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

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2023 LIGO SURF Project Proposal: Increasing 40m Auxiliary Laser Stabilization Speed

Reuben S Mathew

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/

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1 Introduction

The Laser Interferometer Gravitational-wave Observatory (LIGO) consists of two gravitational wave detectors operating in unison at Hanford, Washington and Livingston, Louisiana in USA. Extremely precise laser interferometry is used in these facilities to measure tiny distortions in space-time caused by the passage of gravitational waves. They are part of a collaborative effort by scientists around the world, that include gravitational wave detectors KAGRA (Japan), VIRGO (Italy) and the upcoming IndIGO(India).

The detectors consist of Michelson interferometers built over two L-shaped arms, each 4km in length. Laser light is split and sent down both arms to bounce off the end mirrors and travel back to the starting point, where they recombine to form an interference pattern. When gravitational waves pass through the interferometer, they cause a variation in arm lengths of the interferometers which is reflected in the interference pattern. The long length of the interferometers arms provide for the high sensitivity required to sense the effects of gravitational waves, which are very faint. The interferometer arm cavities are a key component of LIGO, and the precise control of cavity parameters is essential for accurate detection of gravitational waves [1].

The 40m prototype of LIGO at Caltech is a 1:100 scale model of the LIGO facility. It serves as a testbed for prototyping new technologies for future upgrades to the Advanced LIGO (aLIGO) detectors, as well as to carry out minor side experiments.

The 40m facility uses an Arm Length Stabilization (ALS) system, to lock the main laser frequency to the interferometer degrees of freedom through various feedback loops. A frequency doubled auxiliary laser (AUX) is injected into the arms of the interferometer, and locked to the arm cavity using Pound Drever Hall (PDH) technique [2][Fig.1]. The AUX laser is summed with the main laser on a photodiode, to produce a beat note that is indicative of the relative fluctuations between main laser frequency and arm cavities. The beat note is used as an error signal to drive the feedback of the Arm Length Stabilization (ALS) system, that keeps the interferometer cavity resonant with the main laser frequency [3].

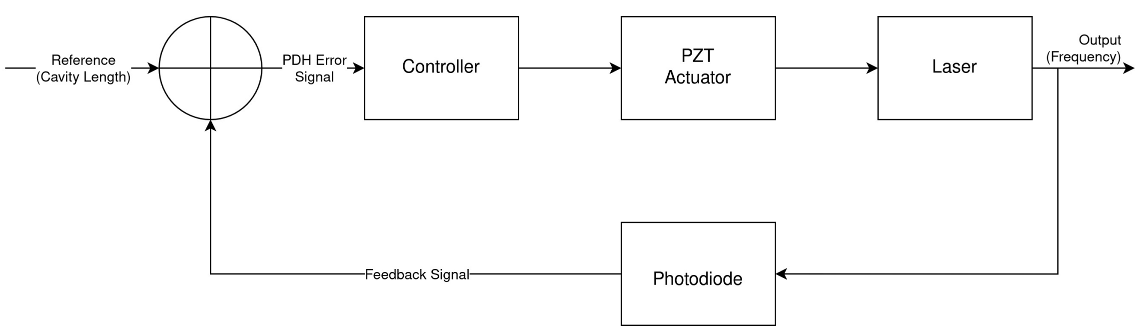

Figure 1: Flowchart showing the Pound-Drever-Hall setup

The AUX NPRO laser is fitted with a piezoelectric (PZT) modulator to enable analogue frequency control through phase modulation. Currently, the PZT has resonances at certain frequencies, which limits the bandwidth of the control loop(∼10kHz). A digital implementation of the servo controller (controller shown in Fig. 2) to compensate for the PZT's resonances could increase bandwidth, and provide a robust framework to implement faster and more optimal controller designs [3].

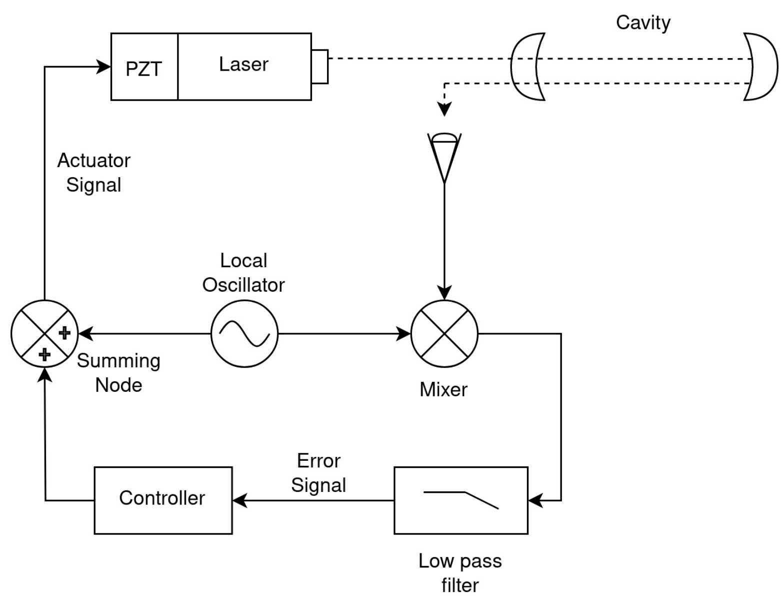

Figure 2: Schematic of the AUX laser locking setup

The improvements in the controller design could lead to implementation of better calibration techniques like Simultaneous Oscillator Calibration (SoCal), leading to better accuracy in measurements. In an astrophysical context, it would enable better triangulation of events in the sky and better estimation of luminosity distance. Improved laser stability could also facilitate profiling and surface roughness characterization of the test mass (mirror) surface. The end goal is to not let the uncertainty in detector response caused by noise and calibration errors limit future measurements [4].

2 Objective

The main objectives of the proposed project are:

1. Characterization of the current analogue control system to prepare for digital implementation.

2. Design and implementation of a digital control system that simulates the existing analogue control system for laser locking to the interferometer cavities.

3. Carry out tests in the digital implementation to check if the frequency response of the digital controller matches that of the analogue controller.

4. Measure the frequency response of the PZT and other components and develop the digital controller for optimal design that can take resonances into account and suppresses them, to increases the bandwidth.

5. Develop the system to make it scalable and flexible, capable of accommodating future modifications in interferometer cavity and controller technology.

3 Approach

3.1 Familiarization with 40m interferometer, control system and related materials

The first step is to familiarize myself with the interferometers, and the analogue feedback system implemented at the 40m lab. Study the working principle behind the currently implemented technologies, get a hands on feel of how PDH works and learn more about control systems theory, and signal processing.

3.2 Characterization of the currently used analogue system

The feedback system currently in use is to be characterized with the goal of developing a digital equivalent in mind, and the frequency response of the PZT and other components can be studied. Moku:Go to be used to collect data for analysis. This will also help to familiarize with loop stability criteria such as UGF, gain and phase margins.

3.3 Design of the digital controller

To provide a starting point to build upon, try and design a digital controller that is similar to the analogue controller. Moku:Go and the Python Control library to be used to implement the digital controller. Test with simulations and experiments to check whether the digital system has a response similar to the analogue system.

3.4 Optimizing controller

Learn and apply principles from digital filter design and feedback design via loop shaping to refine and develop an optimal controller for the system, with an increased bandwidth. The digital controller will be designed with flexibility, scalability, and scope for future improvements in mind.

3.5 Full implementation using Moku:Go

Develop an all-in-one setup using Moku:Go to source phase modulation, demodulate to generate the PDH error signal, apply the controller and drive the PZT.

4 Timeline

Week 1-2:

- Learn more about PDH, control systems theory and signal processing. Gain hands on experience with the PDH technique, Moku:Go and other relevant equipment.
- The first week will be mainly focused on getting an idea of the project scope and develop a plan for moving forward.
- By the end of the second week, the frequency response of the PZT and other controllers, as well as the analogue controller currently in use should be characterized to prepare for the digital implementation.

Week 3:

- Finish characterizing the analogue controller, and start designing the digital controller, using Moku:Go and the Python Controls library.
- Develop the controller till the characteristics match that of the analogue controller currently used at the 40m
- This controller will be a base for future improvements.

Week 4-5:

- Work towards improving the controller to take resonances of the PZT an other components into account and suppress their effects to increase the bandwidth.
- Learn more about control systems theory and digital signal processing to improve controller further.
- Aim to have better bandwidth than the base controller by the end of Week 5.
- Start working on the interim report based on the progress and data collected so far.

Week 6-7:

- Work towards developing the optimal controller using principles from digital filter and feedback design, iteratively refining the controller for increased bandwidth and better response.
- Polish the code. Make it flexible and scalable with with scope for future improvements in mind.

Week 8-9:

- Using the digital controller as a base, start development of an all-in-one setup using the Moku:Go to control all aspects of the laser locking system, that include sourcing the phase modulation and demodulation of the PDH error signal, controlling and driving the PZT.

- Optimize the system and work through potential challenges that might arise while also exploring the potential benefits of the vertical integration of the components into one system.
- Start preparing for the final report

Week 10:

- Conclude the project, apply final touches.
- Finalize and submit the final report.

References

[1] https://www.ligo.caltech.edu/page/ligos-ifo

[2] *Notes on the Pound-Drever-Hall technique*, LIGO Technical Note (1998), https://dcc.ligo.org/public/0028/T980045/000/T980045-00.pdf

[3] Gautam Venugopalan, *Prototype Interferometry in the Era of Gravitational Wave Astronomy*, Chap II (2022), https://thesis.library.caltech.edu/14288/3/main.pdf

[4] Craig Cahillane, *Calibration Methods for Current and Future Gravitational Wave Detectors*, MIT General Relativity Informal Tea Time Series Talk (2019)

[5] The plans for the project is based on discussions with Professor Rana Adhikari *(Experimental Gravitational Physics, LIGO Lab Caltech)* and Radhika Bhatt *(Graduate Student, Adhikari Research Group)*.