Developing Methods of Gravitational Wave Detector Characterization

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1 Introduction

The goal of this project will be to develop new tools and improve previous methods of gravitational wave detector characterization applied to 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 new features, such as constantly updated plots and animations, for summary pages produced by data from the Caltech 40m prototype interferometer. These features will allow for detector characterization data to be presented more clearly and more accessibly on the summary pages. Another goal will be to implement a channel lookup system for the Caltech 40m that is accessible from the summary pages which will enable users to gain information about the state of a specific channel. These new features will allow future signals to be better characterized as either gravitational waves or the result of environmental noise.

2 Background

In 1915, Einstein published his theory of general relativity which described that gravitational forces act 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. Furthermore, similar to the radiation of electromagnetic waves from accelerating charges, Einstein found that the vacuum solutions to his field equations were waves of oscillating strains in spacetime [7]. However, unlike dipolar electromagnetic waves, gravitational radiation is quadrupolar, meaning that the waves compress spacetime in one direction and elongate it in another, perpendicular direction. This radiation travels at the speed of light and is the result of 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. However, 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 which measure the changes in the length of the 4-km-long arms of the interferometer and thus the phase shift of the light from the different arms upon recombination. The central component of 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 functions to increase 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].

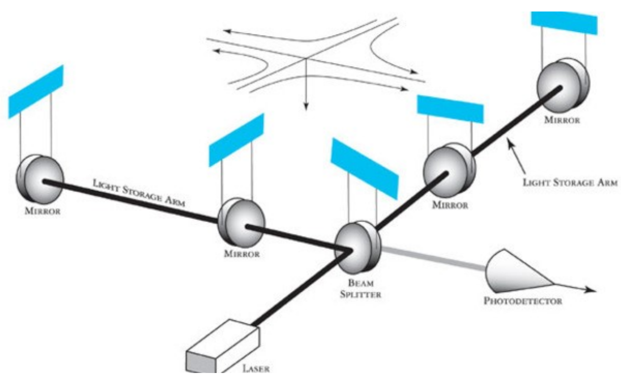

Figure 1: Advanced LIGO optical setup [6]

During operation, a data channel which transmits a measure of the gravitational wave strain on the detector 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 tracking this calibration. Using this method of extracting gravitational strain data, the Advanced LIGO detectors are able to measure strains in the interferometer arms on the order of strains from gravitational waves. The Caltech 40m interferometer operates in a similar manner although the length of the arms is 100 times smaller. The Caltech 40m 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, as with all experiments consisting of reading input signal data, 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. 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 understanding 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

This project seeks to improve the understanding of the state of a given detector in its environment and allow for more certain conclusions to be drawn from data. By improving detector characterization, extracting gravitational radiation signals is made possible. As Advanced LIGO is expected to detect multiple gravitational wave signals per year, the ability to determine whether or not a signal is a gravitational wave, and if so what its properties are, will become increasingly important. By effectively characterizing a detector, noise sources can be isolated and the number of astrophysical sources that the detector is sensitive to is increased. More efficient methods of studying and observing noise sources are therefore key to improving the the operation of gravitational wave detectors. By modifying previous methods of detector characterization and developing new techniques, this project will assist the global LIGO collaboration through improving the process of data analysis. Overall, the process of searching for gravitational wave signals would be further refined through improving methods of detector characterization, and the range of astrophysical sources of gravitational radiation that the detector is sensitive to could thus be increased.

4 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 are lifetime tools such as summary pages to which new features are added. Currently, the 40m detector summary pages are updated twice per hour. These summary pages display information from numerous auxiliary channels which describe the state of the detector and its environment, along with the gravitational wave strain data [2, 3]. This project will involve developing new features for these summary pages such as new plots and animations. These new elements 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 and Unix will be used to write code to improve the website as well as to create new plots and animations. 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]. Both of these packages will be modified during this project to improve the generation of the data summary pages. These new methods will then be tested using data from the 40m prototype interferometer, which will relate whether or not they are useful modifications. Additionally, a channel lookup system will be implemented into the summary pages so that relevant channel information can be directly accessed. This system will be added using PHP and JavaScript and will allow for individuals accessing the page to know the status of a particular interferometer data channel.

5 Work Plan

• Pre-SURF (during school year): become familiar with the code and methods of GWsumm and GWpy, learn scientific background for interferometer, begin making changes to the summary-page configuration files and observing the differences between the existing and modified pages.

• Weeks 1-3: create new plots and animations for the summary pages by further modifying the code using Python, implement a channel lookup system that provides information about the status of a given data channel.

• Weeks 4-7: test new features using Caltech 40m prototype interferometer data, refine modifications based on results, observe differences between previous detector characterization and new characterization.

• Weeks 8-10: draw conclusions based on observations, further refine data analysis methods, test modifications based on other sources of data, begin working on final report and presentation and compiling results.

6 References

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