LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Tracking beam location on LIGO optics

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1 Introduction

The advanced LIGO (aLIGO) detectors succeeded in measuring gravitational waves on September 14, 2015, nearly one hundred years after Albert Einstein's initial prediction of the existence of oscillations in spacetime. The aLIGO detectors are a pair of simple (but very fancy) Michaelson interferometers that together (and now with the VIRGO detector) confirm that these tiny disturbances are not just local events, but have astronomical origins [5]. The differential arm length (DARM) that is measured when a gravitational wave passes by is on the order of 10^{-19} meters [4]. Because of the minuscule scale of the measurement, the detectors must be incredibly sensitive. A consequence of this great sensitivity is that the apparatus picks up signals from many other sources than gravitational waves. "Noise" in gravitational wave readout data is anything that appears to be a signal, but is not caused by the quantity of interest–the change in length of the arms of the interferometer, due to the passing of a gravitational wave. Some examples of noise: refrigerators running in the building nearby, birds pecking at the pipes outside, camera shutters opening and closing, and any imperfections in the materials within the cavity. Advanced LIGO can detect gravitational waves with frequency signals between 2[1?]0 to 5,000 Hz. In order to detect frequencies outside of this range, the noise in the measurement must be reduced, which means every imperfection in the experiment must be attended to.

One source of noise in the aLIGO detectors is angular motion of the optics [1]. There is a coupling between the alignment of the optics, and the length of the cavity. When the beam is off center due to optical misalignment, as seen in Figure 1, the distance the beam has to travel is changed. Since the distance between the mirrors is precisely what we are trying to measure (very precisely), it is crucial that we know the angular position of the optics. Additionally, If the beam is not perfectly centered on the mirror, the radiation pressure it exerts on the test mass applies an additional torque on the optic, causing further angular rotation. [LEARN MORE ABOUT THE CURRENT CONTROLS FOR THE ANGULAR POSITION OF THE OPTICS. THAT INFORMATION WILL EVENTUALLY GO HERE-ISH.] If we can identify where the beam is, we may be able to improve our ability to calculate the angular motion of the optics, and subtract another layer of noise from the measurement. Small rotation of optical elements can cause some angular noise, but this is a dynamic effect, and not the focus of this project.[?????]

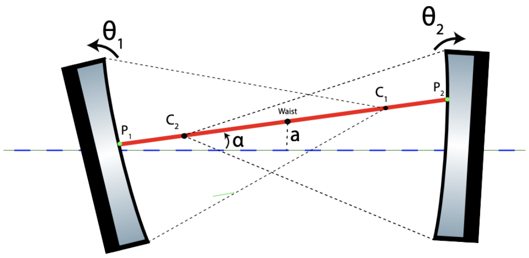


Figure 1: Fabry-Perot cavity with mirrors misaligned to show the change in beam travel [8].

Currently there is no way to continuously monitor the position of the beam on all optics. In some places, Quadrant Photodiodes (QPD) can be placed behind mirrors, so the fraction of the beam that transmits through can be detected and tracked, but these can not be used on optics where the beam needs to travel through to the other side, like in the case of a beam splitter, or the Input Test Masses (ITM) [3].

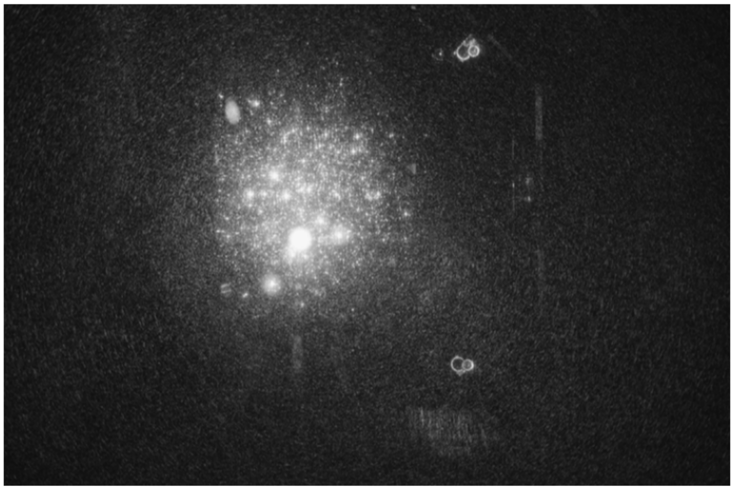


Figure 2: Image of aLIGO Test Mass (1.3 second exposure) [9]

Ideally, the beam would be invisible on the surface of the test masses from any perspective other than the incident angle, because the mirrors would perfectly reflect all the 1064nm light. [COULD EXPLAIN HOW COATINGS HAVE DIFFERENT INDICES OF REFRACTION AND ARE LAYERED IN WAVELENGTH DEPENDENT THICKNESSES SUCH THAT THAT REFLECTED LIGHT CONSTRUCTIVELY INTERFERES] We live, however, in reality and not an ideal world, and some light does scatter off of the surface roughness and point defects [MAYBE INCLUDE A DIAGRAM OF THE MIRROR SURFACE TOPOGRAPHY] that are present in the structure of the optical coatings, as can be seen in Figure 2. This scattered light is another source of noise in the experiment, as it can bounce around the cavity, recombining with the main beam and adding a random phase into the otherwise coherent [is this an okay way to use the word coherent?] wave. Plenty of people are working on reducing the effects of scattering noise, but it can also be used as a tool, as it allows us to see where the beam is on optical surfaces [3]!

Because the possibility of perfecting mirrors is far off in the distant future, this scattered light provides a useful opportunity to continuously track the location of the beam using a video imaging system. That information about the movement of the beam will allow us to calculate the angular noise of optics and subtract it from the measurement.

2 Objectives

The goal of this project is to continue in previous efforts to track beam motion with sub pixel accuracy using a Gigabit Ethernet (GigE) camera similar to the one shown in Figure 3. This schematic describes an apparatus at the 40m lab, but a conceptually similar set up is used at the aLIGO site. A mirror is set in the chamber at a 45 degree angle from the beam axis and the view port. The light then travels through a beam splitter, half of it going toward an analog detector [WHAT DOES ANALOG MEAN?], and the other half going through a two lens telescope that focuses the image onto the sensor of the GigE camera. In the 40m lab the optical path length between the 3 inch optic and the telescope is about 70cm [3]. At aLIGO, the test masses are 34cm in diameter and the camera is [????] a meter away from the End Test Mass (ETM). We have about 20 minutes of footage of both X and Y End Test Masses from the [WHICH?] detector. [WHERE IS THIS FOOTAGE STORED?]

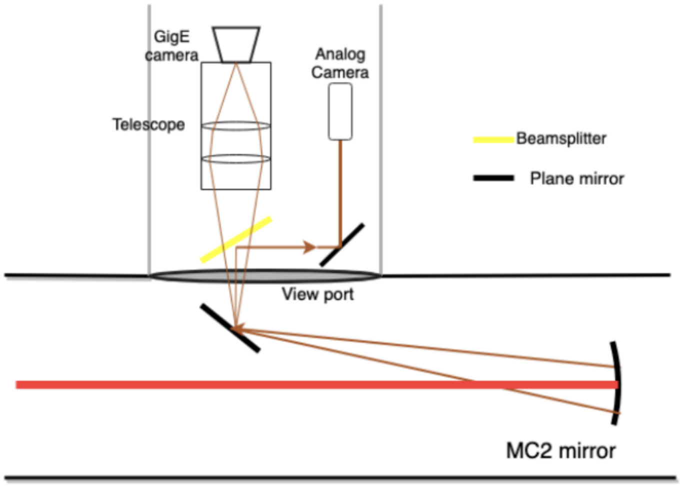
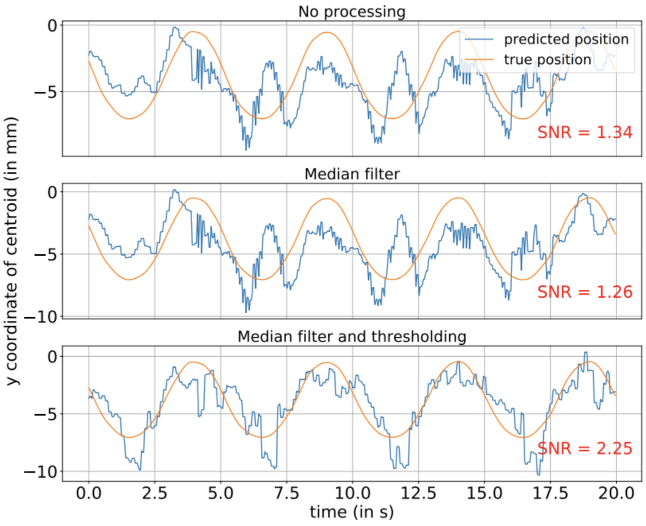


Figure 3: GigE camera at the MC2 optic of the Input Mode Cleaner cavity at 40m Lab [2].

Past efforts to track beam motion included classical centroid detection, using contouring and center of mass calculations. These techniques worked well on a simple simulation of a uniform Gaussian beam spot moving in a simple way, but failed to track a beam spot in real (noisy) data. The point scatters seen in Figure 2 skew such calculations because as the beam moves, defects in the mirror do not. When the beam illuminates these spots, they contribute disproportionately to the overall brightness in one area. Some attempts were made to correct for these problems, such as the use of thresholding, an image processing technique that segments and simplifies the information in an image. The simplest example of this is to take a gray scale image and create a ”threshold” at one value, changing all pixels above that value to the maximum, and all below that threshold to the minimum. It can also be used to mitigate saturation effects by excludes values that are outside of some range. The bottom panel in Figure 4 shows that when this modification was used, these methods improved significantly, but not enough to serve as a robust solution to the beam tracking problem [2]. When these approaches failed to follow the motion of the beam with a high degree of accuracy, the project turned to machine learning algorithms for their efficacy in solving nonlinear problems.

Convolutional Neural Networks (CNN) are image processing algorithms that utilize a convolution operation to preserve local information about an image. In traditional multilayer



No processing

SNR = 1.34

Median filter

SNR = 1.26

Median filter and thresholding

SNR = 2.25

Figure 4: Center of mass tracking for GigE video from MC2 viewport [2].

perceptron (MLP) neural networks, the information in an array is squished down to one dimension, which throws away information about the relative location of pixels in an image. CNN's use a series of filters (smaller arrays) to scan through a whole image array for certain properties, convolving [WRITE OUT THE ALGEBRA OF CONVOLUTION] and producing another array with refined information according to the element of interest. [Diagram of CNN] The layers of a CNN are a series of filtering processes that shrink the dimensions of the array down until the final step of the convolution process, when the array is flattened into one dimension, and sent through fully connected layers that finally lead to the classification of the image [7]. [DESCRIBE THE VOCABULARY OF NEURAL NETWORKS.]

The neural network is essentially an algorithm that studies a body of problems and their respective solutions, and through this training process, learns how to solve similar problems. They need to be trained on a very large and representative data set in order to have a good chance of success when tested on new examples.

The motivation behind the use of CNN's is to find a solution for the beam tracking problem that can filter out the systematic error that results from the inhomogenceity in the data. There has been some success with this approach, but it has not yet been sufficiently carried out to be useful on real data. Past attempts succeeded in tracking the simulated beam spot motion of one millimeter, and we need to improve that by three orders of magnitude, with the real data [2].

3 Approach

Because real labeled data is limited, (it is fairly disruptive to go into the LIGO detectors and shake the mirrors around) we use a simulation of the beam spot to train the neural network. This simulation must be as close as possible to the actual imaging of the beam spot in order for the network to convolve with the real data.

In order for the neural network to function, we have to train it on something whose expected output is known. This is the other benefit of using simulated data: we can generate huge amounts of labeled data, quite easily. The network will then learn from the simulated, labeled data set, training the weights within the layers of the network until it reliably succeeds in matching the input function of position in time [6]. The additional benefit to using a simulated set to train the network is that the simulation can be layered and adjusted modularly. This will enable us to manipulate the simulation one component at a time and train the network in stages, turning switches on and off so that we can try to understand where and when the network fails, and hopefully figure out how to improve the algorithm. [ADJUST THE BIASES?]

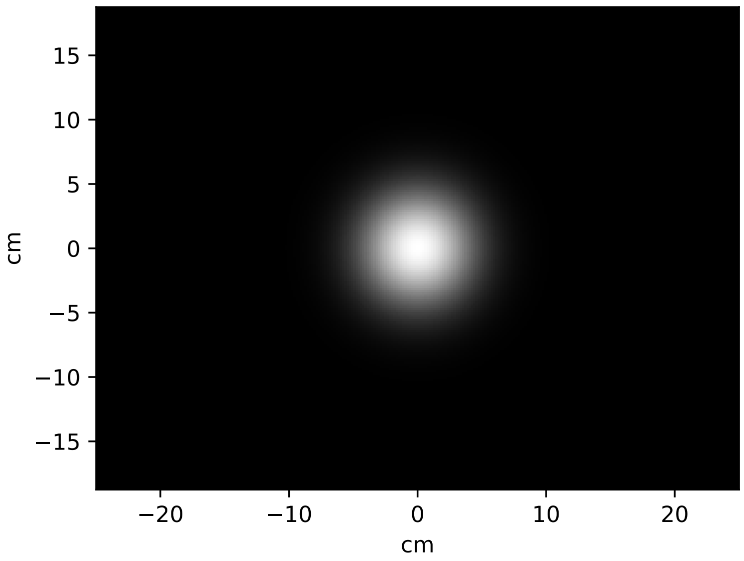


Figure 5: Simulation of scattered light without defects

The simulation started out as seen in Figure 5, a uniform Gaussian beam spot, moving in one dimension. [RESULTS FROM TRAINING THIS SET?] The simulation is now being modified to more closely resemble the video footage of the test masses from the aLIGO detector. The off axis camera sees a skewed Gaussian beam of a more oblong shape, with point defects that glitter as the beam crosses over them. As can be seen in 6 there are also a variety of smears around the beam spot that could be a result of glares from the telescopic lensing system, or other defects in the mirror coating.

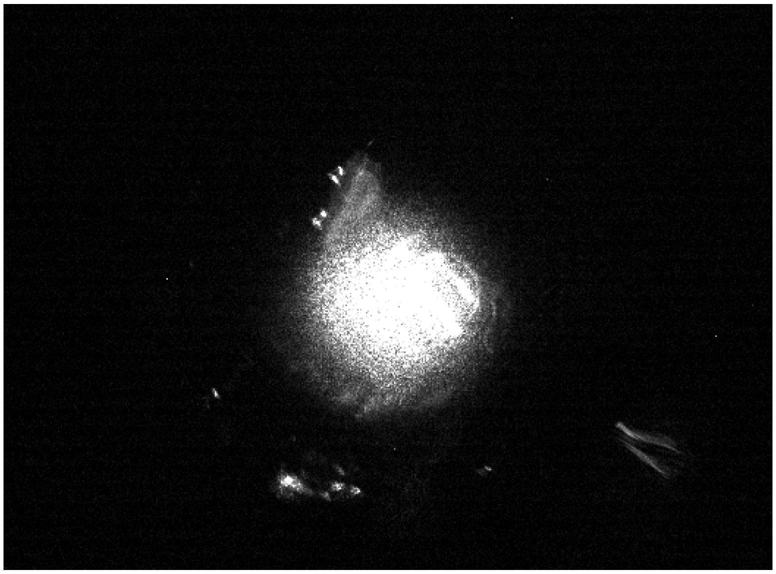


Figure 6: still frame of ETMX at aLIGO

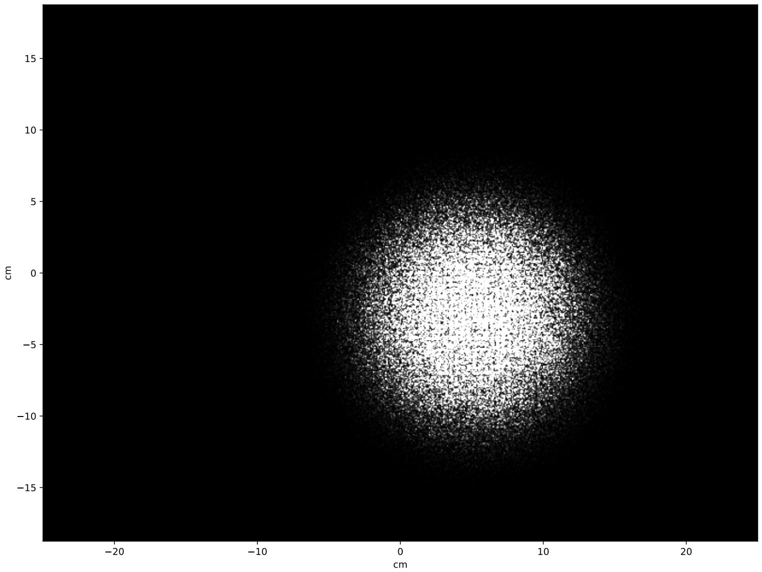


Figure 7: Simulation of scattered light without defects

The power scattered from the mirror surface is represented by the Bidirectional Reflectance Distribution Function (BRDF). The BRDF of the mirror surface at a large angle [BRDF VS. ANGLE FOR MIRROR COATINGS] is well approximated by a Lambertian distribution, with the exception of point scatters. This allows us to make some convenient approximations in our simulation model.

$$BRDF = \frac{P_s/\Omega}{P_i \cos(\theta_s)} \tag{1}$$

where P_i is the incident intensity, P_s is the scattered power reaching the camera sensor, θ_s is the scattering angle and Ω is the solid angle subtended at the sensor. [3]

4 Optical Model

The phase picked up by the electromagnetic wave when it reflects off of the mirror is

$$\phi = (\frac{2\pi}{\lambda})(h(x,y))$$

where $h(x,y)$ is the height of the mirror at every point on it's surface, and λ is the wavelength of the laser (1064 nm). Perturbations due to surface roughness in the optical coatings are between 0.12 and 0.22 nm in height. [DIAGRAM OF RAYS SCATTERING OFF ROUGH SURFACE] Because $h(x,y) << \lambda$ we can take $\frac{\phi}{2\pi} << 1$

Taylor expanding the complex exponential around $\phi = 0$, we get

$$E_{out} = E_{in} + E_{in}e^{i\phi}$$

Since the beam is very columnated, most of that light goes right back into the main beam, and we can assume that all we see is the scattered portion. Subtracting the first term of the Taylor expansion, we get that:

$$E_{scat} = E_{in}e^{i\phi}$$

Starting with this optical model, I will then add layers of complexity on top, to continue trying trying to get closer to the real images. Thus far I have altered the simulation to match the dimensions of the video data, and adjusted the parameters of the model to match that of the real beam and optics. Next steps is to calculate the actual scattering of the

5 Challenges

- Encountered
  - Panic: I came from the woods and this fancy place scares me!
  - Setting goals: It has been difficult to set firm time frames in which to accomplish various tasks.
  - It is hard to tell if I am accomplishing "enough" on any given day...

  - Being around a lot of data analysts instead of in a lab is difficult. There aren't many people to answer my questions in real life and fewer objects/tools/optics to look at and wonder about.

- Anticipated
  - I'm sure there will be more panic. I'm going to try to ask for help sooner when I feel unsure about what I'm doing.
  - I expect that coding the point defects and other irregularities into the simulation to behave like a real mirror may be challenging because of the potential combination of irregularities in the imaging system and the mirror surface itself.
  - I expect that everything will take much longer than I expect it to. I know someone who says "how long you think it should take; change the unit and divide by two"

$$2hours \Rightarrow 1day$$

$$3days \Rightarrow 1\frac{1}{2}weeks$$

References

[1] Peter R. Saulson, *Fundamentals of Interferometric Gravitational Wave Detectors Second Edition* World Scientific, Singapore (2017).

[2] Milind Kumar Vaddiraju, Mentors: Rana Adhikari, Gautam Venugopalan, Koji Arai, *Laser beam position tracking for LIGO interferometers.* LIGO-SURF Report (2019).

[3] Kruthi Krishna, Mentors: Gautam Venugopalan, Koji Arai, Rana Adhikari, *High Fidelity Probe of Optical Scatter from Point Defects.* LIGO-SURF Report (2019).

[4] `https://www.ligo.caltech.edu/page/vibration-isolation`

[5] `https://www.ligo.org/science/Publication-GW150914Detector/index.php#:~:text=The%20L%2Dshaped%20Advanced%20LIGO,miles%20(4%20kilometers)%20long.`

[6] `https://towardsdatascience.com/how-do-we-train-neural-networks-edd985562b73`

[7] `https://towardsdatascience.com/simple-introduction-to-convolutional-neural-networks-`

[8] Brian Seymour, Marie Kasprzack, Arnaud Pele, and Adam Mullavey, *Characterization of Nonlinear Angular Noise Coupling into Differential Arm Length of the LIGO Livingston Detector.* LIGO-DCC, Report (2017).

[9] L.Glover et al., *Optical scattering measurements and implications on thermal noise in Gravitational Wave detectors test-mass coatings* Physics Letters A. 382. (2018)