Examining Controversy Over the First LIGO Detection

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Abstract:

The goal of this project was to evaluate the reasoning of Creswell et al. from the Niels Bohr Institute who claim that the validity of GW150914, the first gravitational wave detection from LIGO, is questionable because of various detector correlations. In order to do this, I attempted to reproduce multiple graphs from "On the Time Lags of the LIGO Signals" as well as understand the meaning behind these graphs and how they contribute to the claims made by Creswell et al.. Multiple graphs that I created using the modified LIGO Tutorials did not match the ones from Creswell et al. and this brought their claims into question.

Introduction

The existence of gravitational waves, which are ripples in the fabric of space-time, was predicted by Einstein through his theory of general relativity in 1916 [1]. These waves remained undetected for nearly 100 years until LIGO—the Laser Interferometer Gravitational Wave Observatory—found evidence of a gravitational wave in September of 2015. This discovery solidified Einstein's predictions, propelling scientific understanding about the creation of the universe.

However, controversy has arisen because an independent group of researchers from the Niels Bohr Institute in Copenhagen, Denmark believe that the validity of actual discovery is questionable due to correlations in detector noise [17]. Finding gravitational waves continues to provide insight into the creation of the universe. If there is doubt about the correctness of the detection, it has the potential to undo all of the insight into the Big Bang that these waves have provided.

In my project, I used data from LIGO's Open Science Center to examine and re-create the graphs originally done by researchers of the Niels Bohr Institute (Creswell et al.). My goal was to find evidence to counter or confirm the claims made by them and to determine if their claims could be supported by LIGO's scripts. This paper will provide an overview of gravitational waves and LIGO, as well as an evaluation of the claims made by Creswell et al.

In order to understand the ideas presented in this paper, it is necessary to have an introduction to the concept of gravitational waves and background information about the LIGO's purpose, methods, and significant events that have occurred; this is provided below.

Background

Einstein's General Theory of Relativity

Einstein's famous theory, the theory of General Relativity, states that matter curves space-time, as shown in Figure 1, and moves in a path that is straightest according to the curve of the space time, even if it is not the straightest path according to the human eye [2]. For example, if there is a star that is currently curving space time, and light from another star passes by, the light will be deflected by the first star's curvature and will travel in a curved path. To an observer, the light will appear to travel in a straight line, but in reality, it is not doing so [2]. Gravitational waves are not caused by the deflection of starlight, but they are effects of the curvature of space-time [3].

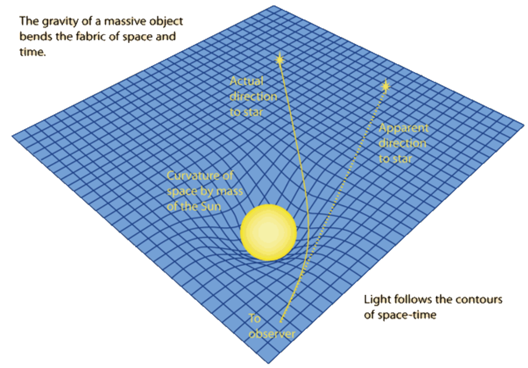

Figure 1: General Theory of Relativity reflected. Space Time is curved and light is deflected as a cause of this curvature [27].

Gravitational Waves

Gravitational waves are essentially ripples in the fabric of space-time caused by massive objects accelerating. For example, two objects orbiting each other and merging, or massive stars exploding asymmetrically, can cause gravitational waves [4]. The objects lose energy in the form of gravitational waves which travel outwards, similar to ripples created when a pebble is tossed into a pond, as shown in Figure 2 [5, 6]. Gravitational waves travel away from their source at the speed of light, distorting space as they move [7].

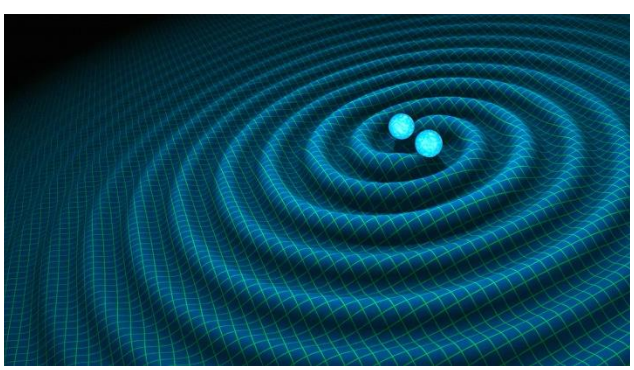

Figure 2: A representation of how gravitational waves spread out like ripples created from tossing a pebble into a pond [28].

When an explosion happens, it is an extremely violent process. However, because it happens extremely far from the earth, these waves lose strength as they travel and are extremely weak by the time they approach the LIGO Observatories [6].

Sources of Gravitational Waves

There are various known causes for gravitational waves. The four main natural causes are thought to be: stochastic background, continuous wave sources, binary inspirals, and bursts [8]. Stochastic waves would be caused by leftover remnants from the creation of the universe [8]. These waves occur randomly and are expected to be relatively small [8]. These waves could provide insight into previously unknown phenomenon regarding the Big Bang. Continuous Waves would be caused by an asymmetrical object spinning, such as a neutron star with a large deformity, releasing waves as it rotates [8]. The waves are continuous because as long as the rate that the star spins at is constant, so are the properties of the wave [8]. Binary Inspiral waves, which are also bursts, are caused by two objects rotating around each other. Burst gravitational waves would be from unknown sources because scientists are unable to make predictions about their behavior and patterns [9]. There is minimal information about this type of gravitational wave; these waves require scientists to search without knowing exactly what to expect [9].

The three currently known types are from two black holes, two neutron stars, and a black hole and a neutron star. As the two objects rotate, they lose energy in the form of gravitational waves, causing them to move closer, orbit faster, and therefore release more waves until they merge into one object [8].

Interferometer

An interferometer is the device used to detect gravitational waves. It is a combination of lasers, mirrors, perpendicular long tubes, and a photodetector as shown in Figure 3 [10]. The

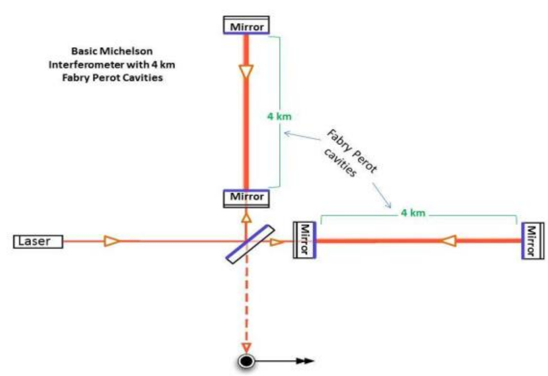

Figure 3: Michelson Fabry-Perot Interferometer which displays the path of the photo beams [29].

specific instrument used by LIGO is called the Michelson Fabry-Perot Interferometer; it has increased sensitivity and therefore is more likely to detect waves [10].

Photon beams that come from the lasers split at the first mirror, travel down the two perpendicular arms, and bounce off of the end mirrors to travel back to their original place. The resulting brightness of the recombined beams is measured by a photodetector [9].

When there is no gravitational wave, the resulting light beams are arranged so as to cancel each other out—there is no light that the photodetector senses. Because gravitational waves distort space, a wave being present causes the mirrors and arms to shift. One arm becomes longer and the other shorter. Because of this, the recombined beams no longer cancel each other out, meaning that the photodetector can detect light, indicating a signal from a wave [11].

LIGO

LIGO, short for Laser Interferometer Gravitational Wave Observatory, detects signals from gravitational waves. The two United States LIGO observatories are in Livingston, Louisiana and Hanford, Washington. They work together to confirm that a gravitational wave exists [12].

The individual observatories detect signals that occur at their respective locations, but only if the same exact signal occurs at both the Livingston and Hanford Observatories within a certain set time can it be mostly certain that it is due to a gravitational wave [12]. If only one observatory measures a signal, it is difficult to know whether it was because of a gravitational wave or another type of signal from background noise, such as earthquakes [12]. However, if the same signal is present at both observatories, then scientists will know that it was not due to a local cause—it was from a gravitational wave [12].

LIGO's First Detection

In 1974, indirect evidence supporting the existence of gravitational waves was discovered—the Hulse-Taylor Binary Pulsar [7]. Two researchers, Russel Hulse and Joseph Taylor found that a pulsar was losing energy and orbiting around another star in a way that aligned perfectly with Einstein's predictions, and won a Nobel Physics Prize for their discovery [13].

Until 2015, the only evidence that gravitational waves existed was indirect. The first physical detection that LIGO successfully made was on September 14, 2015 as a result of the collision and merger of two black holes that were 29 and 36 times the mass of the sun [14]. The actual collision had occurred 1.3 billion years ago in the Southern Hemisphere, because the signal reached Livingston before Hanford [14]. After many years of collecting data, LIGO achieved its first goal.

Significance of LIGO and Gravitational Waves

The detection of gravitational waves is essential for the development of theories about the universe. Knowing that gravitational waves exist and finding evidence that supports their existence is essential for scientists to learn more about astrophysics from a new point of view. Before the discovery of gravitational waves, electro-magnetic radiation was the main method to explore unknown parts of the universe [15]. The discovery of gravitational waves opens a new branch of astronomy to explore and learn more about the origins of the universe; LIGO is the pathway used to understand phenomena that scientists previously didn't comprehend [15].

Controversy over LIGO's First Detection

LIGO's detectors sense vibrations from various sources [11] and scientists differentiate between signals from gravitational waves and signals from background noise [16]. Researchers from the Niels Bohr Institute in Copenhagen have claimed that the detection from LIGO's interferometers doesn't necessarily signify a gravitational wave, but may be background noise that occurred at both Livingston and Hanford within 10 milliseconds of each other [16]. They discuss their claims in a paper titled "On the Time Lags of the LIGO Signals." [17]

Methods

One of the main arguments from Creswell et al. is that the background noise in each detector has the same time lag as the proposed gravitational wave [17]. Their graphs support this notion. To investigate this, I attempted to re-create various graphs from Creswell et al.'s paper and compare my graphs to theirs to see the similarity between them. In order to re-create these I used data from the LIGO Open Science Center (LOSC) at the time of the event GW150914, September 14th, 2015 at 09:50:45 UTC [18].

The first graph I plotted was from Figure 1 of Creswell et al.'s paper, which is the time series of the background noise around the event [17]. I also graphed the Fourier Transform Phases from Creswell et al.'s paper in order to understand how Creswell et al. created their argument.

A method used to plot the graphs is the Fourier Transform. This is an algorithm that converts a function from its original domain, such as time or space, into the frequencies that compose it [19]. It translates the original function into a sum over many sine and cosine functions [19]. It is used sound analysis, which is similar to how LIGO detects the wave signals

[3]. A windowing function was also used to reduce unwanted effects from performing the Fourier Transform.

Results

Time Series Graphs

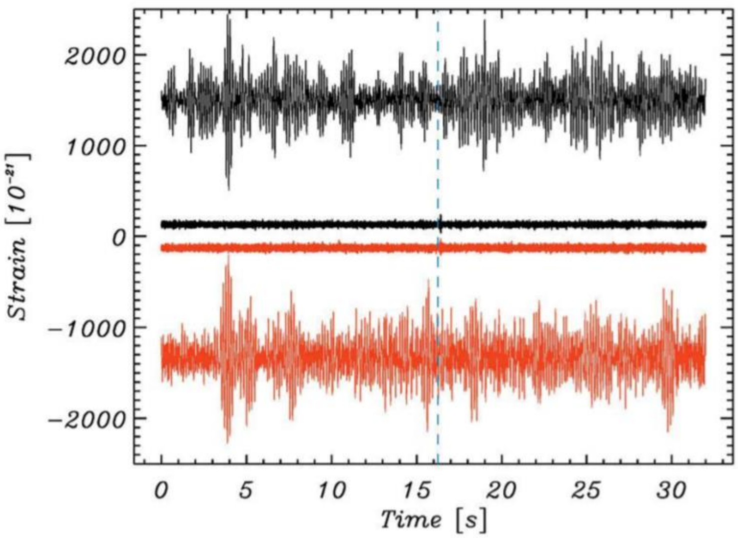

Figure 4: Time Series Graph produced from Creswell et al. The top and bottom plots are raw data. Red is Livingston and Black is Hanford [17].

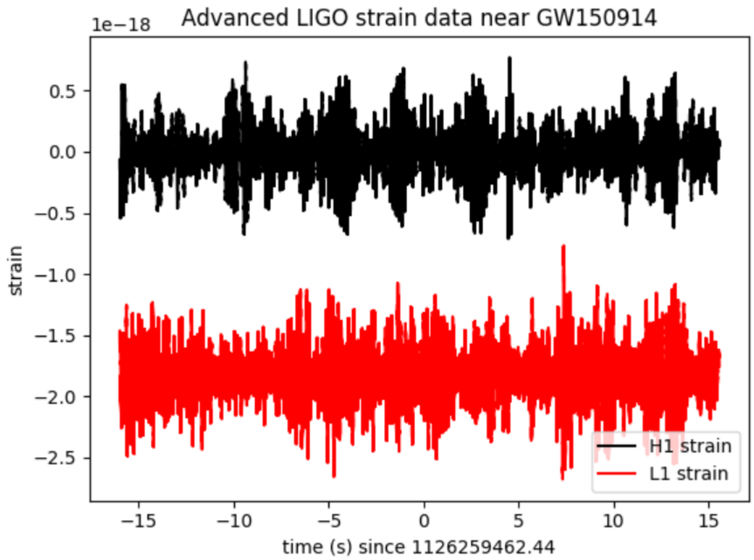

Figure 5: Time Series Graph produced from LOSC. This is raw data. Red is Livingston and Black is Hanford [26]

The first goal in this project was to reproduce Figure 1 from Creswell et al.'s paper, named "On the Time Lags of the LIGO Signals [17]." This graph plots the strain of noise or signal versus time [17]. In doing so, it was expected that both Creswell et al. and LIGO would produce a graph with the same shape because they were plotting the same data [3].

In Figure 4, the event occurs at the dashed blue line, around sixteen seconds [17], and in Figure 5, the event occurs at time 0. Even after considering this time difference, the graphs are not similar in shape. The spikes in LIGO's graph, which represent noise, do not correspond with the spikes in noise from Creswell et al.

Because the GW150914 event graph from the LIGO tutorial did not match Creswell et al.'s representation of the same event, I plotted the time strain series of the other listed LIGO events—GW151226, LVT151012, or GW170104 [26]—to determine if any of them matched the graph from Creswell et al. Using the scripts from a modified version of the event tutorial, called LOSC_Event_Tutorial2.py from Professor Eric Myers of SUNY New Paltz [26], I plotted their respective time series to determine if any of them corresponded. I was unable to find a graph that looked similar to the one produced by Creswell et al..

Continuing my search to reproduce Creswell et al.'s Figure 1, I downloaded the data from an older LIGO Event Tutorial [20] and used the Lots of Plots Tutorial to graph the time series of GW150914 and compare them. This was the data at 16 kHz—the rawest form available [20]—however, it still did not produce a graph similar to the one from Creswell et al. The graph produced by this data was very similar to the one produced when using LIGO data at 4 kHz.

Due to the difference between Creswell et al.'s graph and the one created from the LIGO event tutorial, it is currently unknown what Creswell et al. plotted in their Figure 1.

LIGO Data Offset

Another aspect of this project was to understand the data offset apparent in the time strain, shown in Figure 5 [26]. As displayed, in the graph from the LIGO tutorial, the data from Livingston, in the red, has a much lower average than the data from Hanford, in the black. This is odd, because one would expect the two to have a similar average. While there are different types of background noise, and Livingston and Hanford should not have the same noise, it is expected that they will average out to a similar number, simply because in both places, there are both high frequency and low frequency background occurrences [3]. However, it was shown that Hanford had an average strain of 3.280-20 and Livingston had an average strain of 2.870e-15 [26].

It is common to introduce an artificial offset to improve readability because it would make sure that graphs do not overlap. Creswell et al. included one in their graph of the time series as shown in Figure 4. However, the LOSC tutorial did not create an artificial offset [3]; therefore, it is unclear where it originated from. Regardless, LIGO discussed this offset on the LOSC website in a tutorial titled “Signal Processing With GW150914 Open Data [20]”, which is no longer maintained. The tutorial states that low-frequency oscillations were the cause for the data appearing offset. These low frequency signals were either ignored in data analysis or had no effect [20].

Phase Correlation Graphs

The next goal of this project was to reproduce sections from Creswell et al.'s phase correlation graphs (Figure 6). The phase is the initial angle of a sine or cosine function at its origin [21]. Creswell et al. plotted the graphs of the frequency (Hz) vs. Fourier Transform Phase for the raw event data. They found correlations in the phases [17], represented by vertical lines and horizontal lines [3], as displayed in Figure 6. The vertical phase correlation is outlined in purple,

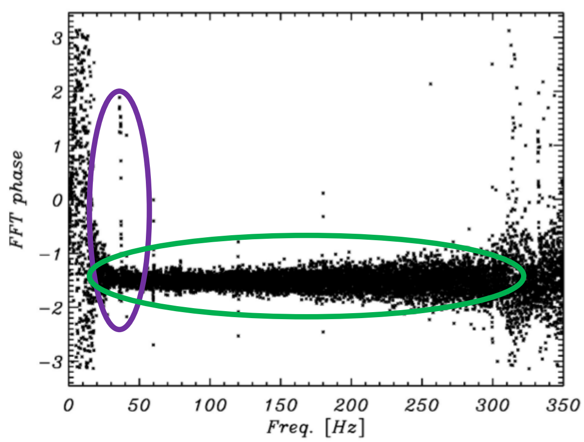

Figure 6: raw Hanford frequency vs. Fourier Transform Phase data, produced by Creswell et al., taken from figure 3 of "On the Time Lags of the LIGO Signals" [17]. This graph shows correlations in the phase data.

while the horizontal phase correlation is outlined in a green oval.

Creswell et al. reason that having phase correlations reduces the certainty of LIGO's gravitational wave detection [17]. This is because wave detections are dependent on the lack of correlations within residual noise from each detector [12]. If there are correlations in the data, then it introduces the question of whether a potential detection is due to an actual gravitational wave passing through, or if it is due to residual noise correlations occurring at both detectors [17]. This graph was included in their reasoning. Below, an evaluation of this reasoning is discussed.

It is important to understand the significance of a Fourier Transform in Creswell et al.'s argument. A Fourier Transform translates the original function into a sum over many sine or cosine graphs [22]. In order to represent the function accurately, the Fourier Transform assumes that the function already is periodic, because both the sine and cosine graph are periodic [23]. Each sine and cosine function has a period that it eventually cycles back to and repeats. If a function is not periodic, the Fourier Transform could make the new function be plotted with a periodicity that the original one didn't have [3]; this has the potential to introduce artificial phase correlations [17]. Creswell et al. acknowledged this potential issue in a footnote while describing the phase correlations in their argument [17], but did not explain it, warranting my recreation of these graphs in order to see whether I found the same phase correlation.

In reproducing these graphs, I produced Figures 7 through 10. I used a modified version of the LOSC Lots of Plots Tutorial, called the DFTPhaseStudy.py [24], and created by Professor Eric Myers. This script plotted the raw Fourier Transform Phase vs. Frequency graph as well as the windowed version of the same graph [24]. Figures 7 and 8 display the raw Fourier Transform Phases from Livingston and Hanford and Figures 9 and 10 portray the windowed version of the same plot.

Windowing is used to reduce the severity of the artificial phase correlations caused by plotting a Fourier Transform [3]. This windowing function is in the time domain and weights each point in a way that will allow them to be separated and diminish the artificial correlations from the Fourier Transform [3]. Scientists at LIGO use the Blackman window in order to reduce spectral leakage [25] and I also used the Blackman window to plot figures 9 and 10, both from the DFTPhaseStudy.py tutorial [24].

Artificial phase correlations would most likely appear in Figures 7 and 8 because they represent the raw Fourier Transform Phase graphs [3]. There was some correlation at the low and high frequencies; however, the level was very low compared to the correlation that appears in Figure 6 [3]. There was no correlation in either of the graphs that used the windowing function, because all of the dots were spaced out, covering the entire graph [24]. I was unable to produce a graph that had as strong correlations as the ones from Creswell et al.

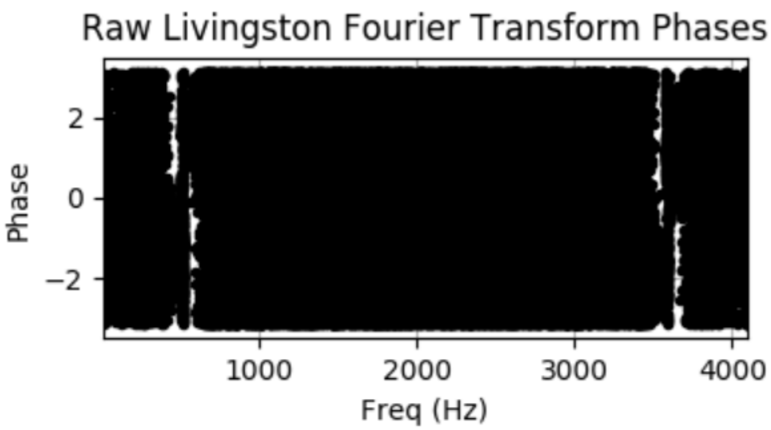

Figure 7: Raw Fourier Transform Phase data vs. frequency plot from Livingston [24]. This shows the phases without the windowing function, meaning that artificial correlations have the potential to be introduced [17].

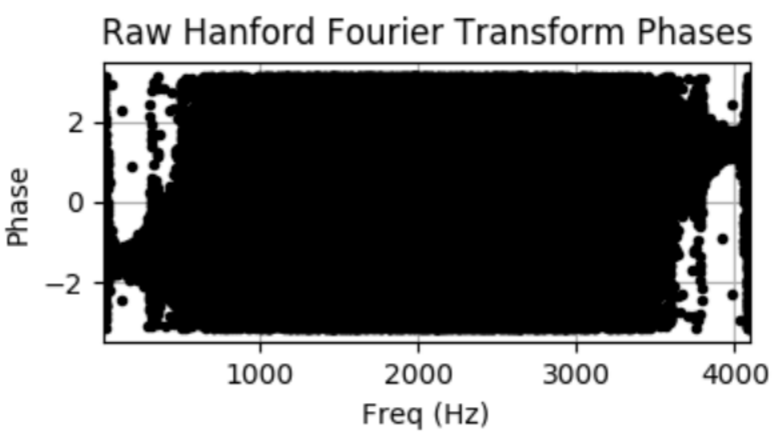

Figure 8: Raw Fourier Transform Phase data vs. frequency plot from Hanford[24]. This shows the phases without the windowing function, meaning that artificial correlations have the potential to be introduced [17].

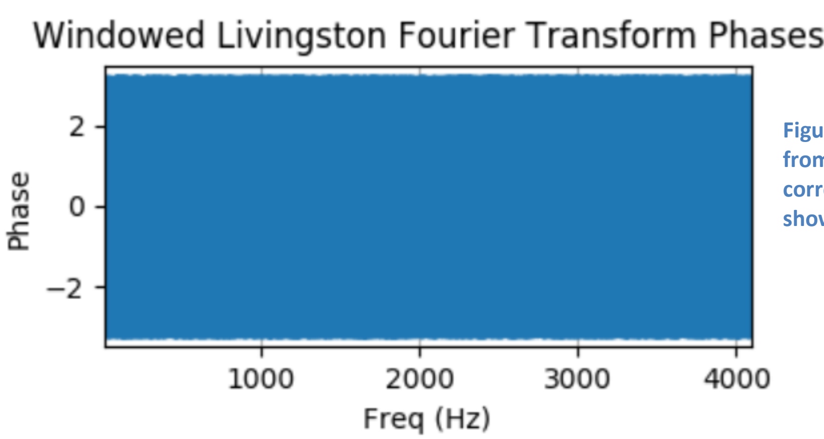

Figure 9: Windowed Fourier Transform Phase data vs. frequency plot from Livingston [24]. The purpose of the window is to reduce artificial correlations that are caused from the FFT. There are no correlations shown in this graph.

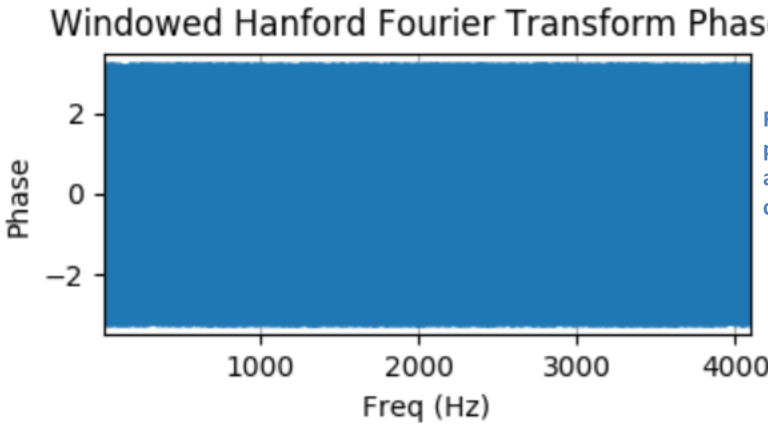

Figure 10: Windowed Fourier Transform Phase data vs. frequency plot from Hanford [24]. The purpose of this graph is to reduce artificial correlations that are caused from the FFT. There are no correlations shown in this graph.

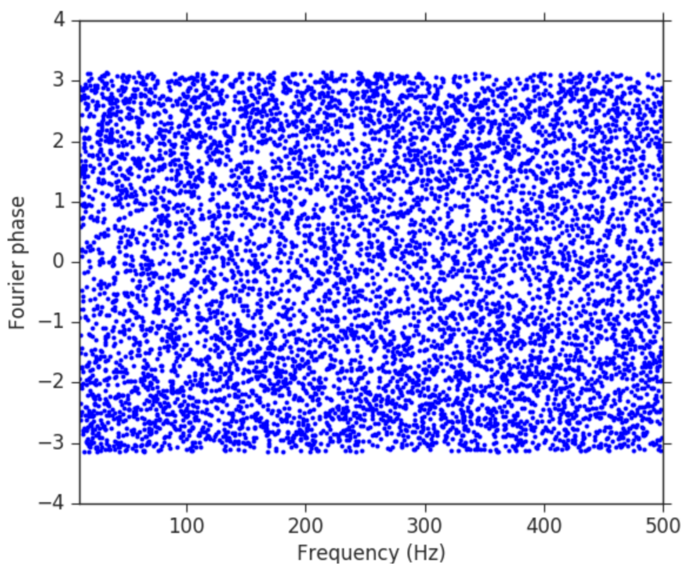

Figure 11: The whitened noise graph from Dr. Ian Harry's response to Creswell et al. There are no signs of correlation in this graph [23].

Dr. Ian Harry who is from the Max Planck Institute for Gravitational Waves and is a member of the LIGO collaboration [23] wrote a response to Creswell et al. titled "A Response to 'On the time lags of the LIGO signals.'" He produced Figure 11 using scripts from LIGO, and displayed that the whitened noise did not have phase correlations because the data points that form the graph are also spread out to cover the area of the graph [23]. The graphs that I plotted, Figures 7-10, support the graphs done by Dr. Harry.

Discussion

The goals of this project were to reproduce parts of Creswell et al.'s paper and evaluate the validity of the argument coming from Creswell et al.. After plotting various figures and understanding their meaning, there were various problems encountered with Creswell et al.'s argument. The time series graphs from Creswell et al. and LIGO are different from each other, and the phase correlations that Creswell et al. argue with are not apparent in plots that are from LIGO Tutorials. Dr. Harry's graph produced the same result that the graphs from the DFTPhaseStudy.py [24] script produced. Because of the large discrepancy between the time-series graph and the absence of phase correlations in the graphs containing the raw Fourier Transform phases, the validity of Creswell et al.'s claim comes into question.

Further research may need to be done to determine whether evidence that supports the claim of detector correlation from Creswell et al. can be reproduced and whether the these correlations have an effect on the confidence of the GW150914 event. In my research, I used modified LIGO Tutorials provided by Professor Eric Myers. To complete further research, one may go to the LIGO GitHub site where they have more extensive scripts that perform more detailed analysis. The website can be found at: https://ligo-cbc.github.io/ .

Summary

This paper provides an overview of gravitational waves, LIGO, and the methods and analysis of my project which was to evaluate the claims made by Creswell et al. regarding the significance of the GW150914 event. I reproduced various figures from Creswell et al.'s paper and Dr. Ian Harry's response using LIGO Tutorials modified by Professor Eric Myers of SUNY New Paltz. After creating various graphs and comparing them to the original graphs, there was discrepancy between the graphs from Creswell et al. and the graphs from the LIGO. The time series graphs for the event GW150914 did not match each other and the phase correlations that Creswell et al. graphed were not able to be reproduced. This brought the claims of Creswell et al. into question. For someone who desires to do further research into this controversy, there are various scripts located on the LIGO GitHub website.

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