Verifying the time lags of LIGO detection

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1 Introduction

Astronomy until recently has relied heavily on electromagnetic waves. Telescopes of various kinds receive these waves (photons) emitted by objects in space in order to detect the objects. However, celestial objects undergo various processes that emit something other than photons. These signals, also known as messengers, provide insight into astronomy. With further development of technology, multi-messenger astronomy is becoming increasingly important, where gravitational waves play an important part.

In this paper, I calculated the time lag between the two stations of a proposed event(GW170104) and the time lag of the residual noise. I found out that the two time lags are almost the same, which meant that the time lag is a systematic effect rather than a numerical coincidence. In addition, I graphed the phases in a frequency domain and found that there was no strong correlation between the phases of signals detected at the two sites.

2 Background

2.1 Gravitational Waves

Similar to electromagnetic waves which are oscillations of the electric and magnetic field, gravitational waves are time-varying oscillations of the gravitational field. According to Einstein's general theory of relativity, they are a phenomenon generated by the curvature of spacetime. In this modern understanding of gravity, mass curves the spacetime around it like a rubber sheet with a bowling ball on it. Another principle is that objects that are moving in spacetime always follow ”straight lines.” These are not literally straight because spacetime is curved. So, moving mass causes changes in mass distribution that stir up spacetime and causes waves. Gravitational waves are generated by changing quadrupoles in analogy to e-m waves generated by changing dipoles. [1]

Gravitational waves can only be produced by nature. One possibility is that they were created in the early universe, just like the Big Bang would have wiggled the universe and created a cosmic microwave background. Besides, spinning objects, like a neutron star, would give continuous wave sources. There might also be bursts from a supernova or some other kind of cataclysmic event. Also, the gravitational waves detected are produced by the coalescence of binary systems, including pairs of black holes or pairs of neutron stars or one black hole and one neutron star. We have detected a chirp from a black hole swallowing a neutron star.

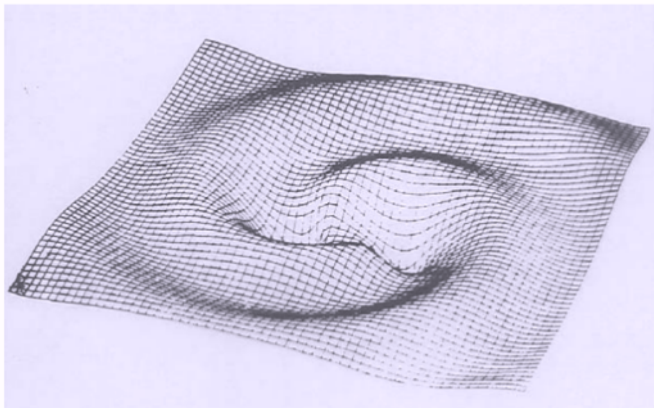

Figure 1: Gravitational waves emitted by a binary system [2]

Uncharged binary systems can also emit gravitational waves. They can also travel through any intervening matter without being hindered a lot. So gravitational waves are a good messenger for exploring space.

2.2 Detection and LIGO

Detecting gravitational waves is extremely difficult because they are extremely small changes in the length of spacetime. Strain is calculated by the formula $h = \frac{\Delta L}{L}$, where L is the length of the interferometer. Strain represents the curvature of spacetime and is in proportion to the gravitational wave amplitude. When they reach the Earth, they have a small amplitude with a strain of approximately 10^{-21}. The first device theorized to detect the expected wave motion is a bar detector,which is two masses connected by a spring. The inventor Weber declared he had detected gravitational waves, but his experiments couldn't be reproduced.

Another type of detector uses a Michelson interferometer to measure gravitational waves. A coherent source of light is split by a half-silvered mirror. When they combine again, the waves undergo either constructive interference, where they reinforce each other, or destructive interference, where they cancel each other out, depending on the arm lengths. If one arm is anchored, moving the other arm, one wavelength of the wave will create a shift from light fringe to dark fringe and light fringe again. This is how interferometers measure very small distances, which also applies to the detection of gravitational waves. Measuring ΔL allows for the measurement of strain.

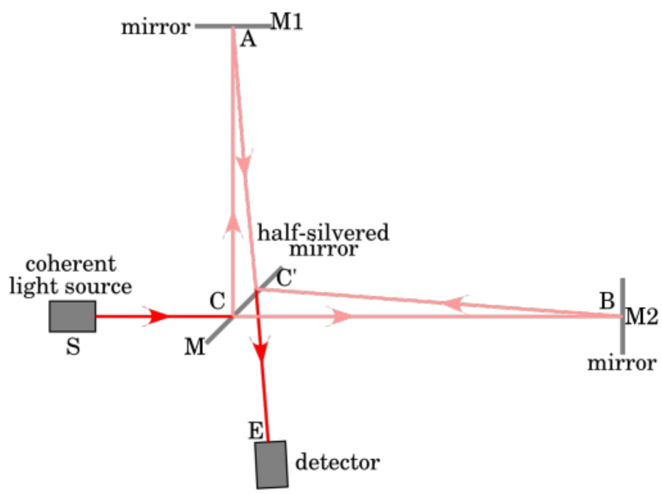

Figure 2: The structure of a Michelson interferometer [3]

Hence, National Science Foundation funded the construction of LIGO. LIGO stands for The Laser Interferometer Gravitational-Wave Observatory. Two stations, LIGO Livingston and LIGO Hanford, were built to rule out the vibrations that differ between the sites and look only for identical signals that occurred at both locations. Also, the design of two sites helps to determine the directions of the gravitational waves because different directions result in a different time lag. The first interferometric gravitational wave detectors were built in the late 1960s and 1970s. Funded by the NFS, the construction of LIGO started in 1995 [4]. The first light of lasers was received in 1999. It first started collecting data from 2002 to 2007, during which time many adjustments were made but no gravitational waves were detected. Then enhanced LIGO was installed. LIGO worked with enhanced sensitivity from 2009 to 2011, but still, no detection was made. Another three years(2012-2015) was taken to install the advanced LIGO. [5] Finally, only days into the run, the first detection was made in 2015 and published in 2016.

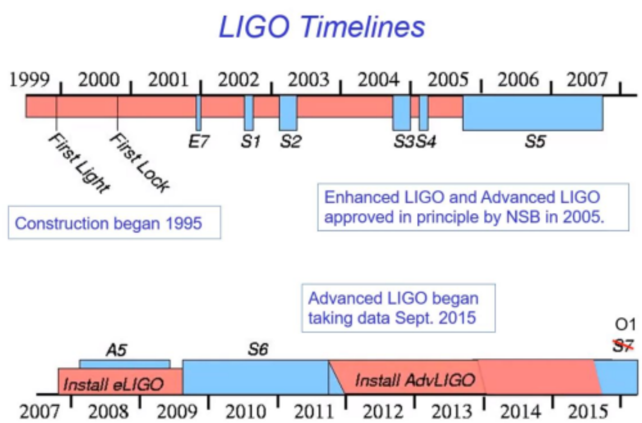

Figure 3: Timeline of the construction of LIGO [6]

But this detection is only a start. LIGO leaves a lot to be improved. When measuring the amplitude of gravitational waves with the equation $h = \frac{\Delta L}{L}$, background noises may affect sensitivity and cause interfering signals. The sensitivity of equipment depends on the smallest strain signal that can be distinguished from background noises. One of them is seismic noises, generated by earthquakes, traffic, or weather, anything related to the earth. Also, the vibrations caused by temperature influence the sensitivity as well . At higher frequencies, there is shot noise, which comes about from the quantum nature of electric charges. There's a gravity gradient that we cannot detect anything beyond it.

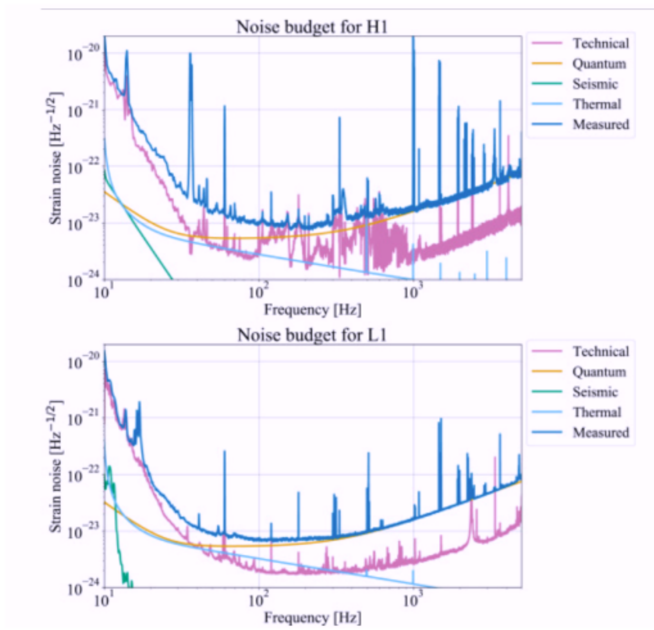

Figure 4: The noise curves of Hanford and Livingston observatories [7]

To increase the sensitivity of LIGO detectors, they are getting upgrades to increase their sensitivity and detect even more events. Japan has built KAGRA, and LIGO-India will hopefully be operational by the mid-2020s. To minimize seismic noises, space-based gravitational wave observatories, like LISA, are also included in the plan.

In short, gravitational waves are a proof of the general theory of relativity and serve as a new messenger in astronomy. LIGO, as the leading interferometer detector, plays a vital role in collecting signals of gravitational waves.

3 Project Description

A previous study analyzed the time lag between the two LIGO detectors in the event GW150914 [8]. The two detectors in Hanford and in Livingston, which are about 3000 km apart, detected a signal with 6.9ms time delay that was consistent with the merger of two massive black holes. The study analyzed whether the noise before and after the event is maximally correlated between the two detectors. They also found a strong correlation between the phases.

This study is crucial because it determines whether or not the time delay is an intrinsic property of the noise.

This paper is aimed at doing the same study as Creswell in a new event(GW170104).

4 Method

Gravitational Wave Open Science Center (https://www.gw-openscience.org/about/) [9] has released strain data from S5 to O2 and the event data of particular events. They also provide Python scripts that can be used to compute and analyze the data.

All data from the website are 4096s or 1024s segments formatted into the HDF5 file format. In order to process the data, I installed python and the readligo.py module in the website tutorial. Since the data was a strain time series, to process this signal, I transformed the signal from its original time domain into its frequency domain through the Fourier Transform. It was easily done with the help of NumPy.

After the Fourier Transform, I applied a matched filter to maximize the SNR and minimize gaussian noise. I then subtracted the matching template from the original data so I could get the strain data of the noise. I then analyzed the amplitudes and phases as the previous study did. Codes are also available on the GWOSC website.

The next step was to compute the cross-correlation coefficient between the Lingvingston and Hanford strain data. The coefficient would be significantly large if there is a perfect correlation between the two strains, which serves as a qualitative analysis of the correlation.

Specifically, cross-correlation is a loop over the offset between two time series. When the value of the correlation reaches a maximum, the offset is the time lag between the two series.

5 Event GW170104

5.1 Strain Correlation

I looked at the event GW170104, which was readily available in the Binary Black Hole event tutorial. The first step was to read in the strain data. For either site, the strain data contains 32 seconds of usable data.

The next step was to perform the Fourier Transform [10]. Specifically, I performed the Fast Fourier Transform, which could be achieved through python code np.fft.rfft.

$$A[f] = \sum_{j=0}^{N-1} e^{-2\pi j \frac{ft}{N}} x[t]$$

This transformed the time domain into the frequency domain, which made possible the matched filtering.

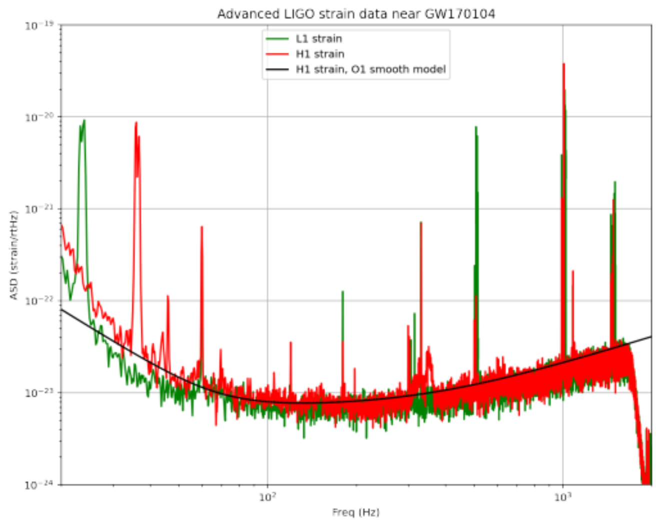

Figure 5: Amplitude Spectral Density

The next step was to whiten the data [11], which meant using the above Fourier Transform, transferring the data into the frequency domain and dividing it by amplitude spectral density. This balanced the data to make sure that they are of the same amplitude in order to eliminate the error caused by different sensitivities.

Then I employed the matched filtering, where I used the proposed template. After that I took the Inverse Fourier Transform (IFFT) of the filter output and put it back in the time domain. I found the two maximum signal to noise ratios and the time indexes of these two maximums. The two GPS times for the detection in Hanford and Livingston were 1167559936.6084 and 1167559936.6113 respectively. The time lag between the two events was -0.029 millisecond. I subtracted the matching template from the whitened strain data to get the residual noise, which produced the two graphs below.

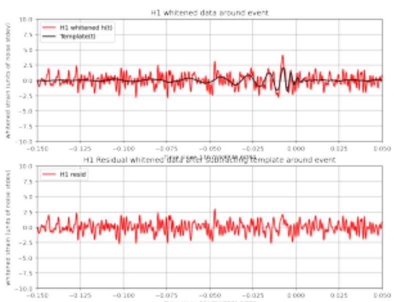

Figure 6: Hanford

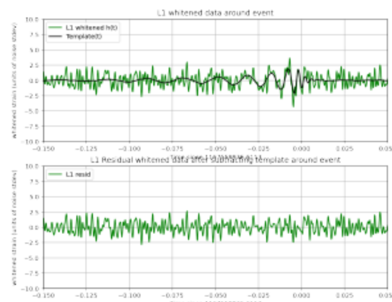

Figure 7: Livingston

The final step was to calculate the cross-correlation function between the two noise series. The np.correlate function automatically looped over the time lag and produced the graph below.

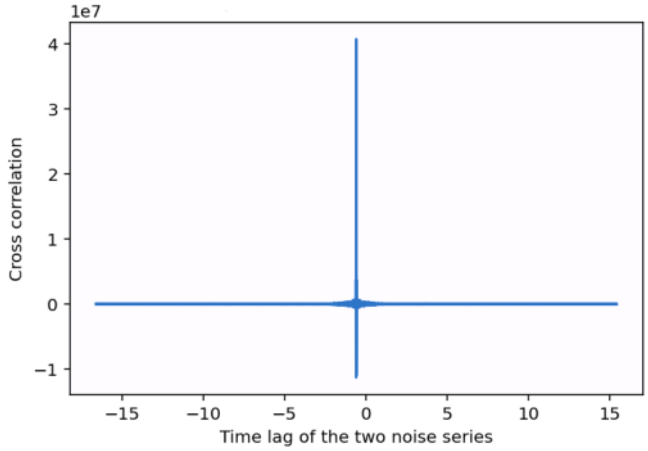

Figure 8: Cross-correlation function for the whole noise series

As is shown on the graph, the time lag of the noises was significantly bigger than that of the two events(-0.029 millisecond). The problem was that before -15 and after 15 millisecond, there were signals large in strain but not related with the event.

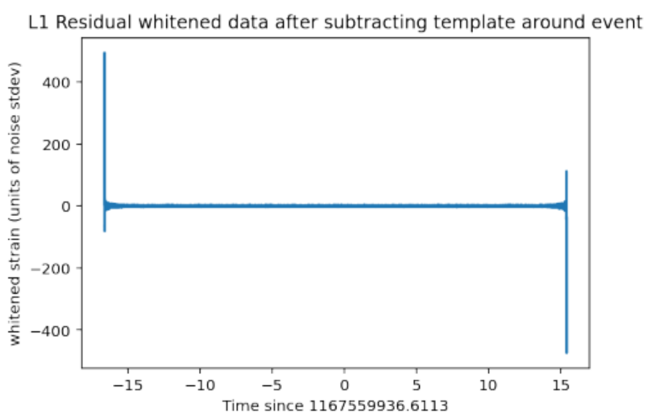

Figure 9: Noise of L1

To eliminate those disturbances, I set upper and lower boundaries of the noise signal. This produced a graph significantly different from the previous one. I zoomed in and found the time lag was -0.0324 millisecond, which was very close to the time lag of the two event signals.

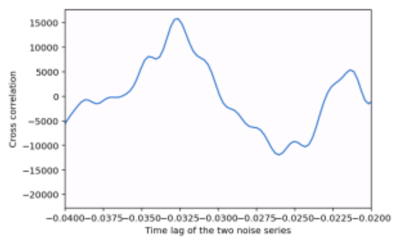

Figure 10: Cross-correlation for part of the noise series

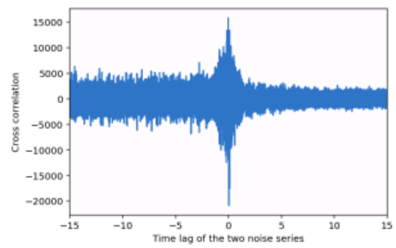

Figure 11: Zoomed cross-correlation for part of the noise series

5.2 Correlation of the Phases

Creswell [8] found a phase correlation between the Livingston and Hanford data. However, it was wrong. I tested his method with the Event GW170104.

After the Fourier Transform, the strain data is transformed into an array of complex numbers. I utilized np.angle to take the phases of the transformed strain data. I plotted the phase of data for both sites and a correlation between the arrays of phases.

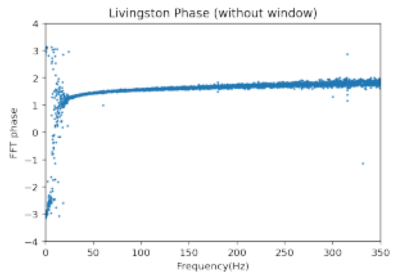

Figure 12: Fourier Phases for Livingston

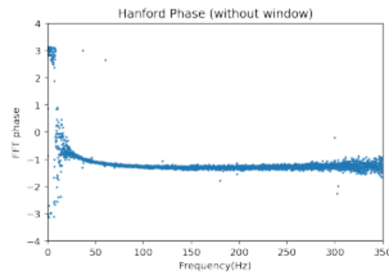

Figure 13: Fourier Phases for Hanford

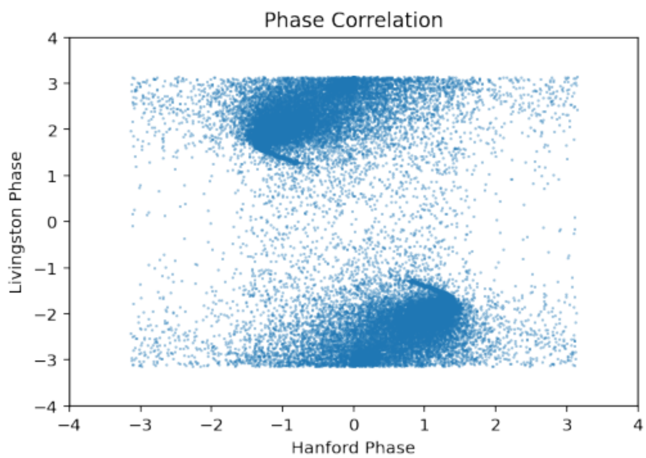

Figure 14: Phase Correlation

Based on the perfect symmetry of the graph above, Creswell maintained that there was a strong phase correlation. Yet he ignored a key part when performing the Fourier Transform: windowing. The Fourier Transform assumes that the data are periodic and if that process is emitted there would be a mismatch. To create avoid this problem, I multiplied the data by a window function which goes to zero at the edges. There are a lot of windows among which I chose the Blackman window.

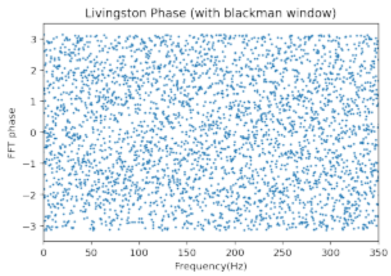

Figure 15: Fourier Phases for Livingston

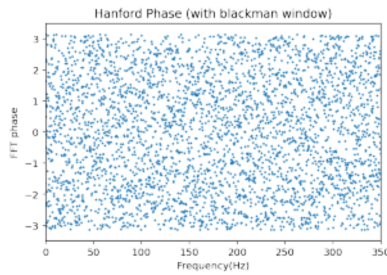

Figure 16: Fourier Phases for Hanford

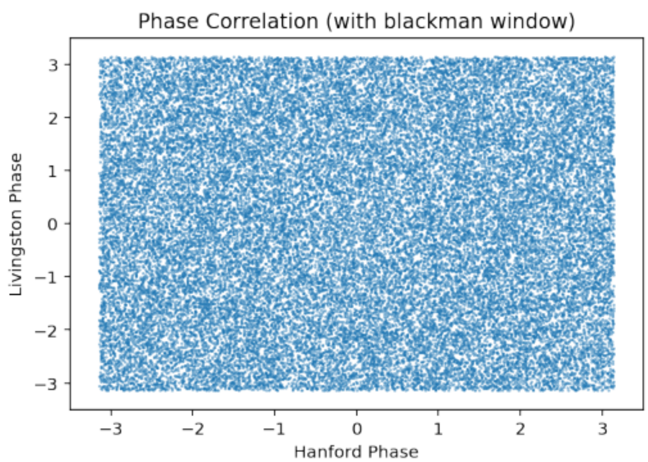

Figure 17: Phase Correlation

Shown from the graphs above, the phases were randomly distributed in the frequency domain, and there was not a strong correlation between the phases.

6 Conclusion

This paper tested two of Creswell's results in a new event(GW170104). The time domain cross-correlation showed that there was a time lag between the noises. That time offset was similar to the offset between the events. The strain correlation of GW170104 substantiated previous findings, but the phase correlation did not. The phases are randomly scattered in the frequency domain. The correlation that Creswell et al found was due to the absence of a proper window.

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Appendices

Google Colab links of my codes

1.Strain correlation: https://colab.research.google.com/drive/1Gdm1Wn4C25Aa_E-GSLUCJalV_VFpL5ps?usp=sharing

2.Phase correlation: https://colab.research.google.com/drive/1jptiWZ_iC0_2ACGy75H5ulU1AZOESuz2?usp=sharing