LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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2024 LIGO SURF Interim Report 1: 40m ALS / SFG

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1 Introduction

The LIGO (Laser Interferometer Gravitational-Wave Observatory) detectors are essentially large scale Michelson interferometers which are designed to sense variations in space-time strain induced by passing Gravitational Waves (GWs). The LVK (LIGO-Virgo-KAGRA) detector network currently consists of two Advanced LIGO detectors in the U.S.; the Advanced Virgo detector in Italy; and the Japanese detector, KAGRA. A third Advanced LIGO detector is to be located in India.

The 40m prototype of LIGO at Caltech is a 1:100 scale model of the LIGO facility. It serves as a testing ground for upgrades aimed at enhancing the Advanced LIGO (aLIGO) detectors. The primary objective of this project is to study the implementation of upgrades that significantly improve the sensitivity of the GW detectors. Currently, the detector faces challenges related to quantum efficiency (QE) in photodetection and laser feedback stabilization.

Laser feedback stabilization plays a crucial role in maintaining stable optical cavity lengths, and decreasing the time required to get back to the observing state in case the locking breaks. This ALS system will employ auxiliary frequency doubled Nd-YAG lasers to sense the lengths of the fabry-perot cavities in the arms independent of the rest of the interferometer. This ALS readout will be used to suppress the residual arm motions to less than 1nm rms, and also detune the arm cavities off resonance with the primary science laser, so that the central degrees of freedom can be locked. Enhancing this system for laser locking holds the potential to increase the number of detections significantly (∼1 per week) due to increase in the time the detector is in observing mode. Previous work on ALS at the 40m lab has focused on feasibility and initial implementations of a digital control system.

Ultimately, the goal is to reduce the ALS noise in order to achieve a much more stable locked IFO state faster. This system has many underlying loops in place which contribute to the RMS or noise spectrum. Identification of the noise contributors is the most crucial step in this process - which is why noise budgeting is so important. It is basically making a catalog of all relevant noise terms in order to explain the observed noise.

The golden triad of Noise Budgeting:

- Noise measurements: collecting data from individual sources under same experimental conditions
- Transfer Functions: applying any open/closed loop transfer functions
- Calibration: converting the measurement to noise in frequency units

Noise budgeting is what the first step for the Sum Frequency Generation would also be and I am planning on eventually transitioning to that, hence helping in both areas of the project. Due to material unavailability and progress of the current ALS project, the effort to carry out a proof of principle sum frequency generation needs to be put on hold. There are steps to getting there, which do not require all the material - like noise budgeting and thermal lensing effects to be dealt with. These will be the focus of my efforts.

2 Theory: Interferometers, Control systems and Noise

Covered the basics of Interferometry, Michelson interferometer, Degrees of freedom involved ie. Common Arm length, Differential Arm Length, Power Recycling Cavity, Signal Recycling Cavity, Auxiliary Lasers and their place in the locking process. [1]

Below is an excellent summary of the aLIGO interferometry as found in [2]:

The X and Y arms are 4-km long, Fabry-Perot cavities formed by the highly reflective end test masses and partially transmissive input test masses. Pre-stabilized laser (PSL) light enters the detector from the left, and is further stabilized using an input mode cleaner optical cavity. Cleaned light then enters the Power Recycling Cavity (formed by a partially transmissive input coupler and two high reflectors), is split by a 50/50 beamsplitter, and sent into the long arm cavities where the light interacts most with the potentially changing gravitational field. The light returning from the arm cavities interferes at the beamsplitter, and is then extracted from the beamsplitter's antisymmetric port by the Signal Recycling Cavity (SRC), similarly formed by two high reflectors and a partially transmissive output coupler. Finally, light exiting the SRC is cleaned with an additional resonant cavity, referred to as the "output mode cleaner". Faraday Isolators (FI) are used for optical isolation of the main interferometer from the rest of the instrument. The transmitted light of the output mode cleaner is split onto two photodiodes, whose output current is turned to voltage, conditioned, digitized, de-conditioned digitally, and then linearly combined to form derr.

Control systems are important for the lock acquisition of the interferometer. I learnt the fundamentals of Feedback controls [3], Signal Processing [4], Linear Systems Analysis and PDH Technique [5].

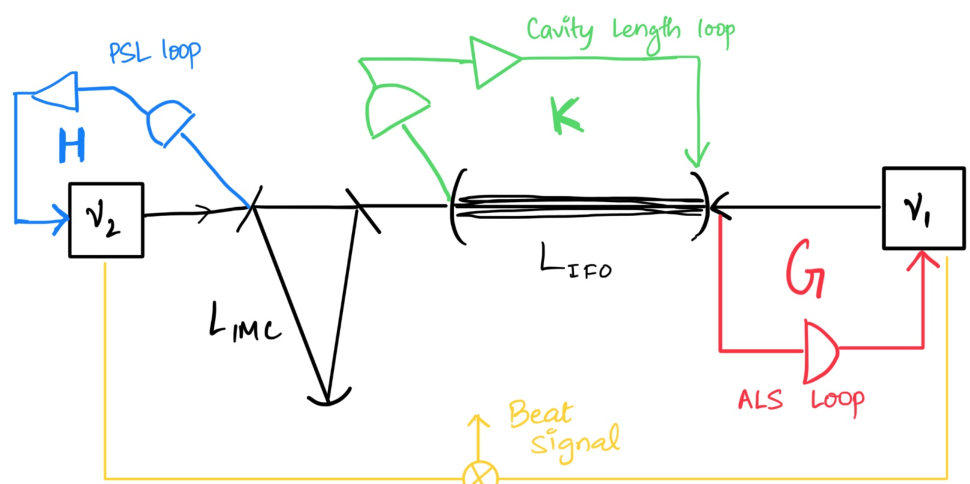

Figure 1: These are the feedback loops involved the the beat signal generation process. L-IMC and L-IFO are the lengths of the input mode cleaner and interferometer arm respectively. G, H and K are the transfer functions of the corresponding loops.

The beat signal is constructed by the difference in output of the PSL and the AUX Laser ($\nu2$ and $\nu1$ respectively in Fig. 1). In order to identify the sources contributing to the out of loop ALS noise (Fig. 2), we first need to consider all the couplings and feedback loops separately. This needs to be done for both arms separately as the loops may be the same, but the extent of noise can vary due to seismic motion acting differently or electronics noise for example.

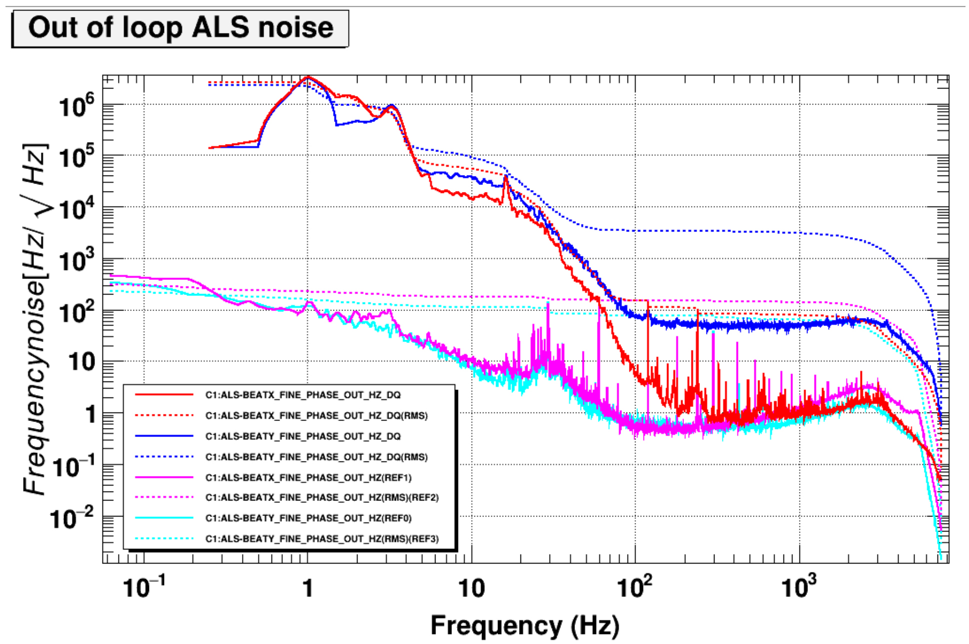

Figure 2: Out of loop ALS Noise

I examined the seismic coupling in YARM, and the AUX REFL PD loop in XARM (Fig. 3).

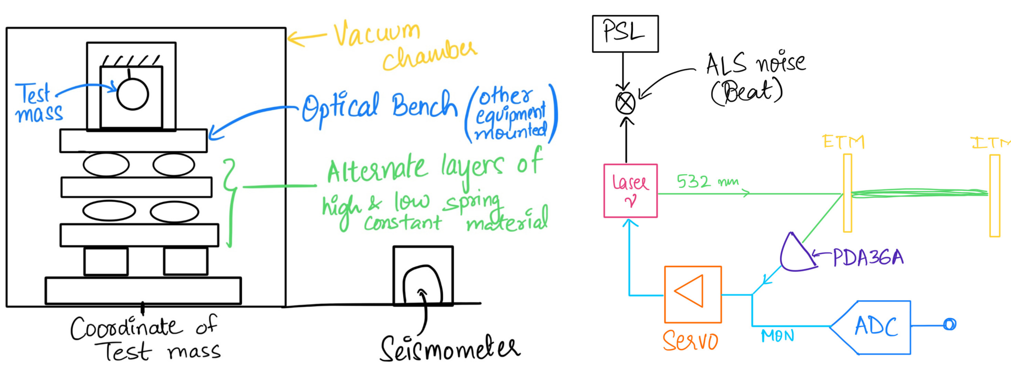

Figure 3: The left diagram is a schematic of how the seismic noise reaches the test mass. The right part is a feedback loop diagram of the AUX Laser.

3 Noise budgeting: Seismic and AUX REFL PD feedback loops

3.1 Seismic coupling

Noise budgeting the seismic part involved examining the coherence between the YBEAT and the seismometer input ie. PEM-SEIS channel. This was done by measuring the data of both the seismic channels as well as the YBEAT. The YBEAT is already strain data but the SEIS channel output is uncalibrated.

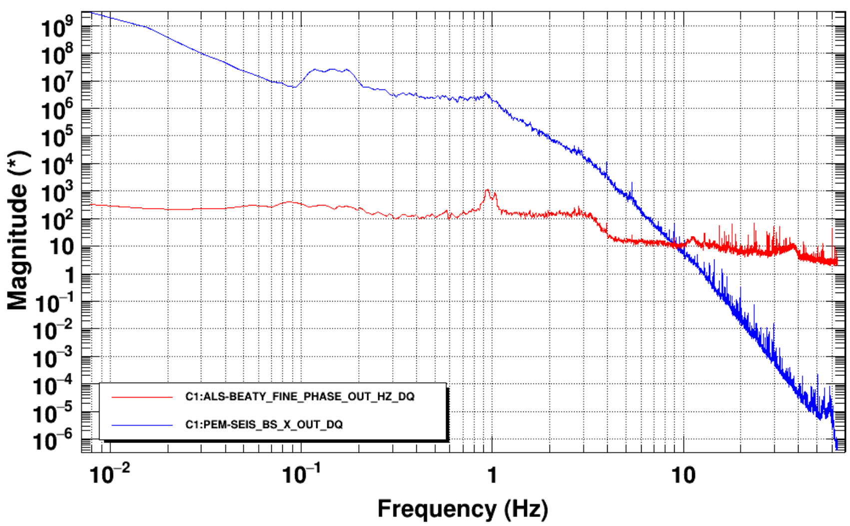

Figure 4: Seismic and Beat signal power spectral densities in units of $Hz/\sqrt{Hz}$

Calibration involves unit conversions - first we find what the seismometer actually measures using the sitemap interface, and it turns out to be the ground speed in μm/s. We can get the displacement adding poles of the Laplace transform at 0, 1, a second order pole at 30 and use the relation $S\_L = S\_\nu * (L/\nu)$ to convert it to the units we need it in. The transfer function is calculated as per the loop configuration for that particular state while taking the measurement. The calibrated PSDs are shown in fig. 4.

3.2 AUX REFL PD feedback loop

The REFL output is the reflection of the AUX laser. It underwent an inversion at the ADC, so we changed the gain to invert it to display a positive value. We also observed an offset, blocked the REFL PD physically to check if the offset we saw on ndscope was due to the PD, but it was electronic and didn't have anything to do with the PD.

The process had 4 stages:

- ADC + PD noise. Connected the output of the REFL directly to the ADC - broke the feedback loop by disconnecting it from the servo thus not considering controls noise.

- ADC noise. Connected a 50 Ohm terminator resistor to the ADC in place of the REFL Monitor cable.
- ADC + PD + REFL noise. Connected the REFL monitor cable back to the ADC.
- Complete loop: ADC + PD + REFL + Controls noise. Closed the full loop including servo connection.
- Complete loop at a higher transmission coefficient value.

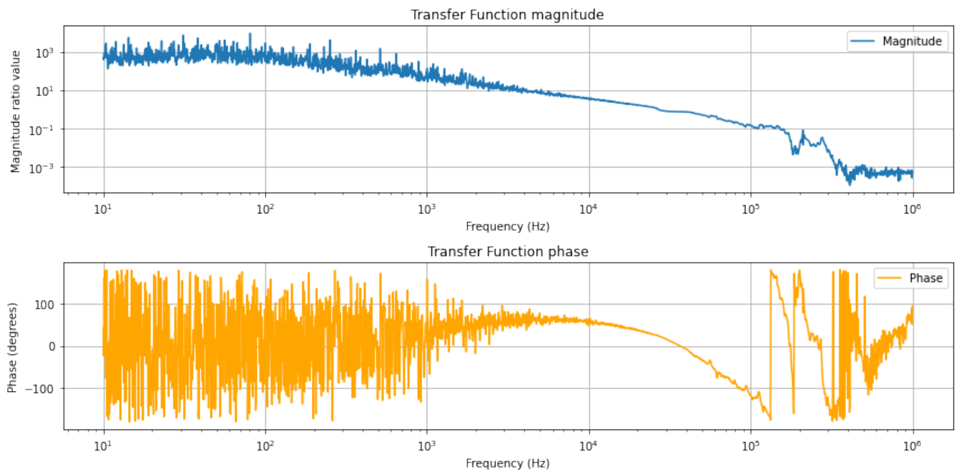

Figure 5: Bode plot of the X AUX system Open loop transfer function

To calibrate the measurements I have for the X AUX REFL PD loop, I measured the X AUX system's open loop transfer function (OLTF) by adding at injection at the error point to get the signal before and after the injection, the ratio of which gives us the OLTF (Fig. 5). I also took a reading of the PDH error signal to calculate the PDH Slope which I need for calibration.

The calibration is to be done from counts - as recieved through the ADC - to hertz. The ADC has a 20V range over 2^{16} bits. This allows us to convert to volts and then we use the PDH slope information to convert to Hertz. This works since the PDH slope is the ratio of the peak to peak voltage in volts and FWHM in hertz. V_{pp} was measured to be 400 mV. The calibrated plots are shown in Fig. 6.

3.3 Measurement and code

For the seismic measurement I used the sitemap MEDM controls to get the relevant information such as channels names, and used NDS2 to get the data at the gps time when YARM was locked.

To get the data needed for the AUX REFL PD loops as well as for calibration, I used the Moku Go FPGA based device. I played around with the device functionalities, the implementation, and how to take readings from it. There was a major roadblock when I

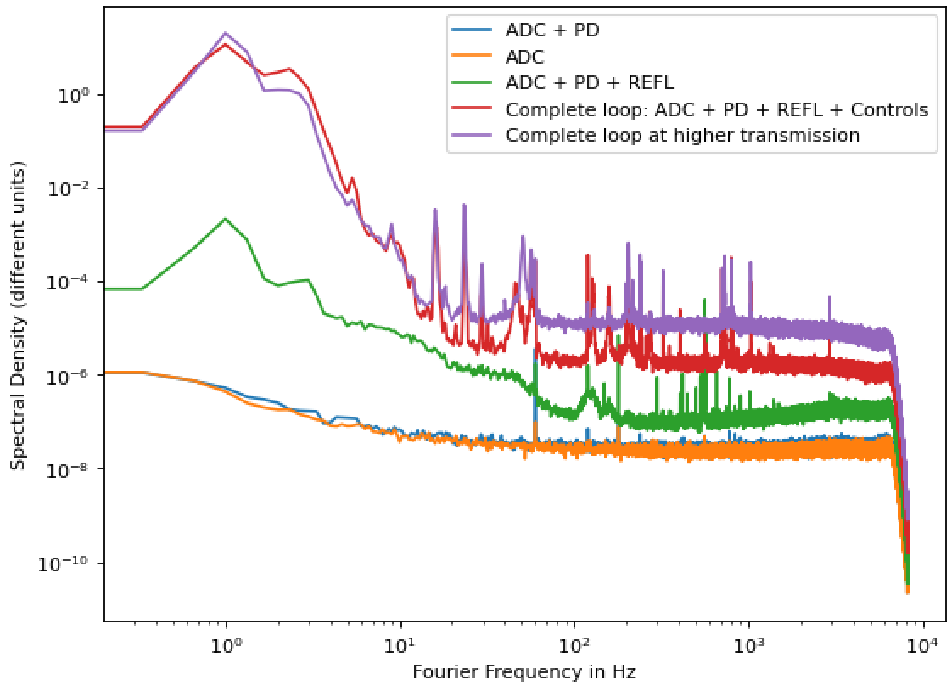

Figure 6: PSD vs Fourier Frequency for different parts of the X AUX feedback loop as indicated

couldn't get the Moku to interface with the 40m laptops with linux. But I used it with the ipad and it worked fine. So I did 2 tasks to familiarize myself with the Moku: Measured the Johnson Nyquist noise using a 50 Ohm Terminator resistor. Measured the transfer function of a low pass filter.

In both cases I analyzed the data collected using a Python script I wrote to generate the power spectra and carry out the frequency response analysis. In some cases I also used 'diag', a command line tool developed at LIGO for doing spectrum measurements and transfer functions on the systems.

4 Other areas of focus

4.1 Locking of the LIGO 40m interferometer

Locking of the 40m interferometer arms and ALS is done from the control room using the MEDM 'sitemap', which has screens which let us interface with the interferometer remotely. There is a specific order followed to lock the IFO efficiently. I ahve worked on familiarising myself with these different controls and basic steps to lock the interferometer.

4.2 Vacuum pressure checker

The vacuum system in the 40m LIGO requires liquid nitrogen to hold the pressure at about 70 psi. These liquid nitrogen tanks last for about 2 to 3 days and need to be replaced regularly. There is a danger to the system if the pressure falls low due to the Nitrogen tanks not being replaced. I am in the process of writing a python script which acts as a checker to send out a notification when the pressure falls below a certain threshold.

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