LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Technical Note **LIGO-T2200206–v4** 2022/07/30

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 distort space as they move through space, which can be detected by measuring extremely small distances. 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. A large part of this improvement is perfecting the surfaces of the test masses in the interferometer to minimize noise due to manufacturing errors.

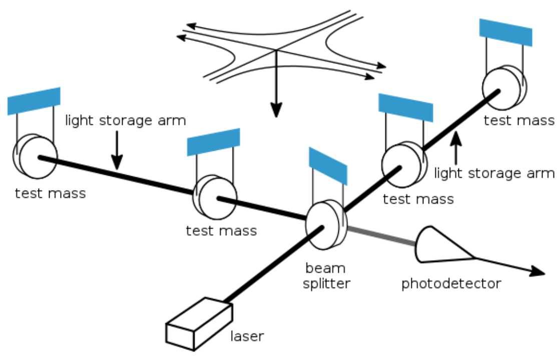

Figure 1: Diagram of aLIGO's Interferometer

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. To begin the process of improving the ring heaters we must first start by ensuring that the thermal imaging system is accurate, which will require end-to-end validation of an infrared camera's data. A simple heater system will be set up in front of a highly absorbent material, behind which an IR camera will capture the heat transfer pattern. The power transfer will be calculated based on the temperature of the heater and distance between the components, and will be compared to the measured results. The objective of this project is to have the expected results be equal to the actual results, so that similar tests may be done on a more complicated heater set up that is similar to the TCS without worry of systematic errors.

2 Objectives

The main objective 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. The system calibration must be correct for future projects wherein different radiance profiles will be expected. Ideally we will capture a sharp and accurate image in the expected shape, with the projected power transfer based on the temperature of the heater and the wavelength of radiation.

3 Project Outline

This project has three main sections: setting up the optical table, calculating the theoretical incident radiance profile of the test mass, and taking data to experimentally fit our calibration. The optical table setup will begin with determining the distances each component must be from each other, and will be complete once each component is secured on the table. The theoretical calculations will take into account the distances between each component, the emissivity of the heater, the absorption of the test mass, the temperature of the heater, and the wavelength of radiation. This will be done both with written power and irradiance calculations, as well as with ray tracing modeling in COMSOL. The data collection will be done through python, as will the system calibration.

4 Approach/Method

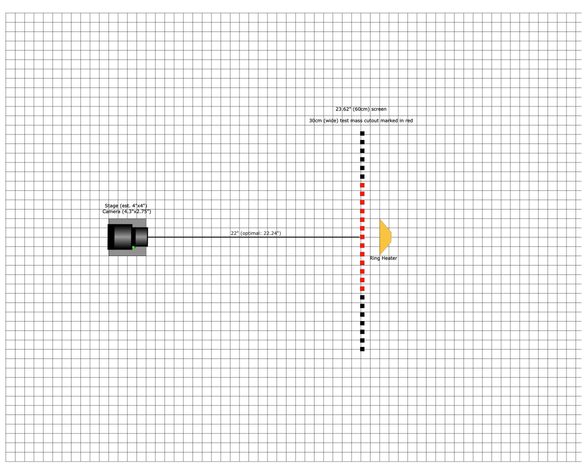

Figure 2: Optical Table Setup Diagram

To begin, the test mass must first be mounted onto the table. Our test mass consists of four 20 cm by 60 cm highly reflective metal velvet foil sheets, put together to create a two-sided 40 cm by 60 cm sheet. This is held in place by 20' optical posts, so that the top of the sheet is equal to the top of the posts. Each side of the sheet will have two posts clamped together to hold up the sheet with pressure only.

The IR camera has a field of view of 51 degrees, and the test mass has a height of 40 cm, so the IR camera must be 41.9 cm, or 16.4 inches, away from the test mass. The mounting of the camera is much simpler than the test mass, as it can directly screw into a stand which can be connected directly to the optical table.

The heater system for this project will be a small cylindrical cartridge heater suspended in a parabolic reflector. The cartridge heater, which will be 20 mm long and 6 mm in diameter, will be held so that its heated end will be at the reflector's focal point, and the main body of the heater will block additional radiation off of the heater. Because we are working with a parabolic reflector, ideally the heater would be a point source at the focal point. This is not possible, so the solution to extra unwanted rays will be this orientation of the heater. The reflector, which has a height of 45 mm, a length of 100 mm, and a focal point of 12.5 mm, will be positioned very close to the test mass, to minimize the occlusion of rays. The rays will hit the test mass in a predictable circular shape for our end-to-end validation of the power transfer.

It was decided to use a parabolic reflector because it would create a circular shape similar to the ring heater of the TCS, but would not take as long to acquire. The physics of a parabolic reflector are well-understood and the theoretical calculations will not be hugely difficult as well. A cartridge heater was the best option for our use, as they are small and affordable, and for a parabolic reflector we want a heat source as close to a point source as possible. We are also using a thermocouple to measure the temperature of the heater. The thermocouple will act as another method of ensuring that our measurements are correct. If the measured irradiance of the test mass does not agree with the measured temperature of the heater, then we know that there is a problem with the power transfer or with our theoretical calculations.

To hold the cartridge heater exactly at the reflector's focal point, a mount must be 3D printed for the entire system. This mount will be designed using COMSOL, and there will be two parts to this mount: a bowl-shaped holder for the reflector itself [Figure 4], as well as a bridge across this bowl for the heater to sit in [Figure 3]. Both parts will be attached to an optical table with 1/2" optical components. The reflector mount will fit the reflector precisely enough that only the bridge going across is needed to hold it in place. There is some difficulty here, as the manufacturers of the parabolic reflector did not provide a CAD model of the reflector nor measurements of the outer profile of the reflector; the only known measurements are of the inner reflective surface. Due to this uncertainty, multiple iterations of the printed mount will be needed to ensure correct fit of the reflector. The mount, once printed, will be held in place by two counterbores on the right and left of the reflector, which will screw into an optical component clamp. The component clamp will be held in place by two optical posts, connected with a right-angle post clamp. These will all be set so that the center of the reflector is held at 308 mm above the table, where the center of the test mass will be. The bridge for the heater will be positioned vertically across the reflector mount, and will be screwed directly into the reflector mount. The bridge will be as thin as possible, so as to obstruct as few rays as possible from the reflector, while still thick enough to be printed. The printer we are using can print objects with a minimum width of 1 mm. There is a small hole in the center of the heater bridge that will hold the wires of the cartridge

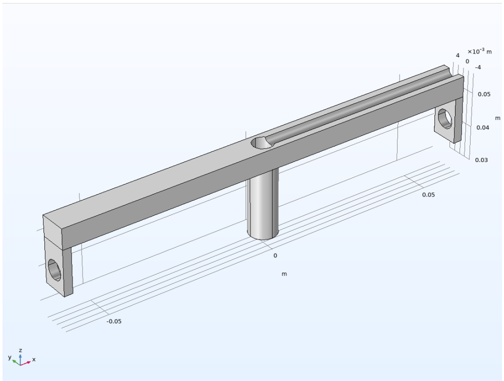

Figure 3: Heater Bridge Model

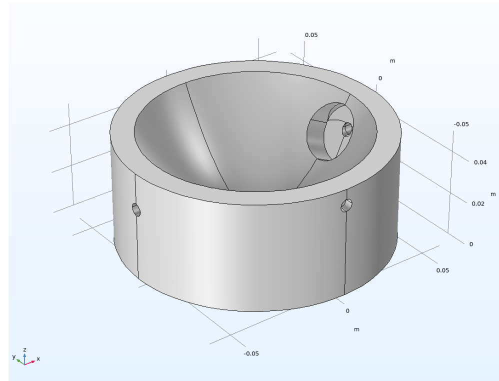

Figure 4: Reflector Mount Model

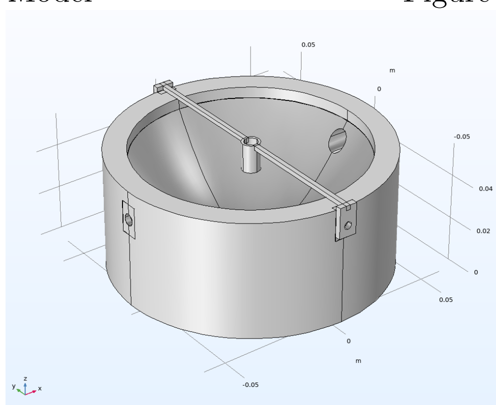

Figure 5: Full Mount Model

heater as well as the thermocouple wires, and will act as a clamp onto the heater. Once this mounting system is printed, it will be set up to hold the reflector and the heater, and will be then connected to the optical table.

Once the table is fully set up, we will begin calculating the theoretical power transfer from the heater system to the test mass. This will be done with consideration to the ray diagrams of the cartridge heater in the parabolic reflector, the inverse square law of power transfer, and Wien's displacement law. While some calculation will be done by hand (namely the projected power output of the cartridge heater and the estimated irradiance pattern projected onto the test mass), the majority of these calculations with be done with COMSOL's geometrical optics modeling. The model consists of the heater, the reflector, and a target plane functioning as the test mass. The heater radiates from all surfaces except the surface facing directly towards the test mass, as this surface is wired and not made of the same metal as the rest of the heater. One difficulty here is determining the exact material of the heater; the manufacturer lists it only as stainless steel and does not provide the properties. If we cannot determine the exact type of metal the heater is encased in, we will need to determine the emissivity of the material ourselves. The inner surfaces of the reflector act as a mirror, and have a coating of polished aluminum. The outer surfaces of the mirror do not interact with the rays directly, and act as a wall. The bulk of the reflector is made of BOROFLOAT, a substance used by Edmund Optics. The target plane also acts as a wall, and is where the deposited ray power is calculated. From this calculation we will know the

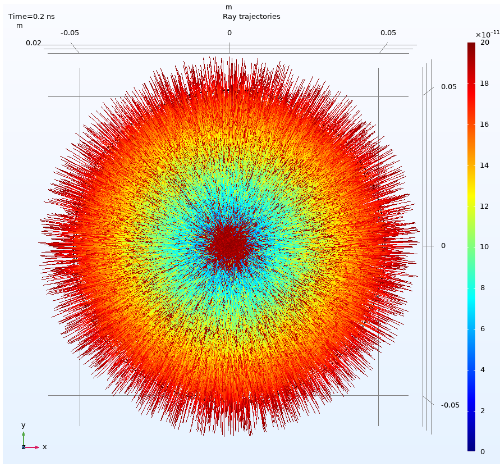

Figure 6: COMSOL Ray Diagram

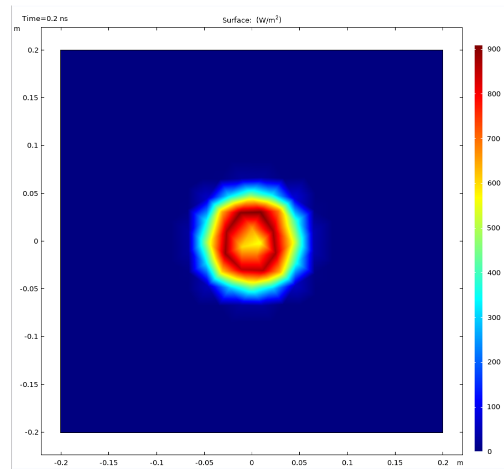

Figure 7: Irradiance Map

accuracy of the experimental results. The COMSOL modeling will provide us with a ray diagram as well as an irradiance map of the test mass. Currently, I have both a ray diagram [Figure 5] and an irradiance map [Figure 6] for a 100,000 ray model. Ideally we will have a model with one million rays, so as to be more detailed, but there is a system error that is preventing this for now. The irradiance map, additionally, is currently segmented and less smooth than expected. This is an issue that is not unique to this project and will require some time to solve, but the approximate shape of the irradiance is correct. In both the ray diagram and the irradiance map, the ring-like shape of the rays can be seen. There is some spreading of the rays, as expected as the heater is not a perfect point source. With a higher number of rays, this will be clearer.

The other part of the calculations is determining the the projected power output of the cartridge heater. This will be done with Stefan-Boltzmann's Law, solving for power. Stefan's Law, as seen below, depends on the surface area of the object A (which is $4.0526 * 10^{-4} m^2$), the emissivity of the object radiating e, the SStefan-Boltzmann constant σ (which is approximately equal to $5.6704 * 10^{-8} W/m^2K^4$), the temperature of the object T, and the temperature of the surrounding area T_o (or room temperature).

$$P = Ae\sigma(T^4 - T_o^4)$$

As the exact material of the heater is currently unknown, the emissivity still must be treated as a free variable. Once the emissivity is determined and the temperatures of the heater and the surrounding air are measured, the power output of the heater will be calculated and compared to the measured power transfer onto the test mass. This will provide our end-to-end validation and will ensure that future tests will be without systematic errors.

5 Challenges

The main challenge of this project will be accurately calculating the theoretical power transfer with taking into account the realities of the setup. If the theoretical calculation is incorrect, the validation of our experimental results will be impossible. To make this calculation as accurate as possible, care must be taken in the setup of the optical table, and considerations must be made for the type of heater system chosen. The mount for the heater is designed to hold the cartridge heater in a specific place, and the reflector has been chosen to minimize loss of radiation. A large part of this has also been uncertainty in the parts that we are using. The parabolic reflector that we are using did not come with a CAD model, so the reflector mount has needed to be reprinted for purposes of correct fit. The material of the heater is currently unknown, so the emissivity cannot be determined exactly. There are also the issues of imperfections in the heater, and considerations have been made as to whether slight bumps and edges of the outer profile of the heater should be taken into account.

6 Progress

1. Create a diagram of the optical table in InkScape and map out components onto the table. This will allow for an easy setup of the table once the parts arrive.

    - **Status:** Complete

2. Mount the test mass and the IR camera onto the table, using 1/2" optical components. Follow the diagram to ensure that little manual calibration will be needed. Once they are attached to the table, view the test mass using the camera's built-in system and calibrate so that only the test mass is in the camera's view. This will consist of moving the camera along four degrees of freedom: rotational in the x-direction, and in the x-, y-, and z-directions, where the x-axis is parallel to the test mass.

    - **Status:** Complete. One thing to note is that when calibrating, the camera"s IR lens and normal lens are in different locations. Because the visual lens is lower than the IR lens, the overlay of the two must also be modified and any manual calibration must be done accordingly.

3. Determine the heater components and design a mount for the components.

    - **Status:** In Progress. The mount design is nearly complete, and only needs to be printed once more to ensure that it will fit the reflector correctly. The heater consists of a cartridge heater suspended in a parabolic reflector. The mount, as seen in section 4, will be a 3D-printed mount for the heater system connected to the table with 1/2" optical components. The mount takes a significant amount of time to print, so this has taken longer than expected.

4. Model a ray diagram of the heater's radiation onto the test mass, and create a irradiance map of the test mass.

    - **Status:** In Progress. The structure of the model has been completed, but can still be improved with higher ray counts and precision in mapping out the irradiance. This will be completed by the beginning of the eighth week of the program.

5. Mount the heater to the table.

- **Status:** Not Started. The heater mount still must be printed before this can be started. Once it is, the components will be mounted to the table. The mounting posts have arrived and are This should be completed by the beginning of the eight week of the program.

6. Observe the power transfer between the heater and the test mass. From the IR camera's data, determine the irradiance profile of the test mass. Repeat this for multiple source temperatures. At the same time, calculate the expected power transfer between the heater and the test mass. Determine what the irradiance profile of the test mass should be.

   - **Status:** Not Started. This should be completed by the end of the eighth week of the program.

7. Once the theoretical and experimental data is determined, compare and analyze. It would be ideal to find that the system calibration is correct, and that this setup may be used for different geometries without worry of systematic errors.

   - **Status:** Not Started. This should be completed by the end of the program.

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