Studying Gravitational Waves from Exceptional Binary Black Hole Merger Events

LIGO SURF 2020 First Interim Report

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Advanced LIGO and Advanced Virgo have detected 66 candidate gravitational wave signals. Each detection contains encoded information about the physical properties of the binary system. As the detectors continue to improve their sensitivity, these developments will allow us to detect rarer systems and introduce more confident statements regarding their source properties. In order to fully characterize the gravitational wave observations, we rely on numerical and analytical models that approximate the signal waveforms from the emitted source as specified by the source parameters (masses, spins, sky location, etc). It has been shown that gravitational waves oscillate at a dominant emission frequency; however, the event GW190412 has demonstrated subdominant higher order harmonic contributions. We will be exploring this phenomena in more detail both in simulation and in recently detected events. The primary focus of this summer project will be to explore higher order modes in gravitational wave signals with newly improved signal models.

I. INTRODUCTION

The Advanced LIGO and Advanced Virgo detectors had acquired improvements before their third observing run (April 2019-March 2020), also referred to as O3, which increased their sensitivity. With these new implementations, all three detectors (both LIGO detectors and the Virgo detector), have been able to expand their range in the quest to detect gravitational wave signals and have successfully accumulated various new detections. With the observations of 56 new gravitational wave signals, the need for models of the emitted sources is essential [1].

It is expected that with the new data run, unique sources (compact binary coalescences) that include unequal masses or misaligned spins will be well within the astrophysical reach of the observatories. Earlier parameter waveform families were not sufficiently sophisticated to include higher order modes; however, by detecting exceptional events, these models of the gravitational radiation now include more accurate means of measurements. Not only will these models provide us with information regarding the inspiral, merger, and ringdown of the source, but by using the underlying theory of general relativity, we can test its validity more deeply [2].

In particular, in this report, we will be discussing the properties of the event called GW190412, which was observed on April 12, 2019 at 05:30:44 UTC by the Advanced Virgo detector and both Advanced LIGO detectors [2]. Its signal waveform included its signature dominant quadrupole radiation; however, it contained *detectable* higher harmonics which will provide us with a greater insight to the dynamics of coalescing binary black holes. Therefore, the focus of this study this summer will be on events like GW190412 both in simulation and in recent signal detections.

II. PROGRESS

The first three weeks were spent on learning how to use LIGO and Virgo strain data along with their affiliated software libraries. The programming exercises provided by the GW Open Data Workshop #3 have allowed me to utilize the gravitational wave data as well as their software tools. Upon completing all of the tutorials, I began to learn how to use Bilby, a Bayesian inference library for gravitational-wave astronomy, through their gravitational wave tutorials [5]. Through the Bilby tutorials, I

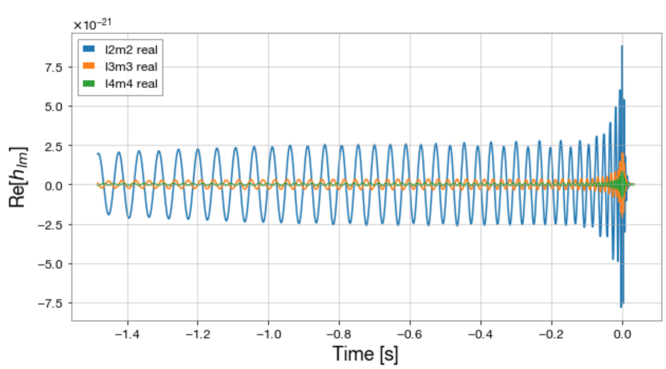

FIG. 1. The real part of the (2,2), (3,3), and (4,4) modes of the NRSur7dq4 surrogate model waveform. To produce this figure, all waveforms used a q=4, χ_1=[-0.2, 0.4, 0.1], and χ_2 =[-0.5, 0.2, -0.4]. Each waveform has been time shifted so its total amplitude appears at t = 0.

was able to run parameter estimations on different astrophysical systems. My last week was spent learning the dynamics of surrogate modeling, and how to use the newest surrogate model, NRSur7dq4 (Numerical Relativity Surrogate with 7-dimensions $q \leq 4$).

A. Surrogate Modeling

The models that participate in the analysis for binary black hole mergers are improved from a variety of previous gravitational wave signal models. Specifically, the newest model, NRSur7dq4, which is derived more directly from numerical relativity through interpolation of the waveforms across parameter space using *surgate modeling* [4].

Numerical relativity simulations are able to accurately model the complications of binary black hole mergers; however, the simulations are computationally expensive. Surrogate modeling solves this problem as they are substitute models for the outputs of these simulations.

The effective-one-body (EOB) family is a model that consists of a post-Newtonian waveform that includes the inspiral, merger, and ringdown stitched together with a numerical relativity waveform that contains black hole perturbation theory [2]. In contrast, the phenomenological family is a hybridized model of the EOB-inspiral and a numerical relativity merger [2].The improved models branch from the precessing models of the EOBNR family and the phenomenological family which include effects of higher multipoles.

This data driven approach begins by creating a database of waveforms. We then want to make a basis which will represent the space of the waveforms. To do this, we select the waveforms which are more standard to form the basis. This iterative technique allows us to reduce the dataset to a collection of basis functions. Since the accuracy of surrogate modeling improves when using slowly varying functions, we decompose the strain of the gravitational wave, which is highly oscillatory, into many various other "data pieces" [3].

The empirical interpolation method is then used upon creating the basis. This method constantly selects the time values (referred to as empirical time nodes) which are more representative [3]. The empirical time nodes are then used to compose an empirical interpolant in time [3]. The next step to evaluate the waveform is to obtain the basis coefficients which will allow us to project the basis function [3]. Using the empirical interpolant method, we only need to evaluate the waveform at the empirical time nodes to obtain the coefficients. Upon evaluation, we can project the basis function to obtain the amplitude evaluation.

B. NRSur7dq4 Model

To generate a waveform in the time domain using the NRSur7dq4 model, inputs are required to calculate the parameter space metric. These inputs include, the system's mass ratio, dimensionless spin vector of the two black holes, total mass of the remnant black hole, maximum ℓ index of the mode, reference frequency, and various others (See Table I).

To explore the detectability of higher order modes in varying parameter space, I began by plotting (as show in Fig.1) the real part of the (ℓ, m) =(2,2), (3,3), and (4,4) mode in the time domain. The results are as expected since higher order modes generally have lower amplitudes. To analyze gravitational wave signals, it is often helpful to convert the waveform in the frequency domain. This can be accomplished using a fast Fourier transform. I did this transformation using the produced signal from the NRSur7dq4 model. Before implimenting the fast Fourier transform, I applied a Tukey window to the time domain data which will smoothly zero-value data that is outside the interval being used. This windowing function will allow us to reduce the effects any leakage during the fast Fourier transformation.

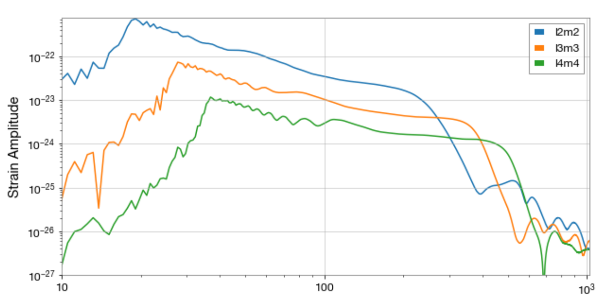

FIG. 2. The (2,2), (3,3), and (4,4) modes of the NRSur7dq4 waveform in the frequency domain.

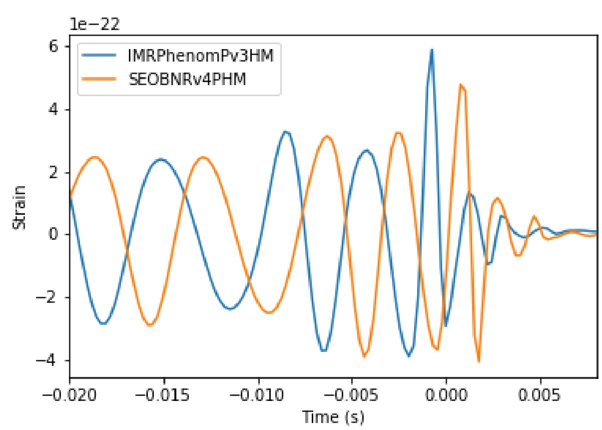

FIG. 3. Time domain comparison of IMRPhenomPv3HM and SEOBNRv4PHM with mass ratio 0.11 and total mass $M = 25.6M_{\odot}$.

TABLE I. Parameters used to evaluate all waveforms

q	χ_1	χ_2,	$M_\odot$	d (Mpc)	ℓ_{max}
4	[-0.2, 0.4, 0.1]	[-0.5, 0.2, -0.4]	70	100	4

As expected, Fig.2 shows that as the mode of the waveform increases, the amplitude decreases. The 'wiggles' located at the lower frequencies are more probable to be an artifact of signal processing. The flattening frequencies, roughly 50-250 Hz for the blue (2,2) mode, describe the binary black hole merger while the following steep decrease in frequency is the ringdown. The frequency at merger behaves accordingly to m which means $m = 4$ is one and a half the frequecy of $m = 3$ and twice the frequency of $m = 2$. We also note that the 'wiggles' located after the ringdown are not physical rather they are an artifact of Gibbs phenomenon. This problem can be solved using hybridization waveform techniques which provide us with information about the event at low and high frequencies– capturing inspiral, merger, and post-merger.

C. GW190814

It is critical that both experimental and theoretical models of a gravitational wave signal agree with the measurements made from Advanced LIGO and Virgo. Typically, these models include the dominant $(\ell, m) = (2, 2)$ mode, however this is not always the case. When the sources have a mass ratio close to one, these models are sufficient to analyze the source parameters of the system, such as distance and inclination. However, when the black hole binary contains an unequal mass ratio, subdominant multipole models may be remarkably more accurate.

What makes GW190814 so unique is the notable asymmetry of the black hole masses, that is– one of the black hole's mass is roughly three times heavier than the other [2]. This makes GW190412 a favorable system for identifying the presence of higher order modes. Recently, I have included the parameters of GW190814 to the IMRPhenomPv3HM and SEOBNRv4PHM models. Fig.3 shows their plotted waveform in the time domain. The two waveforms seem to be out of phase... ExplainMoreHere.

III. FUTURE WORK

I will continue to use NRSur7dq4 to investigate the characteristics of higher order modes using distinct regions of parameter space. Once I have familiarized myself with NRSur7dq4, I will be applying this model to other unique events in O3. I also plan to use Bilby to infer the significance of exceptional compact binary coalescences from a signal model that includes higher order multipoles. By having a greater understand of higher order modes in gravitational waves, we can apply tighter constraints which will ultimately allow us to provide more accurate source parameters.

[1] The LIGO Scientific Collaboration and Virgo Collaboration, Gravitational-wave candidate event database, https://gracedb.ligo.org/superevents/public/O3/.

[2] The LIGO Scientific Collaboration, the Virgo Collaboration, R. Abbott, T. D. Abbott, S. Abraham, F. Acernese, K. Ackley, and *et al.*, GW190412: Observation of a binary-black-hole coalescence with asymmetric masses (2020), arXiv:2004.08342 [astro-ph.HE].

[3] V. Varma, S. E. Field, M. A. Scheel, J. Blackman, D. Gerosa, L. C. Stein, L. E. Kidder, and H. P. Pfeiffer, Surrogate models for precessing binary black hole simulations with unequal masses, Physical Review Research **1**, 10.1103/physrevresearch.1.033015 (2019).

[4] G. Ashton, M. Hübner, P. D. Lasky, C. Talbot, K. Ackley, S. Biscoveanu, Q. Chu, A. Divakarla, P. J. Easter, B. Goncharov, and et al., Bilby: A user-friendly bayesian inference library for gravitational-wave astronomy, The Astrophysical Journal Supplement Series **241**, 27 (2019).