Studying Gravitational Waves from Exceptional Binary Black Hole Merger Events

(LIGO SURF 2020 Proposal)

Erin Wilson
Spelman College
Atlanta, GA

Mentor: Alan J. Weinstein
LIGO Laboratory at the California Institute of Technology
Pasadena, CA

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I. INTRODUCTION AND BACKGROUND

First predicted by Albert Einstein in the year 1916, gravitational waves are the results of the squeezing and stretching, or strain, of space over time. According to Einstein's Theory of General Relativity, gravitational waves are created through the acceleration of any object in space. However, only the acceleration of incredibly massive compact objects create gravitational waves strong enough to be detected by LIGO. The intense movement of these objects disturb space-time to such an extent that it ripples outward in all directions at the speed of light [1].

Though much theoretical work was done after 1916 to further prove the existence of gravitational waves such as Schwartzchild's solution to Einstein's field equations in 1916 (which describes black holes) [2] and Kerr's 1963 calculations of Schwartzschild's solution to suggest the existence of rotating black holes [3], gravitational waves were only experimentally discovered for the first time on September 14th, 2015 by LIGO detectors in Livingston, LA and Hanford, WA. [4]

The significant event GW150914, detected by Advanced LIGO in September 2015, was discovered to be a binary black hole merger from a distant galaxy. Thus, the spacetime "ripples" picked up by LIGO detectors Livingston and Hanford appeared to originate from the merging two stellar-mass black holes. Eventually, after investigating the GW150914 signal data by (1) using its parameters to match it to a General Relativity-derived waveform, (2) subtracting the GR waveform from the signal data, and (3) analyzing the residual waveform using a cross correlation techinique across the Livingston, LA data and the Hanford, WA to ensure the residual waveform consisted of just noise, it was concluded that the data from the GW150914 event was consistent with gravitational wave behavior predicted by Eintein's theory of General Relativity [4].

Since this event, LIGO has detected over 60 new compact binary coalescence events, each emitting their own, unique gravitational waves. Our job is to now test how General Relativity holds up for not just a singular significant event, but several. Doing so will give us important insight on if Einstein's predictions were entirely correct. If not, this may imply that gravitational waves may hold secrets that even General Relativity is not able to reveal.

II. PROJECT OBJECTIVES

The purpose of this summer research is to test that the data gathered from binary black hole merger events are consistent with General Relativity (GR). To test that these significant merger events behave as expected from General Relativity, actual merger data will be compared to GR-predicted waveforms. This will be done under the assumption that Einstein's Theory of General Relativity correctly describes the behavior of gravitational waves from environments of strong field, highly dynamic gravity. Thus, the GR waveforms should be accurate models of the signal from the compact binary merger in the LIGO data [5].

This research will be successful if we are able to develop an data analysis software capable of correctly distinguishing whether the data are consistent with a GR based model [5]. As a result of such success, we will be able to address two main outcomes. (1), the waveforms predicted by General Relativity are accurate models of the data gathered from both the Livingston, LA and Hanford, WA LIGO detectors, thus implying that general relativity is the correct theory to describe the behavior of gravitational waves from environments of strong field, highly dynamic gravity. Or (2) the GR-predicted waveforms are not accurate models for the GW data gathered from the merger events, which would suggest that General Relativity does not completely describe the behavior of the source of these gravitational waves. This could potentially be evidence for physics and astrophysics beyond General Relativity [5].

III. APPROACH AND METHODS

We want to test that binary black holes are well described by General Relativity. A digital signal processing software, written in Python, will then be written with the intent to subtract a best fit, parameterized GR waveform model from noisy data from the LIGO detectors. This will result in a waveform known as a residual. If these parametrized GR based binary black hole waveform models are an accurate representation of the signal in the data, then the residuals will be consistent with noise only. This implies that the binary black hole merger event behaves as predicted by General Relativity [5].

The GR waveforms that will be subtracted from the instrument data will be created and matched with the data using Bilby [6], a Bayesian inference library. Our digital signal processing software will then use Bilby to estimate the parameters of the signal in the noisy data so that a model waveform template can be generated for the detectors both Hanford and Livingston. The content of the residual waveform will then be analyzed for correlations to Gaussian noise and any signal remaining in the data. Should the noise sources from the Livingston, LA detector and the Hanford, WA detector have an average root-mean noise that tends to 0, the noise will be considered uncorrelated. This implies that general relativity correctly describes the behavior of the merger data. However, if the noise is uncorrelated , there may still be a signal still left in the residual. This could imply the GR waveform generated by Bilby was not not an accurate model due to incorrect calculation of signal data parameters. However, if a signal found in the residual waveform is not the cause of computational or instrumental errors, this may imply that General Relativity may not always hold for binary black hole merger events occurring in environments of strong field gravity.

The biggest milestone of this research will be the creation of the digital signal processing software. This step should ideally take a month and a half to complete. Once the code is proven to accurately analyze the behaviors of simulated black hole merger events, the code will then be used to analyze the gravitational waves from multiple newer merger event data. This step should also ideally take month an a half to complete [5].

IV. WORK PLAN

Before the summer program begins in June 2020, I will prepare a project proposal (this document), in addition to more reading and learning in preparation for summer work. This research will last for 10 weeks. Within the first 3 weeks we will write the first interim report. By the 7th week, a 2nd interim report will be due. By the 9th or 10th week of the program, both a final presentation and a final paper will be written for the research, and on the last day of the summer, the results of the research will be presented.

The time in between interim reports will be spent learning more about the project, developing Python code that simulates a signal, adds it to the LIGO data, estimates the parameters, and estimates the signals in various detectors. Additionally, time will be spent learning how to subtract GR waveforms from signal data as well as how to estimate detector noise for cross correlation. Once the digital signal processing code is written, its performance will be tested on simulated loud signals then quieter, more realistic merger signals. Finally, the software will be used to analyze new, actual merger events [5].

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