LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Improving frequency stabilisation at the 40m with digital controllers

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1 Abstract

The LIGO interferometers need to robustly lock its various degrees of freedom to detect Gravitational Waves. The LIGO 40m prototype uses an auxiliary (AUX) laser as a reference to lock the main laser to the arm cavity and stabilize it. The AUX laser is stabilized by locking it to the arm cavity using the Pound-Drever-Hall (PDH) technique. The stability of the AUX laser is crucial for the stability of the main laser. Mechanical resonances of the AUX laser's piezoelectric (PZT) actuator and the rigid nature of the currently implemented analogue PDH controller limits the performance of the system, hindering noise suppression especially at low frequencies. This project aims to develop a digital controller to replace the currently implemented AUX laser locking system. A digital controller will be more robust and easily customizable. Specifically, the features to be implemented include better controller performance in the 10Hz-20kHz range, where the AUX laser noise has greater contribution, delivering an increased bandwidth over the current analogue system. It also enables faster lock reacquisition when lock is broken and adding resonant gain filters at specific resonant frequencies to facilitate calibration of the interferometer.

2 Introduction

2.1 Background

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 distortions in space-time caused by the passage of gravitational waves. They are part of a collaborative effort by scientists around the world, that includes the gravitational wave detectors KAGRA (Japan), VIRGO (Italy) and the upcoming LIGO-India.

The detectors consist of Michelson interferometers built over two L-shaped arms, each 4km in length. Laser light from a single source is split and sent down both arms to reflect 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 detected in the interference pattern. The long length of the interferometer's arms provide 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 precise sensing and 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 other minor experiments.

2.2 Motivation

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 [Fig. 3]. 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], to track the length of the arm cavity. 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].

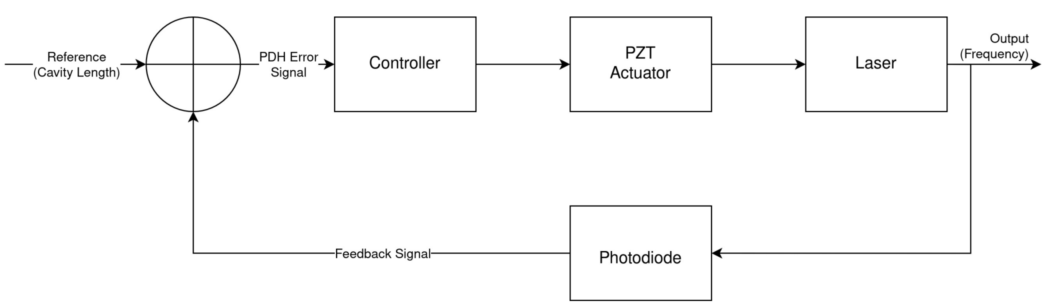

Figure 1: Flowchart showing the Pound-Drever-Hall setup

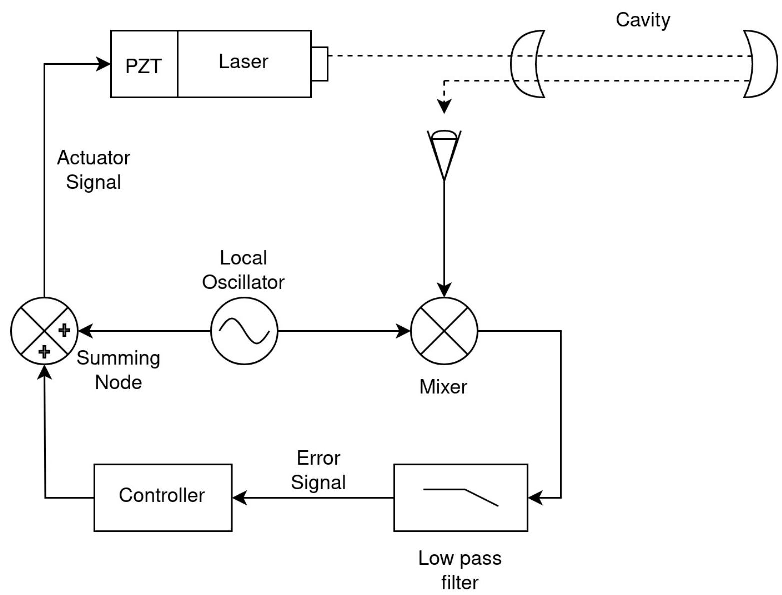

Figure 2: Schematic of the AUX laser locking setup

The AUX NPRO laser is fitted with a piezoelectric (PZT) modulator to enable analogue frequency control through phase modulation. The limitations of the analogue PDH controller and mechanical resonances of the laser's PZT actuator diminish the controller's performance at lower frequencies, and brings down the bandwidth(∼10kHz). A digital implementation of the servo controller (controller shown in Fig. 2) provides a robust framework to easily implement more optimal controller designs, and compensate for the PZT's resonances to increase the bandwidth.[3].

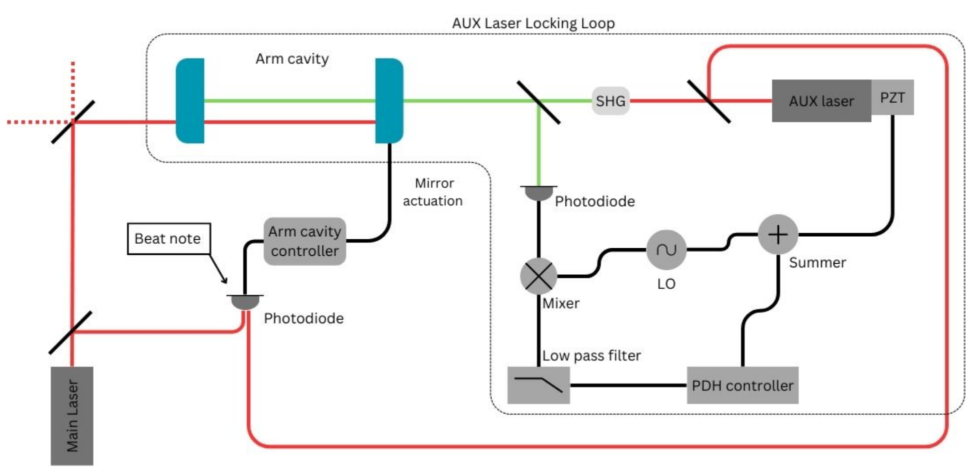

Figure 3: Simplified diagram showing how the AUX locking setup feeds into the main laser system

Currently, locking is done by an analogue universal PDH (uPDH) Servo box, that includes both the controller and a demodulator to demodulate the modulated green laser signal. As the AUX laser is being used as a reference for the main laser, stability of the AUX laser is crucial for stability of the main laser. Specifically, the area of interest is in 10Hz - 20kHz range, where the contribution of the AUX laser to the beat note fluctuation is more prominent. The new digital controller would focus on suppressing noise at this frequency range, as well as overall improvement in bandwidth over the current PDH loop. The controller should also be able to detect if the system is out of lock, and switch to a filter designed for faster lock acquisition then switch back to the stable lock filter.

The improvements in the controller design could lead to the implementation of better calibration techniques like Simultaneous Oscillator Calibration (SOCal)[4], 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 minimise the uncertainties in detector response caused by noise and calibration errors.

This report consolidates the work done by me as part of the LIGO SURF 2023 program.

3 Objectives

The main objective of this project was to design and develop an optimal controller to replace the current analogue PDH controller currently implemented at the 40m. The digital controller has the benefit of easy upgradability, better optimal controller design and adding features like resonant gain filters to better aid the calibration. Converting to a digital controller involves characterising the existing system, developing a model of the system, designing optimal controllers using optimisation techniques, implementing the controller using the Moku platform, and working through the challenges faced in the process.

4 Characterisation of the existing control system

The open loop transfer function (OLTF) of the XAUX-PDH loop (PDH loop of AUX laser at X-end) and the transfer function of just the universal PDH (uPDH) controller were measured using the Moku:Go, using its frequency response analyzer instrument. The setup for measurement is shown in Fig.4 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 is done using an SR560 preamplifier. Python scripts were used to read the exported data, plot and find its stability margins and bandwidth (Appendix A). These readings were used to fit the model and acted as a base benchmark for the performance of the system. The bode plots of OLTF of the system and transfer function of the controller is shown in Fig.6 and Fig.7.

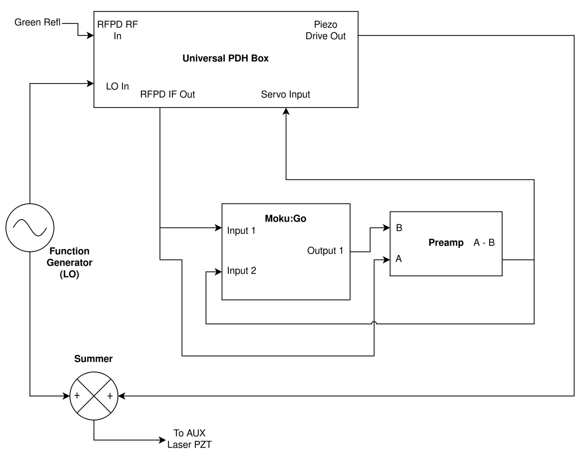

Figure 4: Wiring diagram of the ALS setup at the 40m to take OLTF readings

Figure 5: The AUX laser locking setup at the 40m lab

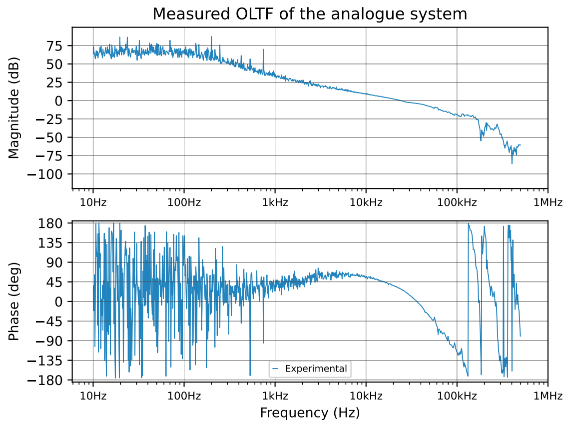

Figure 6: Bode plot of OLTF of the plant measured using the Moku:Go

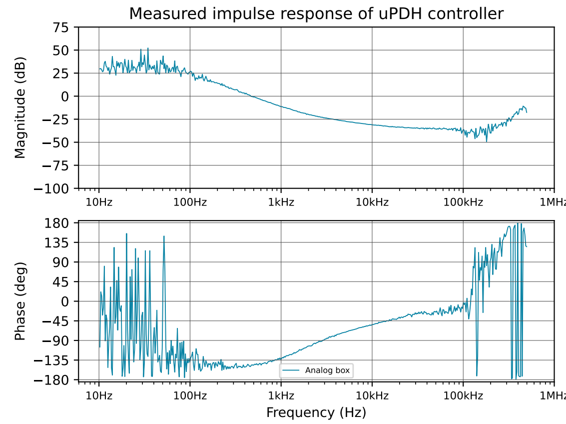

Figure 7: Measured uPDH impulse response

5 Modelling the control system

A model of the system was generated in Python to simulate the impulse response and open loop transfer function (Appendix A). Each individual component in the loop is modelled as a block, and then chained together using Python controls library. The components include PDH controller, PZT, photodiode, low pass filter, cavity and summer junction (breakdown shown in Fig.8 and Fig.9). The impulse response of the uPDH box and the OLTF of the whole system was taken using the Moku:Go, and the zero-pole-gain (ZPK) values of the other components were derived from Gautam's thesis[3]. The code enables us to see the OLTF of the system, the stability margins and quickly see how different controller designs could affect the performance of the system. The poles and zeroes of the uPDH controller were taken from the impulse response of the uPDH box and fitted by eye. The overall gain of the system was also fitted using the measured OLTF, and then compared with the measured data [Fig.10][Fig.11].

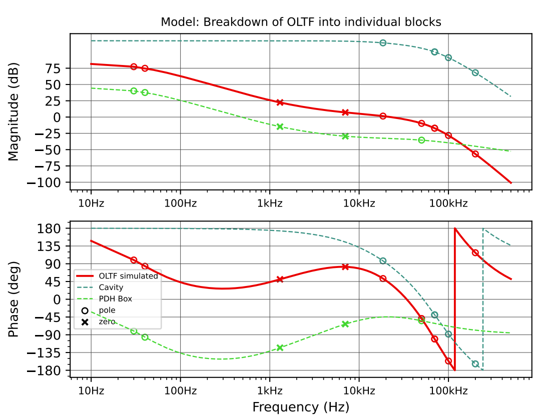

Figure 8: Breakdown of OLTF into PDH and Plant

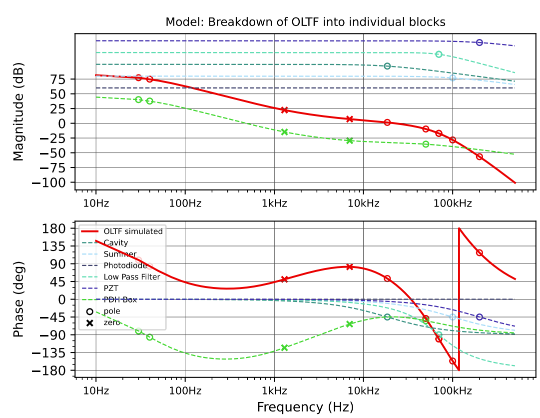

Figure 9: Breakdown of OLTF into components

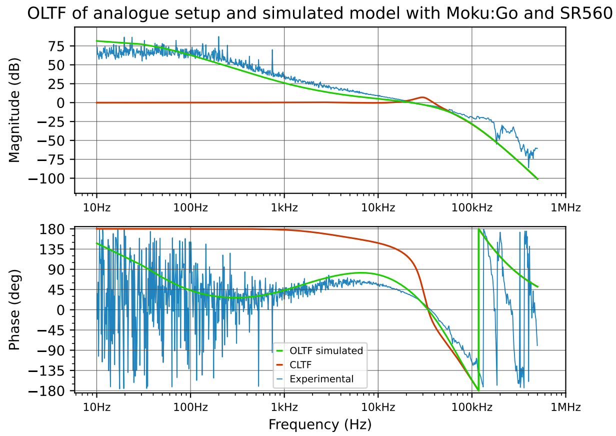

Figure 10: Comparison between measured and modelled OLTF

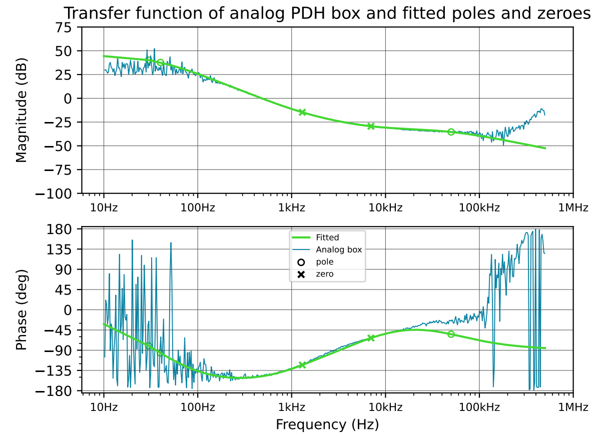

Figure 11: Transfer function with uPDH ZPK values fitted

A basic model of the system is generated, which was used to simulate and study the performance of new controllers.

6 Tabletop Cavity

Figure 12: SR560 preamplifier

An SR560 preamplifier [Fig.12] was used to simulate the poles of the system, with two poles at 30kHz as a rough estimate of system poles. This tabletop model of the cavity enables us to test out physical implementations of controller designs without actually testing on the interferometer itself. A digital controller with fitted ZPK values of uPDH box using the Moku:Go was connected and OLTF was taken, and the results compared to the experimental data and model [Fig.14]. The SR560 can have only two poles, which limits the roll off of the system at higher frequencies (as seen in Fig.13). Nevertheless, at lower frequencies it can be used as good model of the plant. This idea was not explored further due to time constraints.

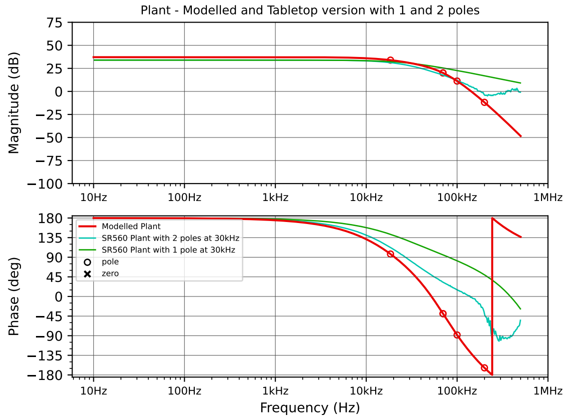

Figure 13: Comparison between tabletop cavity and modelled cavity

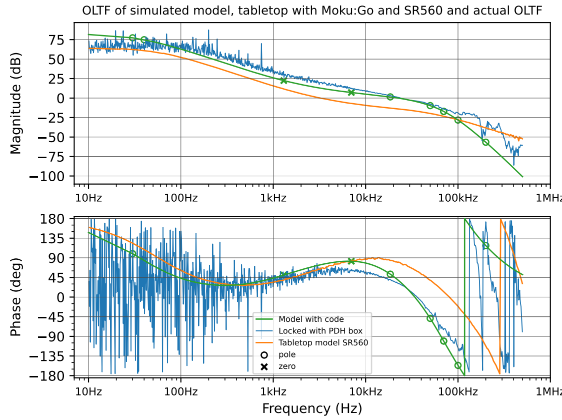

Figure 14: Comparison of OLTFs

7 Digital controller

This section details the equipments used and the manner in which the digital PDH controller was implemented and measurements taken.

7.1 Moku:Go

The Moku is a robust hardware platform that provides a lot of utilities required for the setup including frequency response analyzer, digital filter, lock in amplifier, oscilloscope and waveform generator. It can be controlled through the provided Moku GUI or via Python API. The feature to implement custom digital filters with Second Order Section (SOS) coefficients was used to make the digital controller. A script, written by Radhika and Anchal (See Appendix A) converts filter ZPK values to Moku SOS coefficient files, which can then be loaded onto the Moku.

Figure 15: Moku:Go

Figure 16: Moku:Pro

7.2 Locking

As a first step, the fitted ZPK values of the uPDH box was loaded onto the Moku and lock acquisition attempted. The universal PDH box was still used to obtain the demodulated error signal. Lock was acquired and the transmission on the cavity was brought up to around 0.7. This sets a base upon which better filter designs can be implemented. Locking with the Moku:Pro, a better version of the Moku:Go with more features and lower noise was also attempted and lock was acquired.

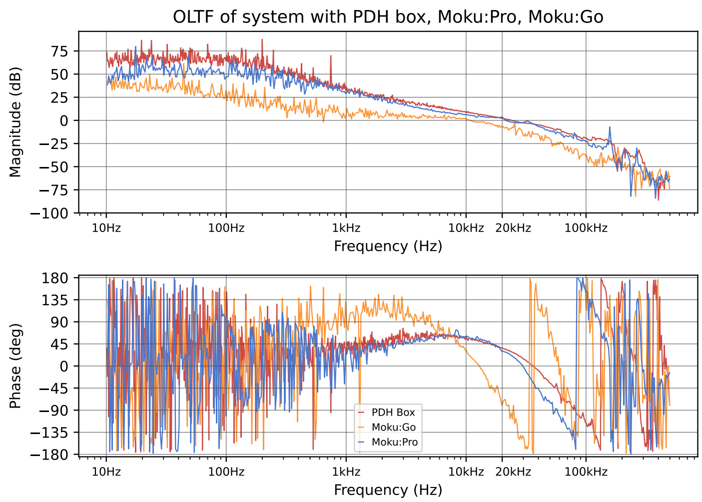

Figure 17: OLTF comparison with uPDH box, Moku:Go and Moku:Pro

The digital filter is replicating the analogue filter box. It can be observed that this basic controller gives similar bandwidth and gain to that of the analogue box [Fig.17]. Further optimisation to the controller can lead to better stability margins and performance.

The phase discrepancy seen with the Moku:Go, could be attributed to an oversight where the difference in sampling rate between the Moku:Pro (39.063MHz) and Moku:Go (3.9MHz) were not taken into account, and the sampling rate of the Pro was used for generating the SOS filter file. This error could not be rectified as lock was acquired towards the last days of the program and further testing was not possible due to time constraints.

The Moku has a feature called multi-instrument mode, which allows for two instruments running parallel in case of Moku:Go and up to four in case of Moku:Pro. This feature was used to test out some potential features that could improve the laser locking.

One such feature tested was monitoring the reflection line using the oscilloscope instrument to detect when lock is broken (reflection drops when locked), switching the filter to reacquire lock quickly, then switching to another filter to hold lock once it is reacquired.

A test script was written in Python (Appendix A) to monitor oscilloscope and switch filter coefficients. It was observed that changing filter coefficients on a single filter will break the lock, but having two filter preloaded and changing the input matrix [shown in Fig.19] to flip between them maintains the lock. Because the filter box has only one input matrix, two filter boxes are needed, connected in parallel where the input matrix of the second filter box acts as the output matrix for the first. Only the Moku:Pro allows input matrices in multi instrument mode so filter switching can only be done with the Moku:Pro. The Moku:Go in multi-instrument mode supports only one filter per filter box[Fig.18].

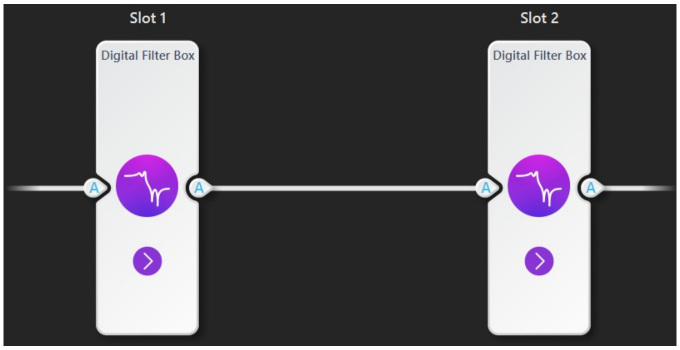

Figure 18: Moku:Go multi instrument mode with two filters

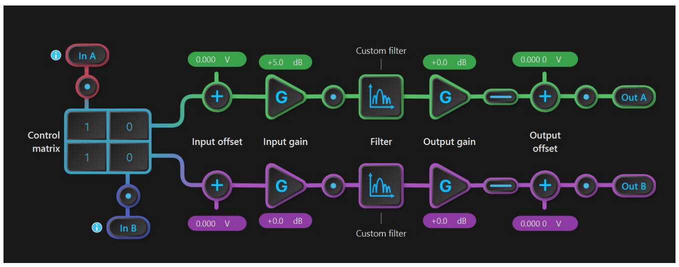

Figure 19: Digital filter setup in Moku GUI

7.3 Replacement of the uPDH box

The next step was to replace the entire uPDH box, including the waveform generator, mixer and low pass filter using the Moku:Pro. The lock in amplifier instrument provides the modulation, demodulation and filtering to give the error signal as output, which can then be fed into the controller. An attempt was made to lock using only the Moku:Go, which was successful, albeit the lock was noisy, as evident from the transmission scope. As the Moku:Go can have only two instruments loaded at once, it makes it impossible to implement reflection monitoring and filter switching. A Moku:Pro had to be used for this purpose. The setup used is shown schematically in Fig 20.

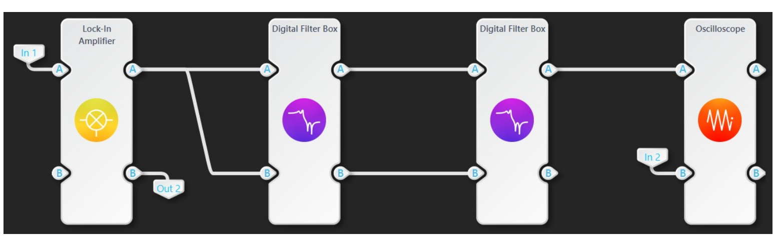

Figure 20: Setup replacing uPDH box with filter control and ouput monitoring

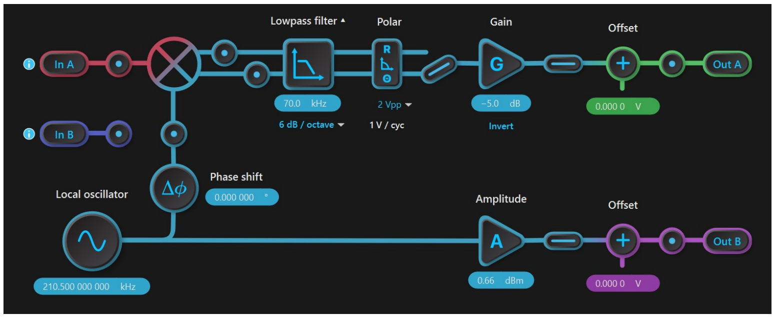

Figure 21: Lock-In amplifier setup in Moku GUI

In [Fig.20], In1 is the green reflection monitoring line,and Out2 is the oscillator output summed to the PZT. The line from the lock in amplifier box is the error signal, and the line from digital filter to oscilloscope is the signal sent to drive the PZT, which is monitored by the oscilloscope.

Locking was also achieved with the Moku:Go, but the transmission line was noisier and filter switching was not possible. The reflection monitoring can be technically done without the Moku through the time series data stream at the 40m lab, but for an all in one system it would be better to do the monitoring through the Moku.

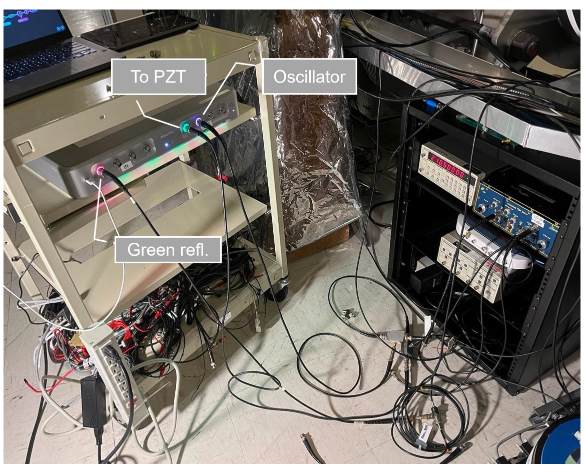

Figure 22: Setup completely replacing uPDH box

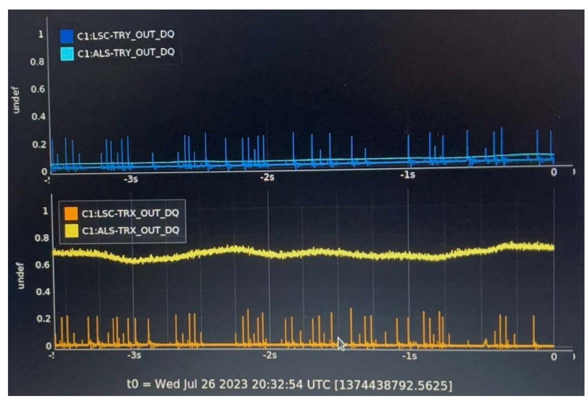

Figure 23: Transmission monitor output when locked

Even though the setups shown are in the Moku GUI, it was replicated using the python Moku API, adding a layer of programmable logic to the controller.

8 Optimal Controller

Even though the goal of the project was to develop and optimize a controller that can lock the laser to the cavity, due to time constraints and interferometer downtimes due to upgrades, the optimisation aspect could not be fully explored. Some potential thought processes and investigations are listed here. Optimising a controller involves defining a cost function and then tweaking the controller parameters to minimise this cost function. A PID controller can be used as a base controller, and then various methods of optimization, like adding a lead compensator, LQR tuning, or particle swarm optimization can be explored.

Linear controllers consider only a linear estimation of the system, and some finer information is lost in this approximation. A potential next step would be to investigate nonlinear controllers and use nonlinear controller design principles to design an even more robust controller.

9 Conclusion

The feasibility of replacing the existing uPDH controller used for locking the AUX laser to the arm cavity with a digital controller utilising the Moku platform is demonstrated. Lock can be acquired with Moku and this enables better control of the digital filter in terms of designing better controllers and implementing new features such as rapid lock reacquisition and adding resonant gain filters to aid calibration. Further investigation into controller optimisation and nonlinear controller theory could further improve robustness of the system and give more stable AUX laser locking, which in turn can improve the ALS system. As a future study, a more look into the noise margins of the Moku go is possible. It would also allow exploration of different controller designs derived using optimal control principles and features like lock reacquisition, filter switching and resonant gain filters.

Nonetheless, this project lays the groundwork that acts as a jumping point for further developing the optimal digital controllers for laser locking.

Acknowledgments

I would like to thank my mentors Radhika Bhatt, Francisco Carcoba, Koji Arai, and Rana Adhikari for all their guidance, help and support. I thank the LIGO Laboratory and the Caltech Student-Faculty Programs office for the opportunity to participate in the LIGO SURF program and for their support throughout the summer. This work was funded by the National Science Foundation.

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[5] The plans for the project are 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*

[8] Bond, C., Brown, D., Freise, A. et al. *Interferometer techniques for gravitational-wave detection*

Appendix A

This section provides a basic rundown of some of the code used as part of this project. They can be accessed at github.com/CaltechExperimentalGravity/LaserStabilization

Moku_API_Examples/ folder contains some examples on how to use the Moku API. They were taken from the API documentation at https://apis.liquidinstruments.com/examples/python/, where more examples can be found

digitalFilterUtils.py and **mokuDigitalFilter.py** are scripts written by Radhika Bhatt and Anchal Gupta for configuring digital filters on the Moku by converting ZPK values to SOS files readable by Moku and load them.

PlantSim/ contains the scripts used to simulate the plant, read Moku data exported, and plot and format the various data and results. **blocks.py** contains the individual blocks of the system, **plantmodel.py** simulates the response of the loop. The rest contains scripts to format the plots, compare various transfer functions etc.