LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
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2024 LIGO SURF Project Proposal: Mapping and Correcting the Wavefront of the GQuEST End Mirrors

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1 Introduction

GQuEST, or Gravity from the Quantum Entanglement of Space-Time, is an experiment with the goal of measuring fluctuations in space time [1]. It does this by using a tabletop optical setup of a Michelson interferometer in order to measure the accumulated phase difference between the light in the two arms of the interferometer. This is indicative of a fluctuation that comes from the proposed quantum nature of gravity. This design and methodology varies from previous experiments since it will have an increased sensitivity in order to measure these changes in the arm length. GQuEST uses a new photon counting method in interferometers in order to more sensitively measure change in the path length of the interferometer.

While there have been many theories centered around what the quantum nature of gravity looks like, these theories are extremely hard to verify experimentally. One such theory, suggested by Erik Verlinde and Kathryn Zurek, argues that the holographic principle provides us with a way to quantize spacetime [2]. These fluctuations, referred to now as VZ fluctuations, could potentially be observed using precise optical techniques. Since the Power Spectral Density (PSD) of these proposed fluctuations scales on the order of L^2, where L is the length of the interferometer arm, these fluctuations are in concept observable using tabletop optics. These fluctuations are extremely weak in amplitude, although it is in principle in the observable range. This is one of the reasons this effect has not been measured, as low amplitudes are harder to detect because they are below shot noise. These fluctuations are also stochastic in nature, and therefore must be described statistically, which is why quantum gravity experiments such as this use a PSD measurement to observe phase difference [1].

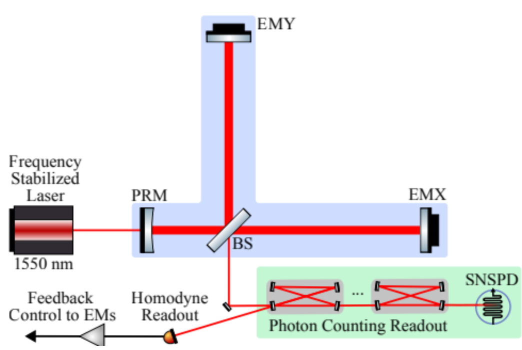

Figure 1: Michelson Interferometer in GQuEST setup [1]

LIGO, or the Laser Interferometer Gravitational Wave Observatory, has a long history of using the properties of light to measure gravitational waves [3]. While LIGO is extremely sensitive, it is not measuring in the frequency regime that would allow us to observe VZ fluctuations. There is also a similar setup to the GQuEST experiment at Cardiff University, known as QUEST which uses homodyne readout, which is slightly different than the planned design here [4].

The design for GQuEST involves a Michelson interferometer, as shown in Fig. 1, which splits light from a laser into two separate arms, where they are then reflected by end mirrors and recombine at the beamsplitter. The light then moves into the photon counting readout scheme, which is a method that measures light output by counting single photons rather than using the typical homodyne readout. This method has yet to be applied to interferometer measurements, and provides some new advantages to the setup, namely that the interferometer is far more sensitive than it would be with the homodeyne readout. The idea is for the laser light in the Michelson interferometer to destructively interfere, then for the VZ fluctuations for perturb the length of the arm, thus allowing for small amounts of light to be observed in the photon counting readout setup. In reality, no interferometer can have perfect destructive interference due to contrast defects, or unwanted light leaking out of the system. Since we are counting single photons, the photon counting method is very sensitive to the extra light. This light can be filtered out, among using other techniques that are used to reduce it. In addition, while the GQuEST setup would not limited by shot noise because of the photon counting method, it is instead limited by classical noise, which is much lower in amplitude. This classical noise is dominated by mechanical noise, both from the optical substrate and the coating, which requires a thin, stiff mirror, with a high quality factor. Lowering this noise in order to obtain a more sensitive measurement comes with its challenges, and these are addressed in the mirror design.

The source of this classical noise primarily includes mechanical noise, which is the vibration of the end mirrors. The vibration can be reduced by making the mirrors extremely thin, around 2 mm. The mirrors have a highly reflective (HR) Bragg reflection coating applied to the surface which applies a stress to the mirror itself. This in turn increases wavefront curvature, which is reflected in the radius of the curvature of the mirror itself and can be described as:

$$r_{curv} \approx \frac{1}{6}\left(\frac{E_s h^2}{\sigma_c h_c (1 - v_s)}\right) \tag{1}$$

where E_s is Young's modulus of the applied substrate, or the stiffness of the mirror, h is the thickness of the end mirror, σ_c is the coating stress, h_c is the thickness of the coating, and v_s is the Poisson ratio for silicon [1]. The wavefront curvature increases the aforementioned contrast defects, meaning the higher the curvature the more light that leaks out of the system. This is because variances in curvature between the two mirrors can cause different spatial modes that do not fully cancel when the light interferes, resulting in an excess of light in our readout. This effect can be mitigated by applying a thick anti-reflective (AR) coating to the back of the mirror, which will partially cancel the curvature caused by the thickness of the HR coating. Reducing contrast defects can also be done by adjusting the curvature difference between the two mirrors. This difference can be found by subtracting the curvature, in diopters, of each of the end mirrors. The goal is such that the mirrors have the same curvature and therefore produce the same optical mode and have the same expected amplitude coefficients. These coefficients (K) for the Hermite-Gauss Mode (2,0) can be described as:

$$K_{20} \approx \frac{1}{\sqrt{2}}\left(\frac{kD_x w^2}{4}\right) \tag{2}$$

$$K_{20} \approx \frac{1}{\sqrt{2}}\left(\frac{kD_y w^2}{4}\right) \tag{3}$$

Where k is the laser wave number, D_x and D_y are the radii of curvature in diopters of mirrors x and y respectively, and w is the beam radius of the mirror [1]. In order to make sure the beams have the same curvature, we can image them, and then apply stress to or move the mirror as necessary to change the curvature to reduce the difference between the two end mirrors. This adjustment can be done by adjusting the custom mount of the mirror, as they are designed to be held in a setup with four spokes that are optically welded to the mirror itself and can allow the mirror to be moved, tilted and adjusted. This can be seen in Fig. 2.

The current proposed experiment provides a total curvature of around 0.26 diopters, which is estimated from Eq. (1) based on the thickness of the mirror, coating, the stress caused by the coating, and the properties of the substrate. The total radius necessary to avoid this "mode mismatch" between the mirrors, however, is less than $3 \cdot 10^{-4}$ diopters. The overall goal of this project will therefore be to use wavefront correction to limit difference in the spatial modes and reduce extra light as much as possible by imaging the mirrors themselves and then building and adjusting the mirror mount.

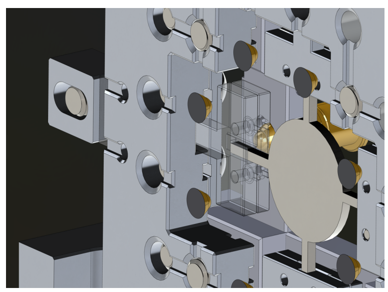

Figure 2: End mirror setup in holding device

2 Objectives

The big picture goal of the GQuEST project is to measure the light signal in the interferometer created by VZ fluctuations using photon counting. This result, whether positive or negative, will give strong indications towards the nature of a theory of quantum gravity.

The goal of this specific project is to lower the amount of light that leaks out from the interferometer. This will be done using wavefront correction on the end mirrors, adjusting them in order to decrease the mode mismatch between the two mirrors.

Other parts of this project will involve building the actual mount for the mirrors, as seen in Fig. 2. These will be used to apply stress in order to change the radius of curvature. Another part of this work will involve seeing how much force the failure points on the spokes can take and finding the maximum amount of stress that can be applied.

Continuing with this project, we will also be writing Python code that will allow us to go from the image of the wavefront curvature of the mirror to a few values that will summarize the coupling between the zero zero and higher order spatial modes.

3 Approach

The approach of this project is to use Fizeau interferometers in order to image the mirrors. Seen in in Fig. 3, these setups are usually used to measure the shape of an optical surface, like a mirror [5]. This involves placing the reference optical component. This is usually a wedge which slopes slightly to prevent the creation of unwanted interference fringes and makes the image sharper, in front of the component we wish to test. Then the light passes through a beamsplitter, through the setup of optical components, and then back to the imaging system, which produces an image of the interference pattern. This system analyzes the interference fringes from the wavefront, since the spatial separation and intensity of the fringes is related to the shape of the mirror. A perfectly flat mirror would show even spaced straight line fringes, so any curvature or roughness of the mirror's surface changes the location and intensity of the predicted fringes. Since the incident angle, intensity, slope angle, wavelength, distance, and most other parameters are known, we can reconstruct the surface of the mirror using these fringe patterns [6]. This allows a image like Fig. 4 to be made, which produces a representation of the surface of the mirror, and therefore allows us to determine the radius of curvature from it. The general steps for changing the radius of curvature will involve imaging the surface, adjusting the stress of the mirror using the custom mount, and imaging again to re-measure the radius of curvature. The goal of this is to ensure that the radii of curvature of the two different end mirrors x and y are equal, to avoid the mode mismatch and decrease the amount of light that leaks from the system.

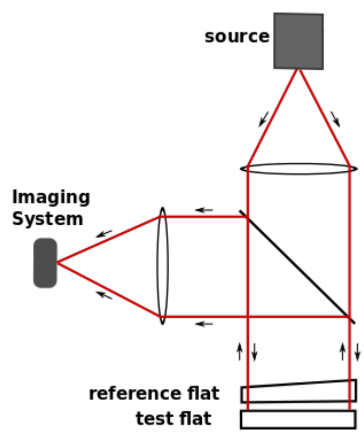

Figure 3: Fizeau interferometer with an optical flat *Wikipedia Commons*

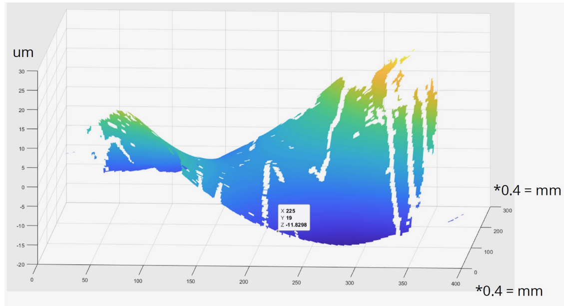

Figure 4: Image from a Fizeau interferometer *Courtesy of Yuiki Takahashi*

4 Project Schedule

With this project lasting around ten weeks, there are a few main goals that we have, as well as a few deliverables with this project. The deliverables include two interim papers, as well as a final report and a final presentation. The first goal of this project is to gain an understanding of the GQuEST setup and the physics behind the experiment. This will mostly be done before arriving at Caltech on June 18th, with the project proposal and by reading papers written by the group and that cover this subject. The next goal is to complete any required safety training and onboarding required to work in the lab. This will likely be done the first week of the project. During the second week, the goal is to work on the cleaning and assembly of the end mirror parts. During week three, the goal is to work on imaging the mirrors using the process above and translating that into contrast defect with code. This is also around when my first interim report will be due, so I plan to complete that as well. Week four will involve correcting the optic and reimaging the mirror again to analyze the corrections. Around halfway through the project we will take a trip to the LIGO site in Hanford as well, which will also contribute to my understanding of the research as well as being an awesome experience. During week six we will continue correcting and reimaging the mirror, and that is also when my second interim report will be due. During weeks seven and eight, we will continue to correct and reimage the mirror, and make any adjustments as necessary. Finally, during weeks nine and ten I will work on my final report and presentation, which will be the final two deliverables.

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