

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Technical Note	LIGO-T2200205-v1	2022/07/29
Developing an In-Air IR Test Facility for Next-Generation Wavefront Control		
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1 Introduction

In 1893, gravitational waves were first proposed by Oliver Heaviside when noting the similarities between the inverse square laws of electrical charges and gravity; a little over a decade later, Henri Poincaré proposed that these possible waves would have to move at the speed of light [5, 6]. However, it was not until Einstein’s Theory of General Relativity in 1916 that gravitational waves were predicted by a physical model [4]. In essence, gravitational waves can be described as ripples in spacetime caused by accelerating massive objects. The strongest, and thus most measurable, gravitational waves are caused by huge astronomical events like colliding black holes and neutron stars, as well as supernovae. Unlike electromagnetic radiation, gravitational waves only weakly interact with matter between source and detection, making them invaluable tools for understanding the mechanisms of their sources. After Einstein’s predictions, however, the existence of gravitational waves was hotly debated, even by Einstein himself. It took until 2015 for gravitational waves, caused by two colliding black holes, to be directly detected at aLIGO (advanced Laser Interferometer Gravitational-wave Observatory).

aLIGO’s construction, building on the initial LIGO model, began in 2008. LIGO is essentially a set of two massive Michelson interferometers, one in Louisiana and one in Washington, with 4 km long perpendicular arms that form an L-shape (see Figure 1). In essence, lasers are sent through the arms, reflected off mirrors at their ends, and then recombined at a photodetector between the two arms. As gravitational waves pass, they stretch spacetime in one direction, causing an interference pattern between the lasers in the two arms. This interference pattern can be measured to understand the character of the wave and, by extension, the event that produced it. However, the precision necessary to detect gravitational waves means any noise can be detrimental to results. The work transitioning from LIGO to aLIGO and current work to improve aLIGO has been focused on reducing noise. The greatest source of noise in aLIGO is quantum noise [3]. One way to decrease quantum fluctuations, however, is to increase the power used: photon shot noise decreases as the number of photons increases (by a factor of $\frac{1}{\sqrt{N}}$).

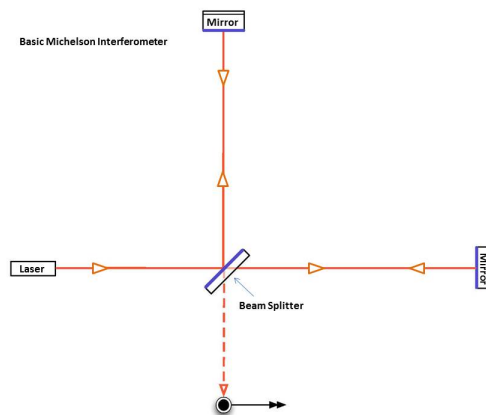


Figure 1: Basic diagram, from the LIGO website [9] showing the Michelson interferometer setup that is the basis of the design of LIGO.

A multitude of additional optics are added to the interferometer to boost the sensitivity of the system. A power recycling cavity, the arm cavities (Fabry Perot cavities), and a signal recycling cavity form four coupled laser cavities within LIGO for this purpose (Figure 2). Power recycling mirrors form the first cavity, which allows laser light that has been sent through the system to be reflected back through it, thus “recycling” the laser power. The arm cavities are Fabry Perot cavities, which bounce incoming laser light between two mirrors about 300 times, increasing the distance the light travels and building up the laser light in the system. Finally, the signal recycling mirror forms an anti-resonant optical cavity that extracts only the frequency of light associated with a signal, thus allowing it to be “tuned” to see specific gravitational wave signals.

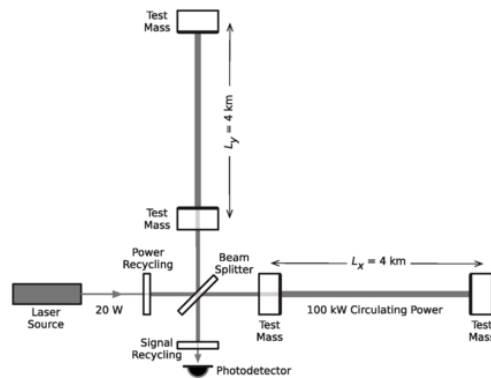


Figure 2: Simplified LIGO diagram showing the Michelson interferometer setup with the power recycling, Fabry Perot, and signal recycling cavities. Modified from Figure 3 in [1]

While these additional optics are imperative to creating a system with enough sensitivity to detect gravitational waves, increasing the power can introduce or amplify other sources of noise or optical losses. One such example is from defects that are physically present in mirrors from their fabrication, particularly point absorber defects [3]. Our project for the summer of 2022 will be to create an in-air facility with a setup to test adaptive optics that counteract these and, ideally, other thermally-induced mirror deformations in aLIGO’s mirrors. The key components of the facility include an infrared-detecting camera, a thin screen to act as a test mass, and the annular ring heater developed by Dr. Richardson and his colleagues [7].

2 Objectives

In order to produce extremely low loss laser cavities, this project seeks to:

1. Construct an in-air optical test facility to allow for the testing of infrared adaptive optics systems.
2. Develop Python code to collect raw data from the infrared sensor in order to test current and future wavefront controlling technology.

3 Approach

3.1 Optical System Setup

The first two weeks of this project were dedicated to setting up the in-air optical table system using a simple triangular optical setup with the ring heater, the IR-absorbing thin screen, and the infrared camera, as in Figure 3. The ring heater, which will have an inner diameter of 0.34 m in its final iteration, will allow for manipulation of the radiation that hits the 0.4 x 0.5 m IR absorbing screen (in place of the 0.34 m test mass in the aLIGO system). The screen, which is 0.1mm thick, is thin enough that the infrared-sensitive camera will be able to detect and map the effects of the ring heater on the test mass based on the image of the back of the screen (the width of the screen is negligible to understanding the infrared pattern).

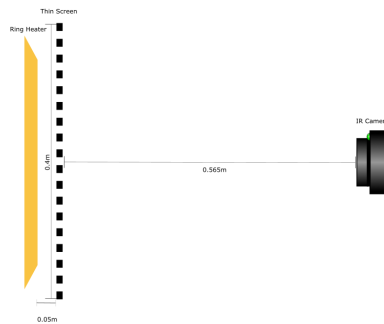


Figure 3: Optical Diagram of the In-Air IR Test Facility Setup

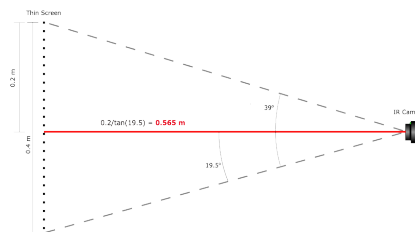


Figure 4: FOV Calculation to Determine Camera Distance from Screen

One key component of this system is the infrared camera, which uses microbolometers to detect infrared radiation based on the changing electrical resistance [10]. The microbolometers, sensitive to IR, are arranged in a 640 x 480 array in the camera used for this iteration of the in-air test facility (the Teledyne FLIR A70). Notably, the camera also has a visual

camera with a resolution of 1280 x 960 pixels and is used for specific camera modes and it is the field of view of the IR camera that is limiting. The IR camera has a $51^\circ \times 39^\circ$ field of view. In order to allow the camera to capture stray light bouncing off the test mass, 0.4 m, the height of the thin screen, is defined as the desired diameter of the camera's view. Using the vFOV, 39° , the equation $l = \frac{0.4}{2} \tan(\frac{39^\circ}{2})$ yields a distance of 0.565 m. Thus, the camera must be 0.565 m from the screen to contain the entire 0.4m area in it's FOV while still maximizing the FOV (as in Figure 4).

Once the correct distances were determined, the table was set up. The table is 4'x10' and the desired optical layout was concentrated on the left side of the table, as in Figure 5. This allows for the most effective use of space and for easier fine adjustment of the camera. The ring heater shown in Figure 5 is a smaller version for proof of concept of the ring heater shown in Figure 3. The ring heater is not yet set up, but the IR-absorbing screen and camera are both mounted (pictured in Figure 6). The IR-absorbing screen was mounted first and has the outline of a test mass painted onto it, allowing the pattern from the ring heater to be analyzed within the parameters of its use in LIGO.

The camera is mounted on a combination of stages that allows for x, y, z, and rotational fine-tuning. The camera was finely adjusted so that the screen just barely filled the FOV, as predicted in the FOV measurements, by slowly adjusting each degree of freedom. Unfortunately, even with the z-stage, the camera is not low enough. A new optical post will need to be ordered that is about 0.5" shorter to accommodate this issue.

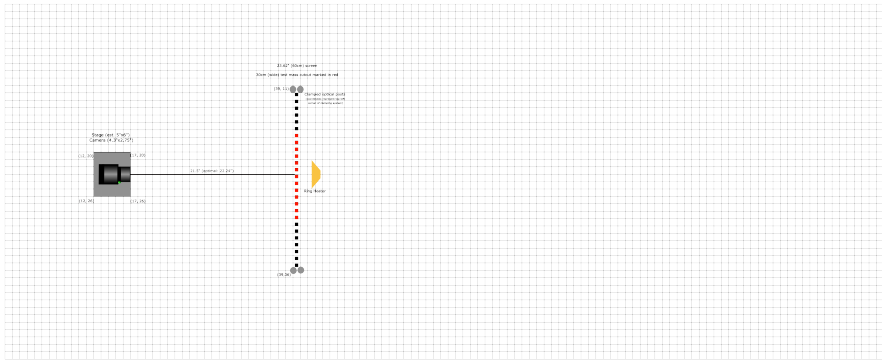


Figure 5: Optical Diagram of the In-Air IR Test Facility Setup Based on the Table Dimensions (1" x 1" grid)

3.2 Controlling the IR Camera

The second portion of this project was to create Python code in order to collect data from the IR camera. Building on the existing API, this code allows for the camera settings to be configured and to collect data characterizing the pattern added to the thin screen by the ring heater.

The current interface created by Python code allows for snapshots of the screen to be taken

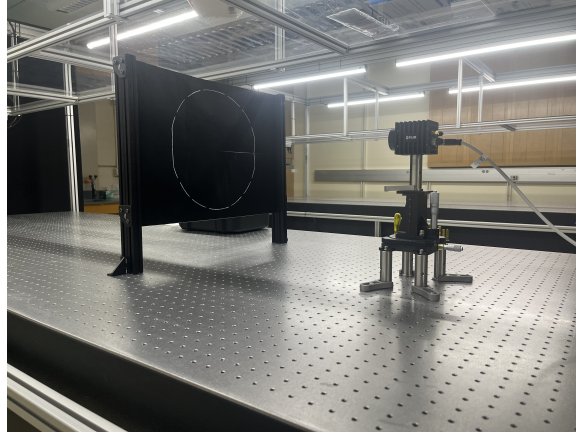


Figure 6: Image of the Table Setup as of July 7

and for a stream of snapshots to be displayed as live imaging from the camera. When configured to the appropriate settings, which are user inputted values, the images include a color bar that characterizes the temperature of the image based on the internal linear temperature feature of this camera, as in Figure 7. Multiple imaging modes are available, notably FLIR's Multi-Spectral Dynamic Imaging, or MSX. MSX overlays details from the visual camera on top of the thermal image from the IR camera to help define the IR image.

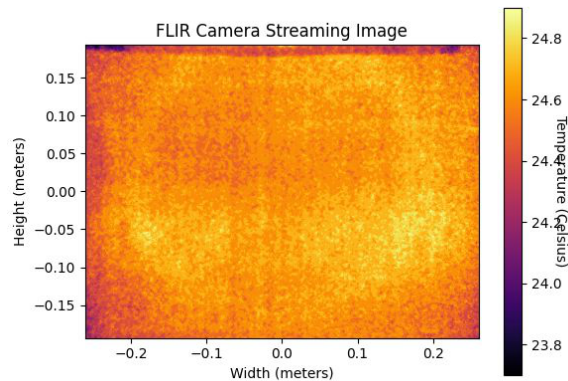


Figure 7: Python Interface When Measuring Temperature

This code will be used for all upcoming work with this camera with the end goal of using the camera to determine the best heating pattern from the ring in order to mitigate power loss from the point sources in aLIGO's mirrors.

4 Challenges and Next Steps

Currently, the system has a functioning IR camera with code for streaming and taking snapshots. The rest of the project will be spent developing the Python code to collect and

characterize the data from the camera's array of microbolometers. The final steps will be to test and refine both the code and the optical table setup.

Once the ring heater and its mounting apparatus are created, the final component of the optical table will be set up. There are no anticipated challenges for this process. Other than the camera's optical post, there are no issues with the components currently set up on the optical table.

Currently, there is one major issue that needs to be addressed for control of the IR camera. Rather than temperature, the IR camera directly measures intensity. Converting this to temperature usually requires complex equations and a myriad of user-defined object parameters. However, this FLIR camera has a linear temperature feature that converts the data into Kelvin values internally as long as object parameters are correctly set. This has to be done with the Mono16 pixel format, rather than Mono8. Unfortunately, MSX, the patented FLIR imaging technology to add visible light details to thermal images, only functions in Mono8. The MSX capability is necessary to view the test mass outlined on the IR-absorbing screen. In next steps, exploring how this MSX technology can be combined with accurate temperature measurements will be necessary.

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