LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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A Calibrated Blackbody Source for Testing Next-Generation Wavefront Actuators

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1 Introduction

LIGO (Laser Interferometer Gravitational-wave Obervatory) was built to detect gravitational waves with two interferometers. The gravitational waves advanced LIGO (aLIGO) detects are much like electromagnetic waves, in that the gravitational waves distort space as they move through space, which can be detected by measuring extremely small distances—interferometers in general create an interference pattern and are often used to make small, precise measurements. For aLIGO, the size of interference measurements caused by gravitational waves is on the order of 10^{-18} meters. aLIGO currently can only observe gravitational events that are extremely large in magnitude, as the waves lose most of their magnitude while traveling through space. The type of events that can be observed are the collisions of two black holes, and the merging of two neutron stars. In improving aLIGO's sensitivity, we will be able to detect smaller amplitude signals; we will see more events within a given volume and more signals from farther out.

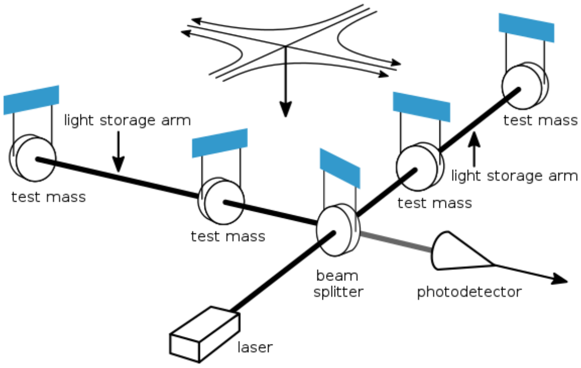

Figure 1: Diagram of aLIGO's Interferometer

aLIGO consists of two arms, which are Michelson Interferometers [Figure 1]. The mirrors on the ends reflect light to create an interference pattern, and a photodetector measures these interference patterns. In other words, aLIGO is designed to measure how far apart the mirrors are. The mirrors are heavy, which reduces noise from photon impacts, and are large, in order to minimize heat deformation from the lasers. To further reduce noise, aLIGO's 200 Watt laser is incredibly stable and its mirrors are highly reflective and polished so that the theoretical design is only atoms away from the actual mirror surface. [8]

Additionally, aLIGO has a thermal compensation system (TCS) which measures and corrects manufacturing errors in the curvature of all optical components. The interiors of the mirrors are created to be extremely reflective at the laser's wavelength of 1064 nm, but their surfaces will naturally warp and shift, making it more difficult to take accurate measurements. The TCS uses ring heaters around each aLIGO mirror to change their radii of curvature and corrects errors with a laser projection system. [2] For our project, we will be focusing on the ring heaters of the TCS and how we can further improve the precision with which they heat the test masses.

2 Objectives

The goal of this project is to validate our system calibration by calculating the theoretical incident radiance profile of the test mass and experimentally fitting our calibration. We will know the temperature that should appear on the test mass, and will convert that temperature into watts per meter squared. By doing this we will determine the incident radiance profile of the test mass and compare that to our theoretical expectation based on the thickness and type of material we are projecting onto. The first step is to create a heated object that will act as a source of radiation which will be projected onto the test mass. On the other side of the test mass an infrared camera will capture the pattern of radiation on the test mass. Ideally we will capture a sharp and accurate image in the shape of the heated object, with the projected power transfer based on the temperature of the heater and the wavelength of radiation.

We will test a few different heater configurations, in order to determine how well the shape of the radiation is transferred, as well as how sharp the resolution of the edges of the radiation shape are. In order to simplify the process, there is no distinct wavelength we are looking for, but rather how well the heater, test mass, and camera adhere to the theoretical power transfer. The purpose of the simple radiation source will be for end-to-end validation of the theory. We will have a clear idea of what the end result should be and will compare the actual result to our predicted theory. If there are systematic errors in the calibration they will be noted and fixed, and the information about the calibration can be applied to future measurements with different and more complex designs.

3 Background

The heaters used in this project will be somewhat similar to the ring heater used at aLIGO. The ring heater at aLIGO heats a band around the circumference of the mirrors, which controls the radii of curvature for the HR surfaces in order to correct and compensate for any minute errors. [11] For our project we will test simpler shapes in order to better observe errors in the power transfer onto the test mass. The purpose of this is to reveal any potential systematic errors in the new experimental setup. By having a very simple geometry, it will be easy to calculate the theoretical expectation. For example, if the apparent power level measured by the FLIR camera does not match the theoretical expectation, we will know that there is a systematic error somewhere in the setup. The simple geometry of our design will make it easy to identify what could have gone wrong, and this will be important to learn for future calibration of different designs. Again, we are aiming to provide an end-to-end validation of our setup and calibration.

The distance between the test mass and the radiation source must be found by considering the power loss over the distance between them. If we take the radiation source to be a black body radiator and the test mass to be a black body, we can use Wien's law $\lambda_{max} = b/T$ to determine the wavelength of radiation with the temperature of the heater. For this we are not matching exactly with aLIGO's specifications, but working with easily predictable data to more easily calibrate the IR camera.

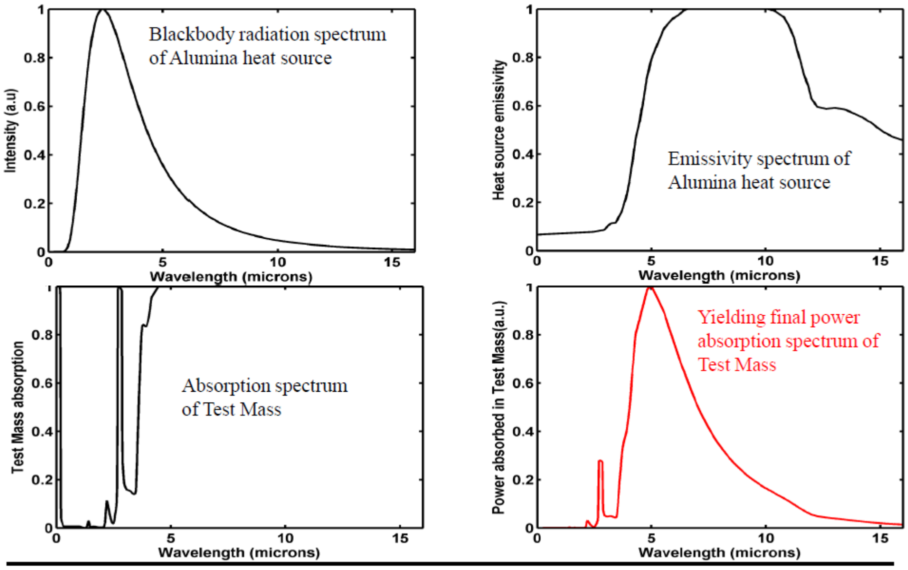

Figure 2: Power Transfer between Source and Test Mass for the CHRoCC at VIRGO

When working with a real source instead of a black body, one must take into account the emissivity of the source and the absorption of the target screen material. Essentially, to find power loss one must multiply the ideal black body curve by the emissivity of the source material and by the absorption of the target screen material, all of which are functions of wavelength. By multiplying all three curves, the final curve will show the final power spectrum of the test mass. For example, the team at VIRGO did the same process to find the power transfer between a real source and a real test mass for the Central Heating Radius of Curvature Correction System (CHRoCC) [6] [Figure 2]. Although the source we use will not be the same as the source used here, the process for finding the final power absorption spectrum will be the same.

4 Approach/Method

Initially we will need to set up a radiation source and its heating mechanism. The heating mechanism will be a ceramic heater with wires running through layers of material, behind a conical reflector. Instead of emulating the heaters aLIGO uses for the TCS system, we will be using simpler heater shapes with easily detectable patterns. The heater will be a square heater, whose heat output will be concentrated in its center, mounted behind a parabolic reflector, whose central hole has a diameter of 30 mm. The heater will be large enough that when placed behind the reflector's hole, its heat output will be directed mostly thought the opening, and little will be lost to the back of the reflector.

To mount the heater and the reflector, we will put the heater behind the reflector. The mounting device will be 3D printed to fit exactly the heater and reflector, as to best customize the mount to our specifications. The mount should not block the heater or the reflector, and needs to connect to the optical tale in a secure manner. Once we build the mount, we will set up the optical table [Figure 3] with the radiation source, the test mass, and the infrared camera.

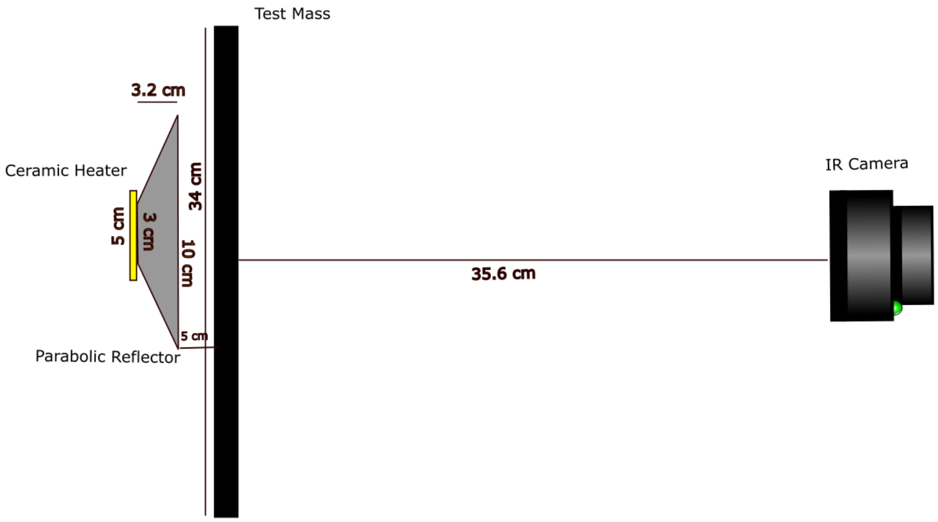

Figure 3: Optical Table Set up

The distance between the test mass and the infrared camera can be determined using basic trigonometry. The camera has a field of view of 51 degrees, and the test mass is 34 cm in diameter, so the camera must be 35.64 cm away from the test mass. The distance between the heater and the test mass will help us determine the expected power transfer.

One the table is set up, we will begin calibrating the camera to capture the pattern projected onto the test mass. As the camera is calibrated, we will take data of what power is transferred onto the test mass and in what shape in appears to measure the temperature profile with multiple different alignments. Then we will compare the data to the theoretical model of how power should have been transferred, and determine how effective it was. This end-to-end validation of our theory will allow us to find and correct any systematic errors, and in the future, will assist in calibration for more complex radiation patterns.

5 Timeline

The first 1-2 weeks of the project will be dedicated to setting up the optical table layout. Following that, we will set up various radiation sources and test them with the thermal imaging camera. Each setup will take a couple of weeks to set up and test thoroughly.

Week 1: Finalizing the design of the optical table and making concrete theoretical predictions for the power transfer. In finalizing the design, we will also be determining the best way to mount the heater and the reflector onto the optical table.

Weeks 2-4: Construction of the optical table set-up. This will include installing the IR camera, the test mass, and the heater, and setting up each element.

Weeks 4-7: Assembly of the calibrated blackbody source.

Weeks 8-9: Collection of data to measure the irradiance profile at multiple source temperatures.

Week 10: Analysis of the data and comparison to the theory.

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