla, *A Calibrated Blackbody Source for Testing Next-Generation Wavefront Actuators*. LIGO T2200206 v6 (2022).

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[5] Aaron Chou, *The Holometer: an instrument to probe Planckian quantum geometry* Classical and Quantum Gravity, IOP Publishing, v34 (2017)

[6] Heinzel, G., Rüdiger, A., & Schilling, R., *Spectrum and spectral density estimation by the Discrete Fourier transform (DFT), including a comprehensive list of window functions and some new at-top windows.* (2002) https://hdl.handle.net/11858/00-001M-0000-0013-557A-5

[7] Cassidy Nicks, *Developing an In-Air IR Test Facility for Next-Generation Wavefront Control*. LIGO T2200205, v6 (2022).