

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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**Progress Report 2: Developing
Features for Gravitational Wave
Detector Characterization
LIGO-T1600335**

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1 Abstract

The goal of this project is to develop new tools and improve previous methods of gravitational wave detector characterization by making use of data obtained from the 40m LIGO interferometer at Caltech. The purpose of detector characterization is to provide an understanding of noise sources and convey information about the state of a detector and its surroundings. This knowledge is fundamental to distinguish an astrophysical signal from noise and thus make a detection. This project will contribute to such efforts by developing interactive plots for summary pages produced, a feature that will allow for detector characterization data to be presented more clearly and more accessibly on the summary pages. This new addition may help us better gauge the significance of future detections. Additionally, this project will also involve developing a system to measure the acoustic noise of the interferometer to further improve detector characterization. The goal will be to set up multiple microphones and amplifiers along the interferometer to eventually study the coupling of acoustic noise to the differential arm length of the interferometer. Furthermore, a new tab for the acoustic noise measurement will be added to the online summary pages.

2 Background

In 1915, Einstein published his theory of general relativity which described gravitational forces as the curvature of four-dimensional spacetime. He found that the effects of gravity on a particle can be explained as resulting from its movement in a geodesic, a "straight line" in curved spacetime. Furthermore, similar to the radiation of electromagnetic waves from accelerating charges, Einstein found that the vacuum solutions to his field equations supported waves of oscillating strains in spacetime, travelling at the speed of light. [7]. However, unlike dipolar electromagnetic waves, gravitational radiation is quadrupolar, meaning that the waves compress spacetime in one direction and elongate it in a plane perpendicular to the direction of motion. The quadrupolar nature of gravitational waves can be derived from the multipole expansion of a system's distribution of mass, as both the monopole and dipole terms must be eliminated due to conservation of mass and conservation of linear and angular momentum, respectively. Although any accelerating mass quadrupole produces gravitational radiation, the amplitude of this gravitational strain is very small, on the order of 10^{-21} , and thus difficult to measure.

Advances in technology from Einstein's time have allowed for the detection of gravitational waves to become a reality, as seen through the first direct observation of gravitational radiation, event GW150914, by Advanced LIGO on September 14th, 2015 [1]. The Advanced LIGO detectors are extremely precise modified Michelson interferometers (see Figure 1) which measure the changes in the length of the 4-km-long arms of the interferometer by determining the phase shift of the light from the different arms upon recombination. The central component of the interferometer consists of a 50/50 beam splitter that is illuminated by a laser source. The transmitted and reflected beams travel through perpendicular paths and are reflected by end mirrors to recombine at the beam splitter. Because strain is inversely proportional to the original length, increasing the length of the arms has the effect of increasing the strain sensitivity of the interferometer. However, as increasing the length of

the arms indefinitely is not feasible due to terrestrial constraints, mechanisms for effectively lengthening the interferometer are used. Fabry-Perot cavities are used to increase the path length of the light and effectively lengthen the arms of the interferometer [5].

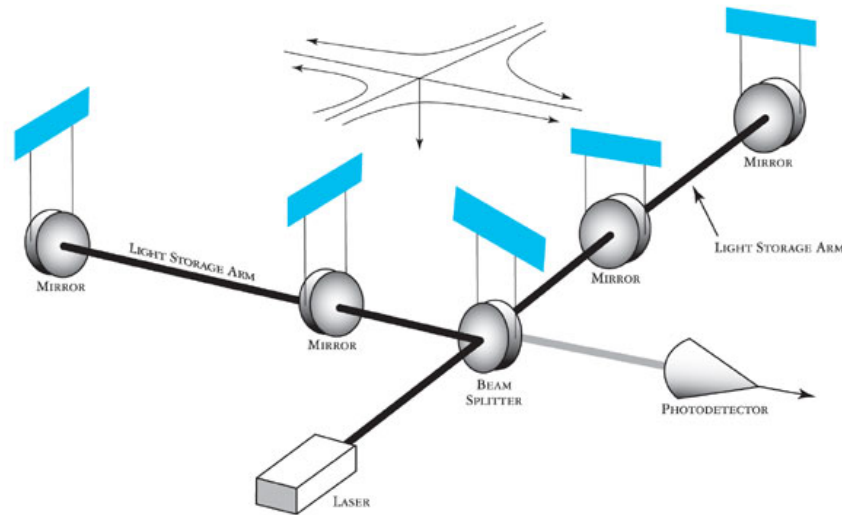


Figure 1: Advanced LIGO optical setup [6]. The arms of the interferometer are 4 km long but the distance the light travels is increased using Fabry-Perot cavities.

During operation, a data channel which transmits a measure of the gravitational wave strain is calibrated by determining the detector's response function, or the relationship between the raw data output and the strain of the arms of the interferometer. This is accomplished by making a model of interferometer response, calibrating the mirror actuator, and monitoring interferometer response. Using this method of extracting gravitational strain data, the Advanced LIGO detectors are able to measure small enough strains in the interferometer arms. The Caltech 40m interferometer operates in a similar manner although the length of the arms is 100 times smaller. This instrument is used as a small-scale prototype for the larger detectors in Hanford, Washington, and Livingston, Louisiana. If new features added to the data analysis or instrument operation procedures of the Caltech 40m are successful, they may be implemented into the larger interferometers.

However, because of their extreme sensitivity, the LIGO interferometers have many noise sources due to both the external environment and inherent disturbances from the experimental design. These noises are categorized as either displacement noises which directly move the suspended mirrors or sensing noises which affect the readout signal without actually moving the mirrors. Some forms of displacement noise are seismic noise, thermal noise, and noise caused by radiation pressure resulting from variations in the power of the input laser source. A few examples of sensing noise are laser amplitude noise caused by power fluctuations, noise from vacuum fluctuations entering the interferometer, and readout noise from the electronics themselves. By effectively characterizing these sources of error and observing the signals caused by them, the LIGO operation is made possible. Without being able to determine which parts of a signal are significant and which are the results of noise, no useful data can be obtained.

Detection of gravitational wave signals is useful for applications in gravitational wave astronomy as well as for improving our understanding of gravity. Just as the ability to detect forms of electromagnetic radiation outside the visible spectrum provided numerous insights into astrophysical processes that could not be observed through visible light, gravitational radiation is able to penetrate regions of space that even electromagnetic radiation cannot. Therefore, an improved ability to detect gravitational waves would allow for a greater understanding of processes such as the merging of black holes or the evolution of binary neutron star systems. Furthermore, studying gravitational wave signals will likely lead to the discovery of astrophysical processes whose existence researchers are currently unaware of. Additionally, detecting gravitational waves allows for confirmations of the predictions of general relativity, a theory which is very difficult to test in a lab setting. However, by analyzing signals and producing simulations, gravitational wave detection functions as a technique to study general relativity using the universe as the laboratory.

3 Objectives and Approach

Because the status of the Advanced LIGO detectors is constantly changing, detector characterization is required to change along with it. Thus, the mechanisms used to provide information about the detectors, such as summary pages, must be regularly improved and enhanced with new features. Currently, the 40m detector summary pages are updated twice per hour using a cronjob, a scheduled execution of a shell command, called `gw_summary`. HTCondor, a parallel computing utility which allows many computers to process the data at once, is also used in order to generate daily pages from large amounts of data. The pages are generated by using the `gw_summary` command line executable to parse given configuration files with the `.ini` format and produce `.html` files. The configuration (`.ini`) files consist of a series of key-value pairs which determine the characteristics of the pages, such as what types of plots are included, the layout of the plots, the data channels used, and more [14]. After being written to a `.html` file, these summary pages display in a browser information through static plots from numerous auxiliary channels which describe the state of the detector and its environment, along with the gravitational wave strain data [2, 3]. The pages are currently used by both people who work at the Caltech 40m on improving the interferometer and people in detector characterization, in both cases mainly for the purpose of quickly diagnosing issues. An example of the current state of the summary pages is given below in Figure 2, which shows a plot from the July 7th page.

Figure 3: CDS FE STATUS MEDM screen from the 40m. This screen conveys information about the health of the 40m Realtime Control Front-End Machines.

A current limitation of the summary pages is that, when data goes awry or does not make sense, there is not a great deal of information regarding the physical state of the detector and its components. This can be helped by implementing an automatically-updating new tab which displays screenshots of important MEDM screens and displays them on the summary pages. This new feature will hopefully increase the usage of the summary pages at the 40m and give the data more context. To create this new tab, scripts written by Yoichi Aso, a former researcher at the 40m, will be modified and formatted to upload screenshots to the summary pages. These scripts had been previously set up to take automated screenshots of the MEDM screens but their use has been discontinued. I will be working on getting these scripts to run from the current network setup and figuring out how to get the summary pages to include these screenshots.

To measure the acoustic noise of the interferometer, previous work will be expanded upon and new features will be tested. The purpose of measuring the sound levels at the interferometer is to observe the coupling of the acoustic noise sources to the interferometer. This way, we can eventually cancel out the effect of these acoustic sources using a feedforward loop. Earlier investigations into measuring acoustic noise have given me a background for where to start in this project. The following circuit schematic was used by previous graduate students at the 40m, although there were some possible issues and elements that seemed like they could be improved.

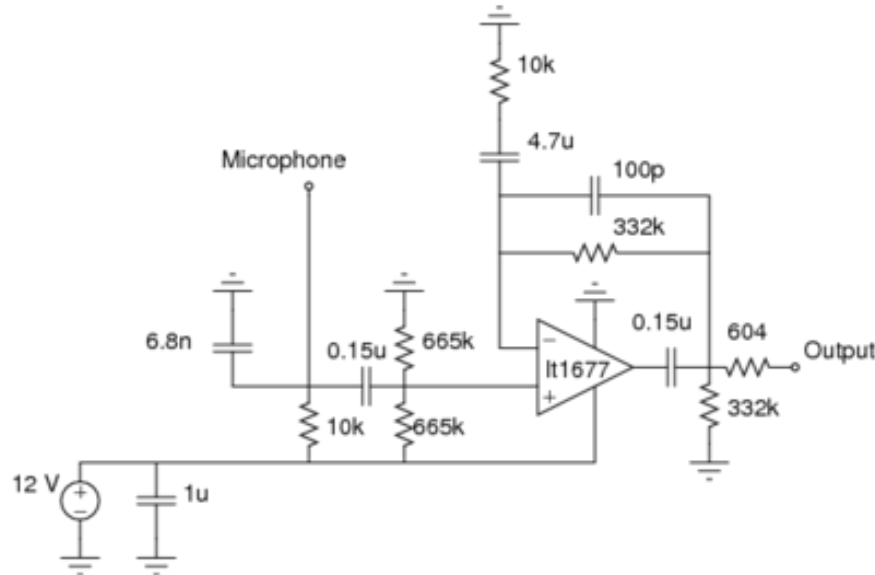


Figure 4: Original circuit schematic by Denis Martynov. Pin 4 from the LT1677 goes to ground rather than being given a negative input voltage. This cuts the range of the opamp in half, which may not be an issue if the signal is completely positive.

In this project, I will be modifying this circuit as well as creating a different system for measuring the acoustic noise. Previously, the setup consisted of placing six microphones around the interferometer and connecting them all back to the same amplifier box, which contained six of the above circuit, and then reading out the data. However, this system may have resulted in more noisy data due to having the unamplified signal travel a long distance to the amplifier box. To the unamplified signal, noise in signal travel could be relatively large. This noise would then be amplified and could make distinguishing between noise and signal difficult. This problem can be avoided by amplifying directly at the microphone so that less noise is picked up and amplified. To do this, I will be making individual amplifier boxes to which each microphone can be mounted. This hardware will be placed at locations around the interferometer to reduce some signal travel time. I will be putting a single one of my modified amplifier circuits in each new amplifier box. The end goal of this project will be to have data channels set up to measure the acoustic noise at locations around the interferometer and to include a new tab on the online summary pages for acoustic noise. This data may assist in measuring the coupling of acoustic noise to the differential arm length at the 40m.

4 Milestones and Ongoing Work

To this point, I have succeeded in learning how to generate the current format of summary pages from both the 40m lab computers and the LIGO clusters. As such, I have gained a knowledge of the command line tools for summary page generation and use of configuration files. I have learned how to write my own configuration files and have added a tab to the main Caltech 40m summary pages to display a suspension coil voltage monitor. Additionally, I have learned how to create tabs based on external html pages, a tool which will be incorporated into creating a screen capture tab for the MEDM status screens. Various amounts of

data have been tested and pages have been created from both Caltech 40m and Livingston site data. Additionally, HTML5, XML, and JavaScript have all been learned at a basic level, which should enable me to continue forward in developing an interactive component, as this new feature will be created using these languages. Figure 3 shows an example plot from the new voltage monitor tab that has been incorporated into the main summary pages.

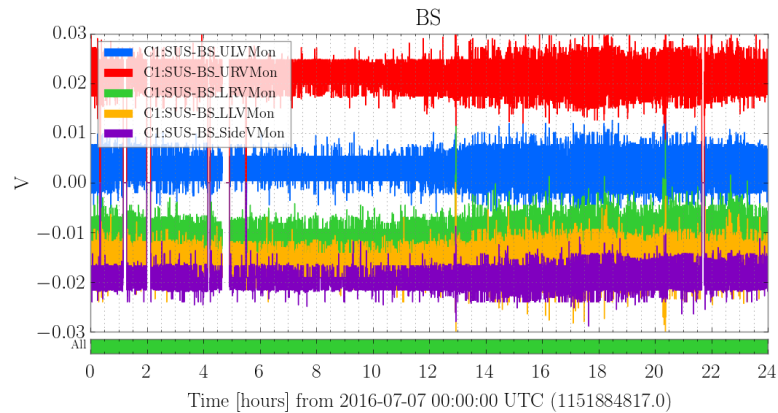


Figure 5: Beam splitter (BS) suspension coil voltage monitor from July 7th page [12].

Furthermore, in these last three weeks I have succeeded in implementing an MEDM screen tab onto the online summary pages. This tab displays some the screens that researchers at the 40m find most useful and updates every 15 minutes. There are a few minor tweaks still to be made to the page, but it is now functional and running. A screenshot of this new tab is given below.

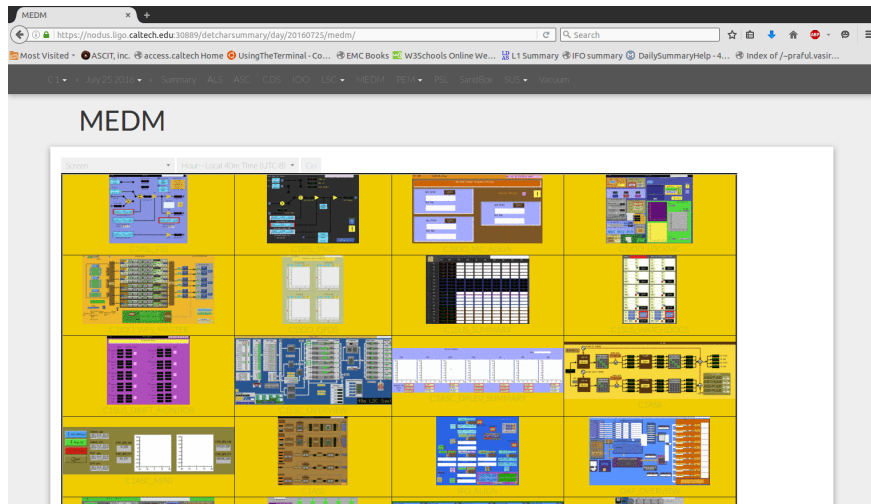


Figure 6: New MEDM tab on online summary pages. The page displays important screens and includes an archive lookup system to search for a particular screen on a given day.

The main difficulties in implementing this MEDM screen tab were setting up the cronjob, which schedules when the scripts to capture the MEDM screens, and configuring the virtual display of the screens. These issues were solved through ensuring that terminal environment variables were set up correctly and explicitly specifying the locations of windows in the virtual display so that the screen capture scripts could find the desired MEDM screens.

Additionally, for the past week and a half, my project has consisted of testing the microphone amplifier circuit built by Denis Martynov and making changes to it. After initially setting up the original circuit, I noticed some clipping issues in the signal through the amplifier. Though the circuit was fed in a sinusoid from a function generator, the output would be a truncated and amplified sinusoid. I attempted to fix this issue by adding a negative input voltage to pin 4 on the opamp. This new addition fixed the clipping issue and produced amplified sinusoids after again being given input from a function generator. However, when the microphone was attached to this new circuit, I ran into more problems such as incorrect voltage readouts along resistors and the output not actually being amplified. I decided to try implementing a different, simpler amplifier circuit to see if my problems could be fixed. The new circuit that I have implemented is shown below. This circuit satisfies the design requirements of the previous circuit from which I could not obtain an accurate transfer function. These requirements include a high-pass filter at 7 Hz and a low-pass filter with a cutoff frequency of 23 kHz. The rolloff, or the steepness of the decline of the gain at frequencies outside of the passband, can be adjusted as well.

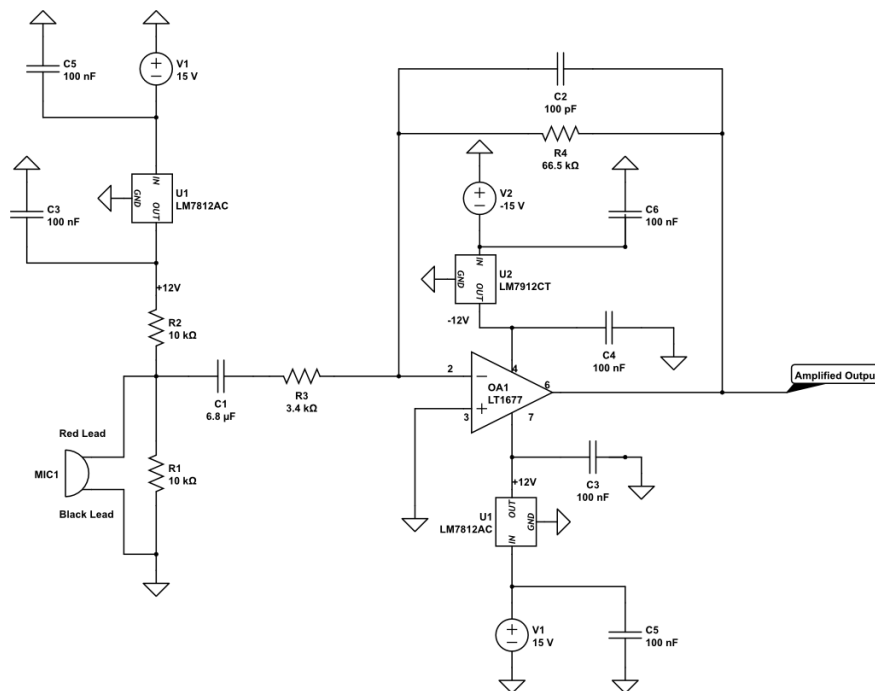


Figure 7: New amplifier circuit to be tested. This circuit includes negative input to pin 4 and includes bypass capacitors from the voltage supplies and power regulators.

Using this circuit, I have been able to successfully amplify microphone input, such as sinusoid tones from audio generators. This circuit can be easily changed to include different cutoff frequencies and increase or decrease the gain by changing the values of the resistors and capacitors. I have also verified that the passband of the amplifier circuit works as expected by measuring the transfer function. I have set a high-pass filter at 7 Hz and a low-pass filter at 23 kHz. The transfer function is given below.

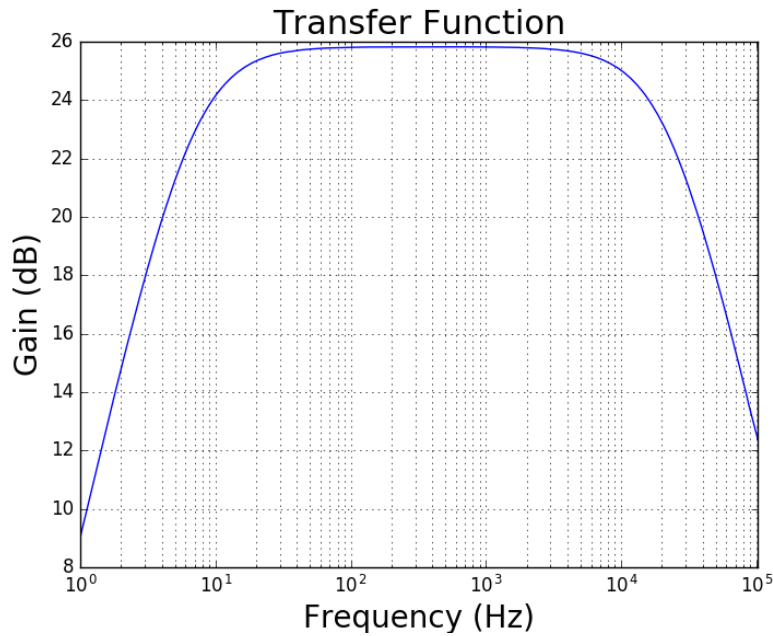


Figure 8: Transfer function of new inverting amplifier circuit. The passband works as expected with a decrease in gain at frequencies smaller than 7 Hz and larger than 23 kHz.

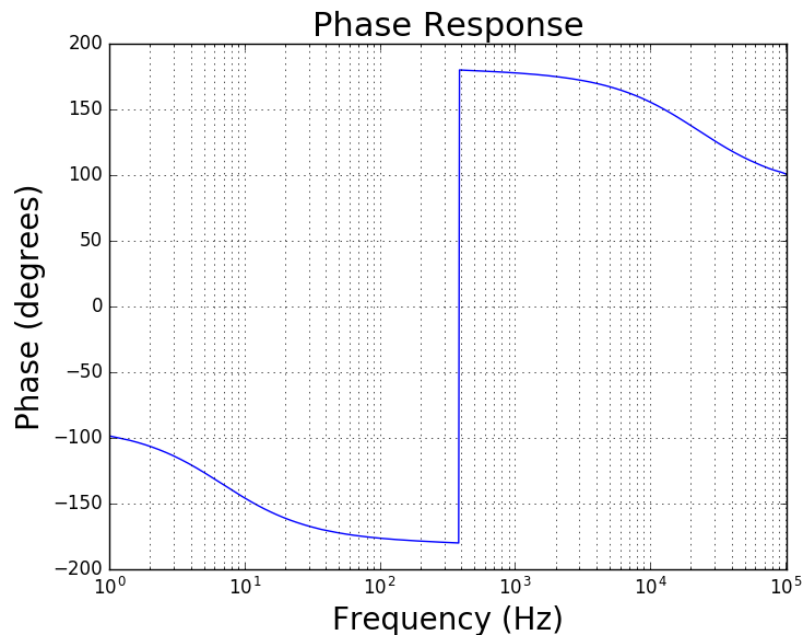


Figure 8: Phase response of new inverting amplifier circuit.

I have also been able to take a spectra of a microphone attached to this new amplifier circuit inside and outside a large box filled with foam to block out acoustic noise. The spectra are given below.

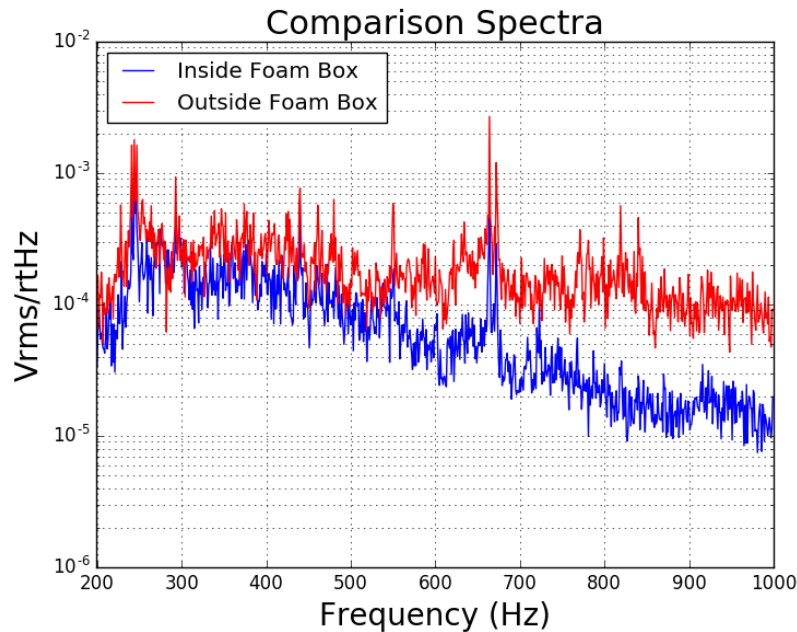


Figure 9: Spectrum of EM172 microphone inside and outside foam box. The two major frequency peaks are at about 250 Hz and 650 Hz.

Currently, my project consists of designing a new amplifier box for the microphones, figuring out where and how to suspend these boxes, and designing an optimal circuit.

5 Microphone Project Plan

- The microphones will be suspended because, if the box has enough weight, it will be isolated from ground motion. Seismic motion is low frequency, below 100 Hz, so a large enough mass is necessary to decrease the cutoff frequency above which the box will oscillate less, as this cutoff frequency decreases with increasing mass. Additionally, a heavier box reduces movement from wind from air conditioning. Overall, the point of measuring the acoustic noise is that it is noise in a different frequency band than seismic noise, so the current systems to reduce seismic noise are not applicable. Finally, the locations of the microphones are determined by proximity to known noise sources (fans, electronics racks, etc.) and to important points along the interferometer in order to study the coupling of the acoustic noise to interferometer readout.
- Finish designing an amplifier box, create multiple boxes. A preliminary design for the box is given below.

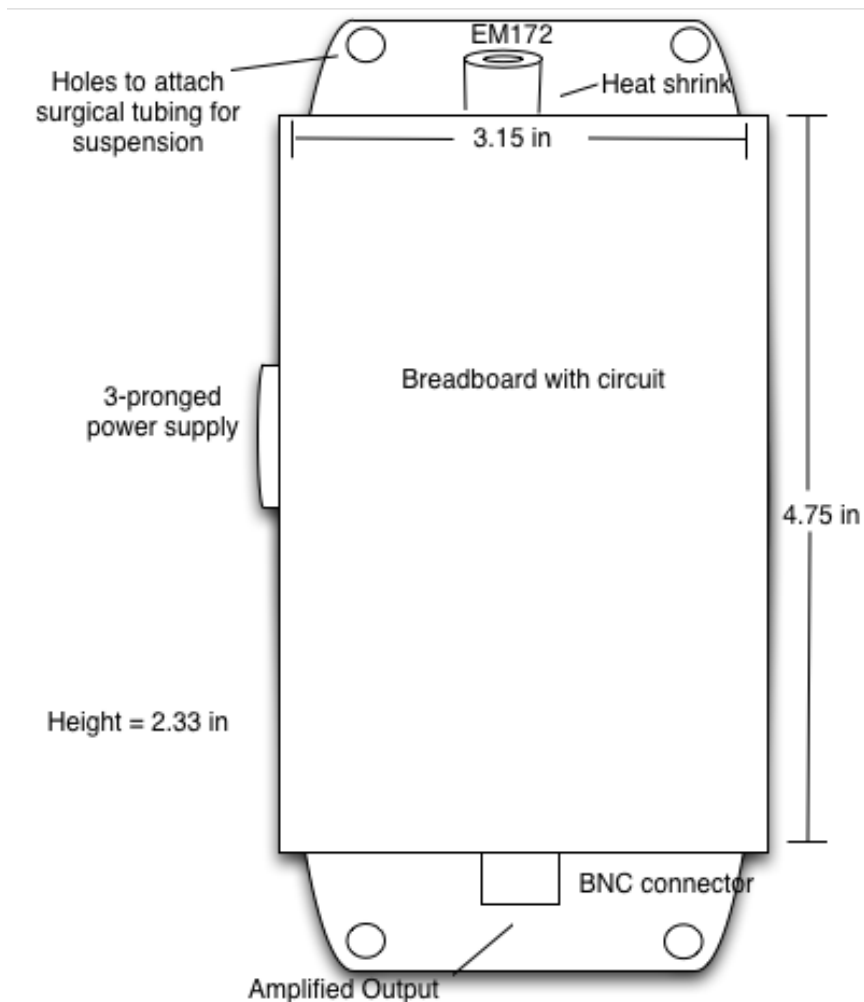


Figure 10: Bottom view of preliminary design for individual microphone amplifier boxes. Surgical tubing will be used to suspend the box and heat shrink will be used to help connect the microphones directly to each circuit.

- Suspend amplifier boxes at the following locations: PSL table, AS port table, mode cleaner, mid points of both arms, ends of both arms, Ex table, Ey table, flow bench, vacuum pumps along x-arm, each electronics rack, and air vents.

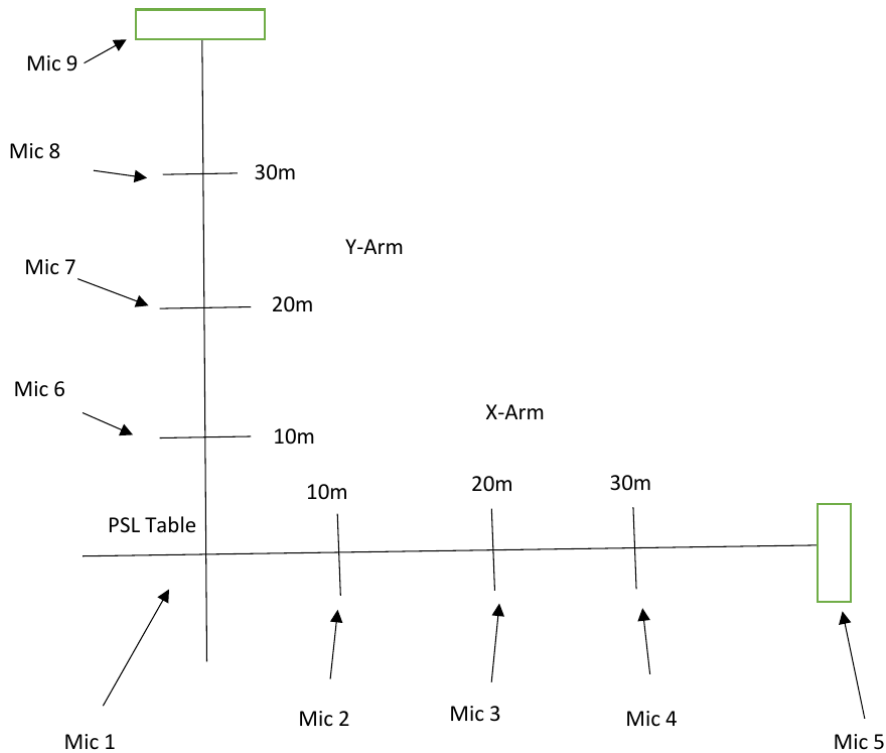


Figure 11: Microphone layout at the Caltech 40m. Microphones will be placed both at important locations of the interferometer and near noise sources to study coupling of acoustic noise to the interferometer.

- Set up data channels for each microphone.
- Add a new tab to the summary pages for acoustic noise.

6 Prospective Timeline

- **Week 1:** Learned how the summary page code of gwsumm works, generated test pages, learned the basics of HTML and JavaScript.
- **Week 2:** Created a new tab on the summary pages to display the readings of the suspension coil voltage monitors, started looking into how the existing MEDM screen capture scripts worked.
- **Weeks 3-5:** Created a new system to implement the MEDM screen capture scripts onto the online summary pages.
- **Weeks 6-7:** Tested and modified microphone amplifier circuit.
- **Weeks 8-9:** Create new amplifier boxes and mount microphones, set up microphones around the interferometer, set up data channels for microphones, add a new tab to the summary pages for acoustic noise.
- **Week 10:** Finish up loose ends on MEDM tab, finish any work left on acoustic noise project, work on presentation and paper.

7 References

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