LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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High Fidelity Probe of Optical Scatter from Point Defects

Author: Kruthi K
Mentors: Gautam Venugopalan, Prof. Rana Adhikari, Dr. Koji Arai

California Institute of Technology
LIGO Project, MS 18-34
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project, Room NW22-295
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
Route 10, Mile Marker 2
Richland, WA 99352
Phone (509) 372-8106
Fax (509) 372-8137
E-mail: info@ligo.caltech.edu

LIGO Livingston Observatory
19100 LIGO Lane
Livingston, LA 70754
Phone (225) 686-3100
Fax (225) 686-7189
E-mail: info@ligo.caltech.edu

http://www.ligo.caltech.edu/

1 Introduction

Gravitational waves (GWs) are ripples in the fabric of spacetime, generated by accelerated masses, that propagate as waves at the speed of light. Their existence was predicted by Albert Einstein's General Theory of Relativity in 1916 and the possibility of using interferometers to detect the gravitational waves was first considered in the early 1960s. After several decades of research and technological upgradations, aLIGO became capable of detecting the extremely small amplitude of gravitational waves. This led to its first detection of gravitational waves, from a black hole coalescence, on 14th September 2015. Gravitational waves provide us a lot of information about their sources such as black holes, neutron stars and so on, and act as a novel tool to probe our universe further.

LIGO consists of a ground based network of laser interferometers designed to detect gravitational waves from distant astrophysical sources in the frequency range from 10 Hz to 10 kHz [1]. Currently its strain sensitivity is more than 10^{-23} around 100Hz, which is millions of times smaller than a proton. The infinitesimal gravitational wave strain is obtained by measuring the variations in the intensity of the recombined light at the detection port, which is a function of the differential arm length (DARM) of the interferometer. It exploits several advance modifications to the usual Michelson interferometer, such as four stage suspension of test masses for seismic isolation [2], highly stable laser - which is about a 100 million times more stable than an ordinary laser - to increase the resistance to intensity noise, test masses made of fused silica to minimize IR absorption, extremely smooth optical coatings to reduce scatter loss, large test masses - with a diameter of 34cm and weight around 40kg - to keep the radiation pressure noise to a level comparable to the suspension thermal noise [3], and use of Fabry-Perot cavity inside each arm to increase their interaction time with gravitational waves through multiple reflections, to increase its potency.

Understanding the noise sources - fundamental, technical and environmental - is critical for further increasing the strain sensitivity. The scattering of laser light by various objects in the interferometer is one such noise source, which also leads to decoherence of the laser beam in the cavities [1].

2 Project

2.1 Problem

LIGO's mirror test masses have been specifically designed and constructed with multilayered interference coatings via ion-beam deposition to minimize optical absorption, mirror thermal noise and light scattering [6]. The fused silica material used for the input test masses is an ultra-low absorption grade, with absorption at 1064 nm of less than 0.2 ppm/cm and is extremely smooth [2].

However, the laser light striking the test masses is still subject to scatter in spite of these precautions. An ideal mirror would appear black when viewed off axis from a source of illumination incident normally on the mirror; the photographs of an Advanced LIGO End Test Mass, illuminated by the 100 kW beam, taken at an angle of 9.8° to the main beam (Figure 1), rather show a large number of light scattering points [6]. The scattering of light

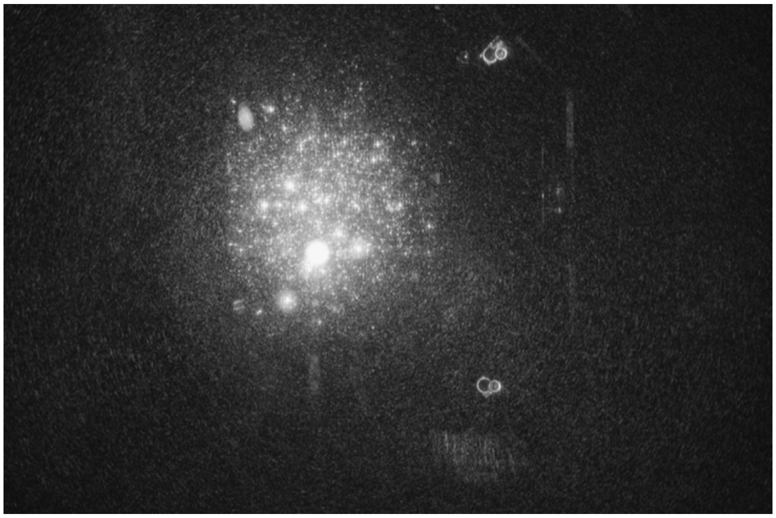

Figure 1: Photograph of an aLIGO End Test Mass; exposure time of 1.3 seconds [6].

reduces the power circulating in the Fabry-perot cavities leading to a low signal to noise ratio. For instance, Y-end reaction mass at Livingston, on occasions prior to February 2017 caused scattering in the gravitational-wave channel approximately up to 90 Hz [4].

Scattering leads to the decoherence of the laser light. Backscattered light, from the moving chamber walls, baffles, mirrors, or photodiodes, couples into the main beam as shown in Figure 2. This modulates the phase and amplitude of main beam, introducing a random phase noise [1].

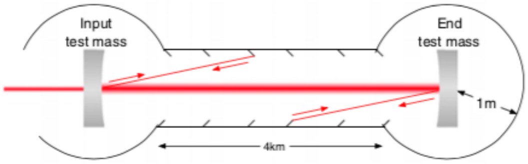

Figure 2: Scattering inside the arm cavity [1]

In order to develop techniques to further reduce the scattering and design optical cavities with lower losses, we, first off, need a repeatable and reliable technique to characterize the loss. This will be the primary goal of the project.

2.2 Major Objectives

- Implement a two lens telescope system to focus the image of the optic onto the CCD sensor.
- Set up a calibrated network of GigE cameras for all the optical cavities in the lab
- Develop a python program to interface with the GigE camera network, and process images thereby captured to obtain data about the losses.

- Using a python program and the data from processed images, quantify losses in the optical cavities by evaluating BRDF of the optic for a range of angles.
- Analyze the data and develop a reliable model to characterize the losses.

2.3 Approach

This project will be a continuation of work done by other students over past few summers. In order to measure the scattered light CCD camera, Basler ace acA640-120gm, with Gigabit Ethernet (GigE) connection will be used such that it can image the test masses.

A telescopic lens system has to be placed between the camera and vacuum viewport to get focused images as shown in Figure 3. This will help us access a variety of focal plane distances and control the field of view captured, in contrast to the use of single camera lens. A Python program will be used to select the appropriate combination of focal lengths amongst the available options such that the combination can focus the entire optic (3" diameter) as well as the beam spot (1" diameter) by varying the distance between the lenses. Following are the considerations made while choosing the lenses:

- As we are required to get real images of the optic to focus on CCD sensor, plano-convex or biconvex lenses can be used.
- As the laser light used is of 1064nm, the lenses need to be V-AR coated at 1064nm to reduce the scattering and enable maximum transmission at this wavelength.
- Lenses with larger diameter collect more light, hence 2" lenses are preferred over 1" lenses.
- As the conjugate ratio is greater than 5, plano-convex lenses will be a better approximation to the bestform lenses that reduce the effects of spherical aberrations.
- Lenses with f-numbers greater than 5 are preferred as spherical aberrations are less pronounced in them.
- Along with these, the dimensions of available hardware such as cylindrical enclosures for the camera and the telescope, and slotted lens tubes to mount the lenses should also be taken into account.

Rays traversing in off axis regions produce varying transverse magnification leading to coma. This can be reduced by judiciously placing an aperture, or stop, in an optical system to eliminate the more marginal rays [8]. Moreover, the lens solution has to be chosen such that the image circle formed at its focal plane i.e. camera sensor just encloses the whole pixel array to ensure maximum utilization of the pixels [5].

Since intensity of the scattered light is angle dependent, bidirectional reflectance distribution function (BRDF) as defined below, will be used to quantify the scattering [9].

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

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.

The scattered power (P_s) is calculated from the images of the calibrated CCD according to

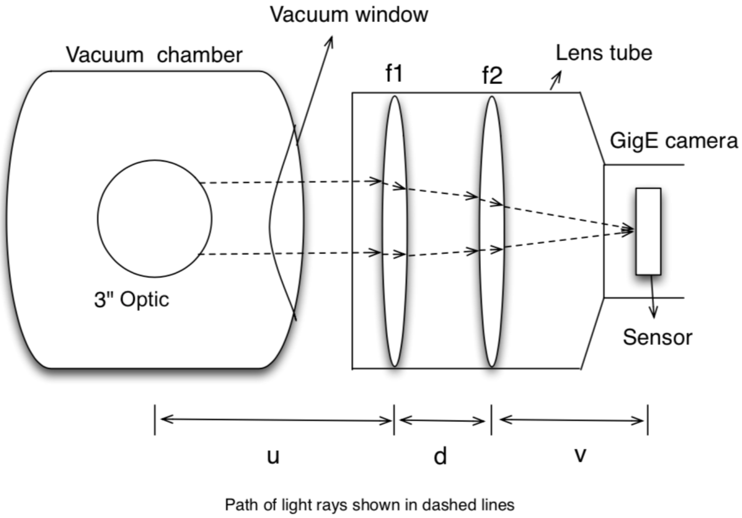

Figure 3: Schematic of the telescopic lens system [5]

the following equation,

$$P_s = CalibrationFactor(CF) \times \frac{\sum_{ROI} PixelValue}{ExposureTime} \tag{2}$$

where ROI is the region of interest selected around the beam spot in the captured images. Here the pixel counts are summed over the ROI and normalized by the camera exposure time. Calibration Factor (CF) represents the power scaling factor due to gain or loss in sensor readout and conversion of charge on a pixel to ADU.

The calibration factor of a camera is obtained by making a comparative measurement between the camera and a photodetector. An ideal Lambertian scatterer like matte coated paper [7], can be used as a uniform secondary source of light. The light scattered from matte coated paper is measured using a photodetector and then snapshots are taken, by exactly replacing the photodetector with a camera, at various exposure times. Equation 3 gives us the formula required to calculate the calibration factor (CF).

$$CF = \frac{P_{pd}}{\text{slope of pixel sum of snapshots vs exposure-time plot}} \tag{3}$$

where P_{pd} is the power as measured by the photodetector.

After setting up a calibrated network of cameras in all optical cavities, we can evaluate the BRDF of the optic for some range of angles and analyze how well the data fits a certain model. Torrence-Sparrow, Maxwell-Beard, Sandford-Robertson, Phong, and Cook-Torrance are some well-known BRDF models that can be used. We can further gather information about the size of the point scatterers using the time-varying scattered intensity.

3 Project Schedule

- **Week 1-3**: Install the telescope lens system and GigE cameras, and develop a python code to interface with the camera network.
- **Week 4-6**: Capture images at different angles, analyze them and calculate the BRDF.
- **Week 7-11**: Analyze the BRDF data and develop an appropriate model to characterize the losses.

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