LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Technical Note **LIGO-T2300145–v1** 2023/05/27

Characterization of the FROSTI next-generation adaptive optic

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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.

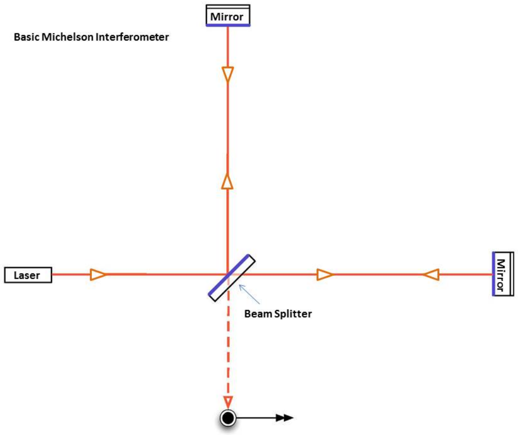

Figure 1: Diagram of basic Michelson Interferometer [2]

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).

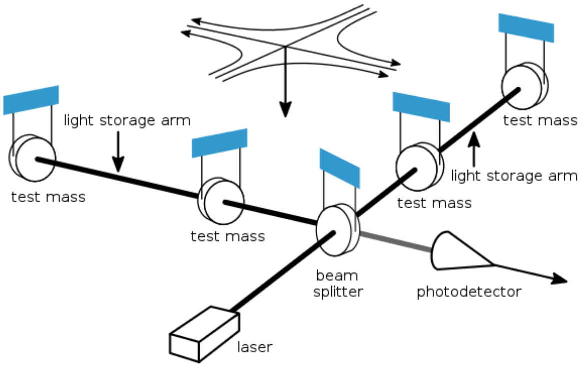

Figure 2: Diagram of aLIGO's updated interferometer [3]

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.

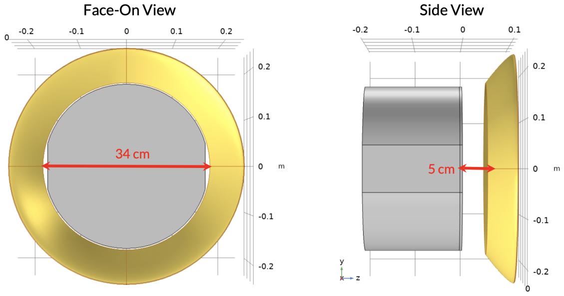

Figure 3: Model of the FROSTI prototype [4]

Theoretical models od the desired irradiance pattern have been produced, but experimental data has yet to be taken to confirm aggrement with the expected profile. This SURF project will focus on reducing power loss from scattering within the LIGO arm cavities by experimentally testing the irradiance profile of the FROSTI prototype and verifying its agreement with existing these theoretical models.

2 Section 2: Objectives

1. Complete assembly of a clean-room optical layout to allow for collection of FROSTI data.
2. Determine agreement of experimental data in relation to existing theoretical models through the development of a Python package.
3. Examine the thermal patterns of individual heating elements within system.

3 Section 3: Approach

The goal of this project is to acquire data on the performance of the FROSTI, an adaptive optic apparatus designed for LIGO A+. The early stages of this project will be dedicated to collecting data on the thermal pattern applied by FROSTI, FLIR A70 infrared camera. This experimental setup relies on the FLIR camera, which takes data from incident radiation, allowing us to compare thermal patterns applied by our FROSTI prototype to theoretical models. The FLIR camera uses a 640 x 480 microbolometer array to detect infrared radiation from changing electrical resistance, which is recorded by the camera as raw ADC values. FLIR has a visual camera component as well, with a resolution of 1280 x 960 pixels, that is used for specific camera modes. In taking data from our FLIR camera, we are limited by the field of view of the IR camera, which is 51◦ x 39◦. Because of this limiting field of view, the camera must be a 0.565m from the screen in order to get the entire 0.4m tall thin screen in the field of view (FOV). We construct the optical table around the capabilities of the FLIR camera on a 4' x 10' optical table. On this optical table, we will have: an IR Absorbing Screen, the FLIR Camera, and the FROSTI Prototype (Figure 4) [5].

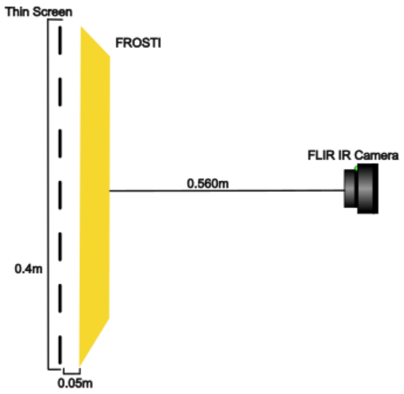

Figure 4: Top view of the set up of the optical table used to collect data on FROSTI's thermal pattern

Once the optical table is set up, the project will transition its focus to write Python code that compares the data collected by the FLIR camera to COMSOL theoretical data. This code is based off a package previously developed in the lab which saves screenshots of the radiation profile detected by the IR camera at a specific time. During this process, it additionally creates a corresponding .csv file containing the given information on position, intensity,temperature, and error measurement for each pixel [5]. Building off of this system, the goal of this project's code is to:

1. Import the collected experimental data from FLIR, along with the COMSOL theoretical data into the program.
2. Perform analysis that searches for disparity between theory and experiment to confirm whether the prototype is operating as expected or if fixes are needed before we are able to commission FROSTI for the LIGO A+ system.
3. Identify sources of error that may lead to deviations between our measurements and the COMSOL theoretical data.

After initial testing of the Python code, we will use it to observe heating patterns of individual elements. This will be done by taking readings of individual elements, and adjusting the radiation that is emitted. Ultimately, we hope to further control the heating elements within FROSTI in order to create more complex spatial profiles of the applied temperature. More intricate control over these spacial profiles will give potential for greatly increased loss reduction, and will help to inform the design of future prototypes. In summary, this code will build off of previous lab work done on the FLIR camera to construct a cohesive Python package which allows us to both collect radiation profiles and to determine what next steps are needed for future versions of adaptive optics within the LIGO detectors.

4 Section 4: Timeline

Week 1-2: Finalize layout of optical table and experimental setup; become familiar with existing Python packages for the project; and take initial data readings.

Week 3-4: Develop Python code for analysis of initial prototype data.

Weeks 5-7: Collect measurement data of FROSTI with all eight heater elements operating and analyze results.

Weeks 8-9: Refine code, and carry out examination of individual heater elements.

Week 10: Complete data analysis and prepare final presentation.

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).

[4] Jonathan Richardson, *Active Wavefront Control for Megawatt Arm Power* LVK Meeting, LIGO G2200399, v1 (2022).

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