Progress Report 1: Developing Features for Gravitational Wave Detector Characterization
LIGO-T1600292

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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.

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].

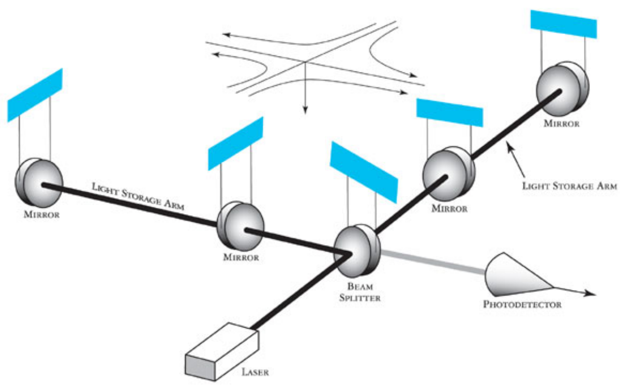

Figure 1: Advanced LIGO optical setup [6]. The arms of the interferometer are 4 km long but the distance the light travels is increased using Fabry-Perot cavities.

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.

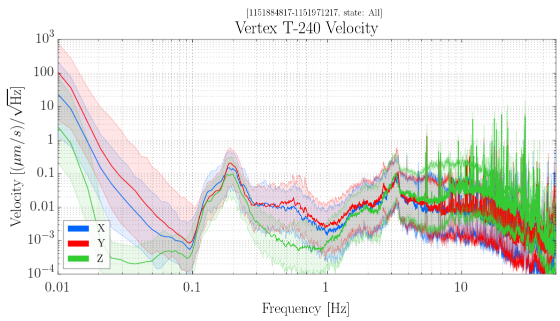

Figure 2: Physical environment monitoring (PEM) seismic data from July 7th [11]. Currently the plots are displayed as static .png files.

This project will involve developing an interactive component to the plots on these summary pages to allow viewers to obtain key data more easily and quickly. For example, if the plot was a time series, this project aims to produce a page where, by hovering over a given point with a mouse, the user is able to view the GPS time at that point. This new element of the pages will be tested using data from the Caltech 40m prototype interferometer. Thus, this work will involve a mixture of data analysis and instrument science, as an understanding of the interferometer's functions is necessary for interpreting the data received.

To develop new features on the summary pages, Python, JavaScript, HTML5, and XML will be used to write code to add a component of interactivity to the pages. The python package `gwsumm` will be used to handle web-page and plot generation on the summary pages of 40m interferometer data [8]. `gwpy`, another python package, will be used to load and handle LIGO data [4]. `gwsumm` will be modified during this project to include an interactive plotting feature. These new methods will then be tested using data from the 40m prototype interferometer, which will relate whether or not they are useful modifications. Overall, the goal of this project will be to produce plots which the user can easily obtain the important data from through interaction with the figure.

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.

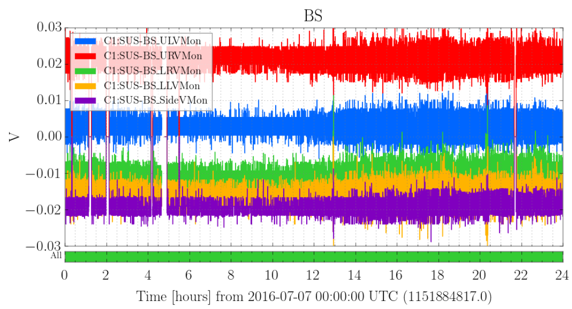

Figure 3: Beam splitter (BS) suspension coil voltage monitor from July 7th page [12].

Currently, the project consists of learning how new plots are created and registered in `gwsumm`. This information will mainly be gained through going through the current code and understanding how the process works. In order to make any substantial changes to the current framework of plot generation, that system must first be understood and replicated. Also, I am working on adding another tab which makes use of a script to take screenshots of the MEDM status screens and displays them on the summary pages as embedded html pages. This will consist of configuring a crontab and linking a new .ini file to display external webpages from a tab.

5 Short-Term and Long-Term Goals

In the next three weeks, this project should advance to the stage of understanding the plotting process of `gwsumm` and having a basic knowledge of how interactive plots, such as the HVETO figures created by Duncan Macleod [9], are generated. An example of one of these HVETO plots is shown in Figure 4.

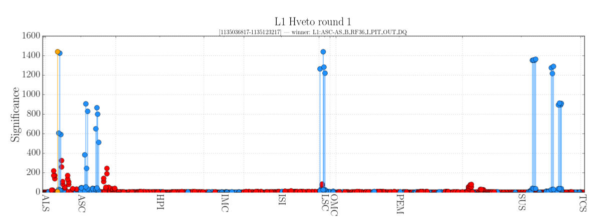

Figure 4: L1 Hierarchical Veto, December 25th, 2015. The interactivity can be seen by going to the referenced link in a browser and hovering over any data point [13].

Interactive plots like these are useful because they allow users to easily determine and quantify the important features of a plot and observe the format and source of the data, such as the channel the data was collected from. Adding interactivity such as in the HVETO plots will require learning how to use Scalable Vector Graphics (SVG), an XML-based image creation format [10]. Therefore, a basic knowledge of how to implement SVG should be obtained in the short term. Additionally, some modifications should be made to the python packages by that time which begin to set the foundation for interactive plotting.

In the long term, this project should have a completed, working example plot which displays the interactive features sought by those involved in detector characterization. The main example plot which will be sought is a time series which displays to the user the GPS time upon hovering over a data point with a mouse. In order to create this plot, SVG will be implemented.

The overall timeline of my project also includes incorporating the MEDM status screen captures into a tab on the main summary pages and setting up a microphone to measure the acoustic noise and adding that channel into the summary pages, in addition to the project goal of creating interactive plots.

6 References

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[10] SVG. https://developer.mozilla.org/en-US/docs/Web/SVG

[11] PEM: Seismic. https://nodus.ligo.caltech.edu:30889/detcharsummary/day/20160707/pem/seismic/

[12] Suspension coil voltage monitor (VMon). https://nodus.ligo.caltech.edu:30889/detcharsummary /day/20160707/sus/vmon/

[13] L1 Hierarchical Veto, December 25th, 2015. https://ldas-jobs.ligo-la.caltech.edu/~duncan.macleod /hveto/day/20151225/plots/L1-HVETO_SIG_DROP_ROUND_1-1135036817-86400.svg

[14] A whistle-stop tour of the INI format. https://ldas-jobs.ligo.caltech.edu/~duncan.macleod/gwsumm /latest/configuration/format.html