LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Technical Note **LIGO-T11XXXXX–vX** 2017/06/23

Characterization of Test Mass Scattering

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1 Introduction

Based on Einstein's General Theory of Relativity, gravitational waves which were once just a prediction, have now been successfully detected due to the precision that the Advanced LIGO (aLIGO) has been able to achieve. The detection is not, however, merely a confirmation of the theory, but it opens up the world to a new regime of gravitational physics which would provide a novel perspective of the universe, complementing the current repository of knowledge. The discovery of gravitational waves ensued years of technical innovations aided by revolutionary advances in mathematical and physical sciences, many aimed at resolving the difficulties associated with detecting their extremely small amplitude. The Michelsons interferometer employed in the aLIGO set up is able to detect at such low amplitudes on account of many modifications it has undergone to increase its potency. The intensity of the recombined light is a function of the differential arm length (DARM) of the interferometer, and therefore, the intensity of the light at the detection port is proportional to the infinitesimal gravitational wave strain. The reliability of the setup to discern the minute fluctuations in intensity is on account of the increased stability of the laser used which is about a 100 million times more stable than an ordinary laser and has an output power of approximately 200 W. The improved stability implies that the laser output is consistent and resistant to intensity noise. The increased stability is attained by reducing beam‘s natural frequency variations and power fluctuations through a series of feedback mechanisms. The fused silica test mass optics for aLIGO are about 34 cm in diameter and weigh about 40 kg to keep the radiation pressure noise to a level comparable to the suspension thermal noise. The beam spot size is sufficiently large so as to reduce thermal noise contributions

2 Problem

As a result of the many precautions taken in the upgradation of aLIGO, the test masses used in the setup are secured against thermal expansion and radiation pressure in addition to being isolated from seismic vibrations and being exceptionally smooth to decrease scatter loss. Active vibration isolation. The 40 kg mirrors in the interferometer are suspended at the bottom of four massive pendulums which increases the inertia of the system and essentially makes it steady against external vibrations as each step of the 4-step pendulum absorbs vibrations from the mass above it. [1] 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. The material also has a low level of inhomogeneity and low mechanical loss. [**?**] However, the laser light striking the test masses is still subject to scatter. The scattering of the laser beam effectively reduces the power circulating in the cavity and thereby increases experimental error. We can define a mirror at a given wavelength by its reflection, R, its transmission, T, and its scatter and absorption losses,

$$S + A = l$$

where

$$R + T + l = 1$$

The values of R, T, and l could be theoretically determined by placing the mirror in a laser path, measuring the fractions of the beam transmitted and reflected, and attributing the

rest to losses.
The input test masses together with the end test masses form Fabry-Perot cavities which are primarily employed to build up the circulating light power and to serve as an accurate length standard for control of the lasers frequency noise. Scatter decreases the power circulating in the Fabry- Perot cavities thereby limiting the sensitivity of the detector. The scattered waves might recombine with the resonant cavity mode, imparting a random phase noise. Furthermore, the optics coatings helpful in one way, contribute to noise due to stochastic particle motion.

3 Major Objectives

- Calibration of the CCD with the implementation of a two lens system
- Determine where the CCD's must be installed
- Write programs to communicate with the camera
- Acquire and analyze images of the test masses
- Develop model to quantify scatter loss

4 Approach

A part of the laser beam scatters or deviates from its desired path on account of roughness of the test mass surfaces and instead of yielding a coherent, collimated beam, the intensity pattern might become angle dependent. This perspective of optical scattering is accounted for by the Bidirectional Scattering Distribution function (BSDF). [3]

$$BSDF = \frac{P_s/\Omega}{P_i cos(\theta)}$$

where P_i is the incident intensity, P_s is the scattered power reaching the camera sensor and Ω is the solid angle. We will be using the Basler ACA640 120 GM, with an image circle size of about 1/4 inches to image the test masses in the LIGO 40 m prototype with test masses about 3 inches in diameter. The first step would be determining the lens to use with the camera. A two lens solution is adopted to access a variety of focal plane distances and control the field of view captured. The determination of the points for installation of the camera depends on whether the entire test mass is to be imaged so as to gather a broad overview of the imaging process itself or if the beam spot is to be imaged specifically. Ideally, we would start with imaging the test mass with an additional area, set the focal plane and then move to imaging specific sections of the test masses. Also determining the exact effective focal length required for imaging would vary as the object distance and size vary, and given the focal lengths of the lenses, the distance between the lenses themselves and their distance from the camera sensor must be altered. [4] The beam spot size would have to be precisely determined from the images too. Generally, in order to measure optical scattering, we need to measure the power of the observable scatter at a resolute area, distance, and angle from the source. Since we are installing Gigabit Ethernet cameras, a program must be written to communicate with the camera to control exposure, angle and distance from the optic. The CCD image is limited by various noise sources which can be either intrinsic to measurement such as shot noise, thermal fluctuation in the test masses, external noise sources possibly due to random seismic motion and finally the noises induced by the camera itself [7] including shot noise, dark current noise, CCD camera noise, read out noise and blooming among others. These need to be digitally subtracted from the image, thereby improving the signal to noise ratio of the image obtained. Techniques are, therefore, required to remove the camera noise without affecting too much of the picture which might range from determining the range of frequencies where image would be most corrupted by noise, estimating noise from the spectral density plots to stacking multiple exposures to reduce the noise introduced by the camera itself. [8] Another interest of the project is to determine the noise coupling of the interferometer, that is the scatter induced due to frequencies ranging from 0.5 Hz to 1 Hz arising due to the actual movement of the object, or due to other perturbation in the setup which might impart a non- linearity to the data.

5 Project Schedule

Table 1: Timeline

Week 1 to 3	Calibration of the CCD with implementation of a two lens system, determining the optimum design, location for installation of CCD's.
Week 3 to 5	Set up programs to communicate with the camera, image acquisition
Week 6-8	Analysis of the data through image processing techniques
Week 9-11	Detecting noise coupling and developing models to quantify scatter loss

References

[1] P. R. Saulson *Fundamentals of Interferometric Gravitational Wave Detectors* World Scientific, Singapore(1994)

[2] Cinthia Padilla, Erik Munz et al.*Low Scatter and ultra-low reflectivity measured in fused silica window* Applied Optics, 53(7), 1315-1321 (2014)

[3] Adrian Avila- Alvarez, Garilynn Billingsley, Joshua Hacker, Joshua Smith *Imaging Scatterometer Characterization of Advanced LIGO Optic ITM06.* Technical Note LIGO-T1400252-LSC.(2014)

[4] Ajoy Ghatak *Optics*.4th Edition (2009)

[5] D. V. Martynov, E.D. Hall et al. *The Sensitivity of the Advanced LIGO Detectors at the beginning of Gravitational Wave Astronomy* Physical Review D-93.11 (2016)

[6] `http://www.ni.com/white-paper/4229/en/`

[7] http://www.qsimaging.com/ccd_noise_measure.html

[8] http://astro.physics.uiowa.edu/~srs/29137_09/ccd-RLM.pdf