LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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2023 LIGO SURF Project: Interim Report #1

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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].

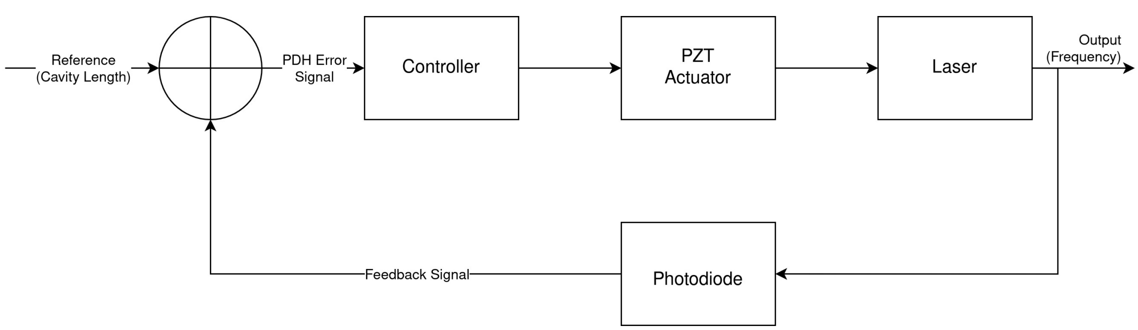

Figure 1: Flowchart showing the Pound-Drever-Hall setup

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].

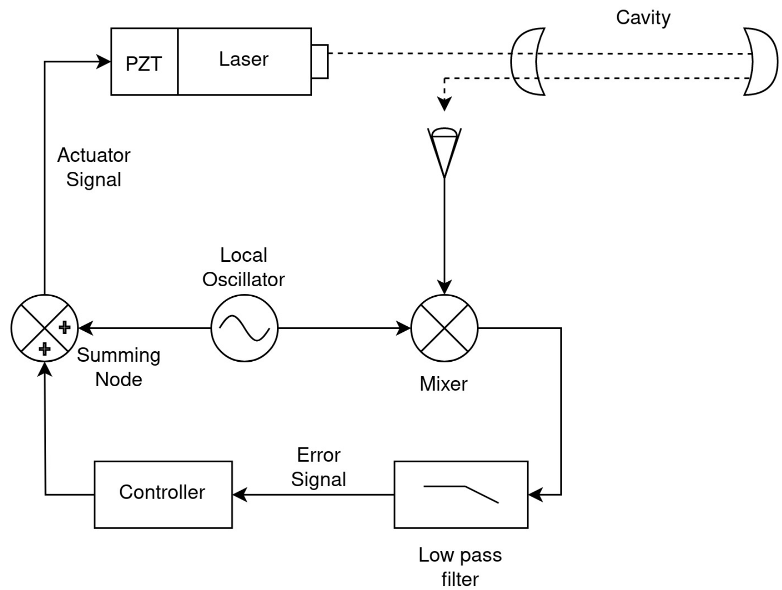

Figure 2: Schematic of the AUX laser locking setup

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.

This interim report consolidates the work done as part of the LIGO SURF program over the span of three weeks.

2 Learning control systems theory

A good chunk of the three weeks were spent studying, familiarizing and experimenting with control systems theory as well as the Python libraries associated with it. I also experimented with the Moku:Go and its usage, as well as the controller currently implemented, how to work with it and take readings from it. The goal is to get the proper foundations of basic controls theory down and then check out some nonlinear control theory which could be useful while designing the controller.

The references used were mainly, Feedback Systems by Astrom and Murray [6], Schaum's Feedback and Control Systems [7], Gautham Venugopalan's thesis [3], LIGO notes on PDH technique [2], lectures on the topics on Youtube and other resources.

3 Measuring the AUX-PDH open loop transfer function

The open loop transfer function (OLTF) of the XAUX-PDH loop was measured using the Moku:Go, using its frequency response analyzer instrument. The excitation was summed with the error signal sent to the PDH controller and the responses were measured at the error signal point before and after summation into the loop. The Moku:Go provided a swept sine excitation and the summing into the loop was done using SR560 preamplifier. A Python script was used to read the exported data, plot and find its stability margins and bandwidth. Further readings should include multiple readings, to try and get an averaged data, as well as to measure the transfer functions of the individual components of the system to compare with the model that is being built.

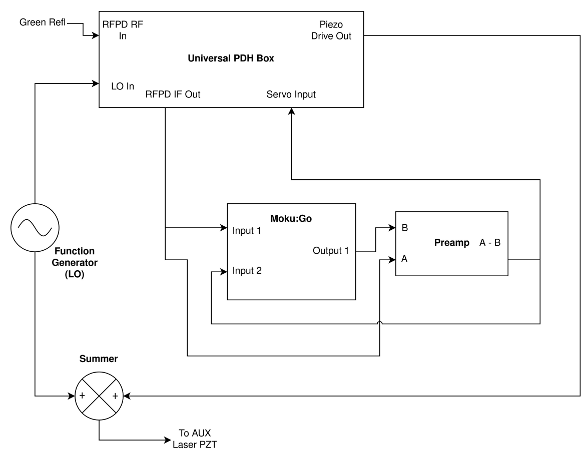

Figure 3: Wiring diagram of the ALS setup at the 40m

Currently, control is done by the universal PDH (uPDH) Servo box, that includes both the controller and a demodulator to demodulate the modulated green laser signal. The controller part is the first thing that is to be replaced with the Moku:Go. Ultimately, the whole system, consisting of the uPDH box and the function generator (local oscillator) is planned to be replaced with the Moku:Go.

4 Code

A script was written (plotter.py) to read the exported frequency response data file from the Moku:Go, draw the bode plots as well as calculate the stability margins. This will make reading transfer function measurements made in the future easier.

Another script models the individual components of the system (cavity, summing junction, photodiode etc.) based on the estimates given in Gautam's thesis [3] and combines it with the already measured responses of the uPDH box and PZT. Combining the transfer functions would require finding the poles and zeroes of the measured frequency responses and converting it into an analytical form. The *iirrational* library can be used to fit measured frequency response to poles and zeroes, but is having some issue with dependencies (will get to figuring

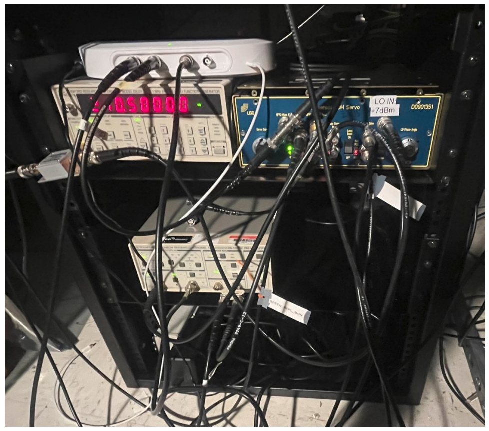

Figure 4: The AUX laser locking setup at the 40m lab

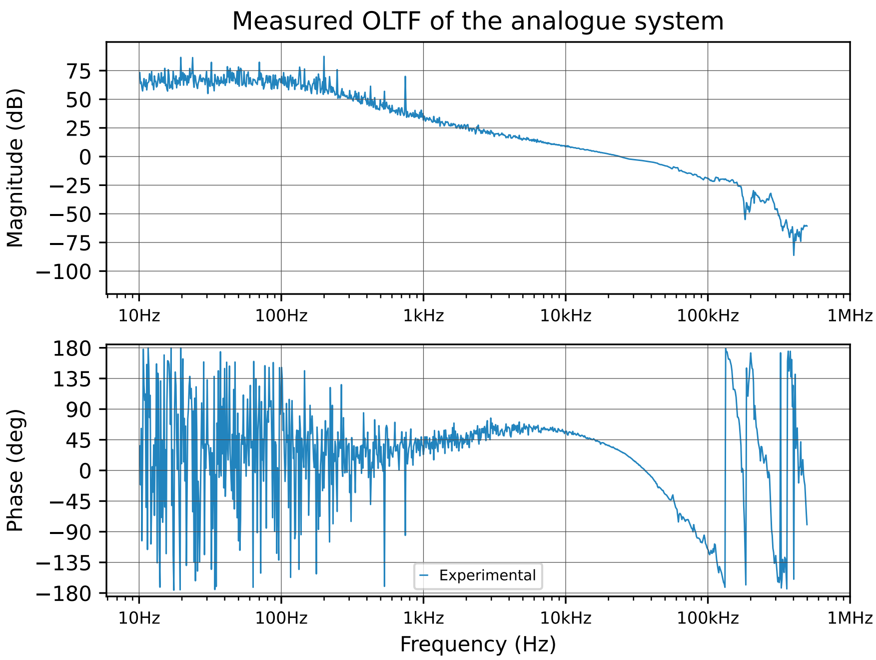

Figure 5: Bode plot of the OLTF measured using the Moku:Go

that out soon). Meanwhile another approach was used, which takes the complex frequency response of the models and multiplies it directly with the measured transfer functions.

The parameters of the models are to be tuned, to match the overall modelled transfer function with the AUX-PDH OLTF that was measured. The code will enable modelling of potential controller designs, combine it with measured and modelled data and test the controller.

5 What's next

The next step is to measure the frequency responses of the various components and use that data to tune the model parameters. Once that is done, then we can start designing and experimenting with various controller designs, and also actually implementing it with the Moku:Go.

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)*.

[6] Karl Johan Astrom, Richard M. Murray, *Feedback Systems*

[7] *Schaum's Outline of Feedback and Control Systems*