Measuring the Effects of Glitches on Gravitational Wave Parameter Estimation

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(Dated: July 24, 2021)

No scientific endeavor ever runs flawlessly. There are always malfunctions and interference that render the data less than perfect. In the case of gravitational wave astronomy, one of the defects found in the signals are abrupt noise transients, commonly known as glitches. These glitches are often difficult to model due to their non-Gaussian behavior. It is not currently routine practice to remove all glitches, although sometimes glitch subtraction must be done when the glitch strongly interferes with the signal. Each glitch is unique, but a very common type are blip glitches. These glitches bare a particular resemblance to signals, with the absence of the extended signal tail. The process of glitch subtraction is time consuming and is not fully automated. In this study we chose to explore whether or not glitch subtraction of a blip is necessary, as avoiding glitch subtraction could save valuable time during data analysis. Our data set is comprised of simulated signals created using a variety of masses and glitch injection times. By analyzing how well the Bilby program is able to recover the set parameters we can determine how much of an impact the glitch has on parameter estimation.

I. INTRODUCTION TO GRAVITATIONAL WAVES AND GLITCHES

The detection of gravitational waves, which requires extremely high detector sensitivity, is made even more difficult by high-amplitude noise transients, called "glitches"[1]. Glitches can be registered as false-positives of signals from merging binary black holes (BBH) and binary neutron stars (BNS), or the rarer case of a black hole-neutron star binary (BHNS). Both black holes and neutron stars are the final stages in the lives of massive stars, although a higher mass is required to form a black hole. When two such objects merge, their orbit around one another speeds up rapidly as they near collision. This combination of high masses moving at high speeds sends ripples through space-time in all directions, stretching and compressing the fabric of space-time as they propagate. When these ripples pass through Earth they stretch the planet by an amount approximately 1/10,000 times the width of a proton, which is measured by the LIGO detectors. This measurable distance is what is called strain. Figure 1 gives an example of the signal we hope to see during binary coalescence, with no glitches present. In this specific case, the frequency of the signal gradually increases from less than 50Hz to more than 100Hz over the course of 30 seconds. The shape of this signal is commonly called a chirp. The signal track is clearly visible in both the Hanford and Livingston data [2].

For contrast, Figure 2 shows a signal covered by a loud glitch. This figure also shows how a model of the glitch compares to the strain data [2]. In the top panel of Figure 2 the glitch appears as a spike in frequency, with a normalized amplitude of about 6, higher than the signal's normalized amplitude which appears to be about 4 or 5 [3]. The bottom frame of Figure 2 shows the glitch model in blue that is fit to the strain data in orange. The cause of glitches is currently unknown, although they are thought to be the result of environmental disturbances or instrumental malfunctions. Multiple problems arise from the presence of glitches: the detection of signals becomes less significant, and search sensitivity is degraded [4].

Our assumption was that the presence of a blip glitch would make parameter estimation (PE) using Bilby more difficult. Additionally, we predicted that as the glitch was moved closer in time to the signal, the parameters found by Bilby would have more variation from their true values.Our study, however, showed this not to be the case for our chosen glitch model and signal combinations.

II. METHODS FOR GENERATING A DATA SET

Our initial data set consisted of 12 simulated events. The signals were generated using the IMRPhenomD model, all using inc = 0, $delta_t = 1.0/16348$, d = 1200 Mpc, $f_{lower} = 10$ Hz, where the inc is the inclination angle, $delta_t$ is the sampling rate, d is the distance to the

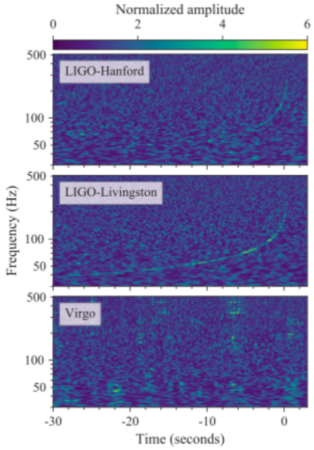

FIG. 1. This figure is adopted from [2] and shows three graphs of the detection of a signal without any glitches present from event GW170817 [2]. The LIGO-Livingston observatory detected the signal most strongly. This is a good example of glitch-free data.

merger, and f_{lower} is the cut-off frequency. The masses of the black holes were the only input parameters we changed. Three events were created for each combination of masses. For simplicity, both black holes were assigned the same mass, with these values varying between $20M_{Sun}$ and $50M_{Sun}$. Next we generated Gaussian noise to add to our signals using the functions pycbc.psd and pycbc.noise in python.Lastly we added the glitch to each simulated event. We chose a simulated glitch using a random blip generator, to make the study more general, rather than an examination of any particular event. An example of one such glitch can be found in Figure 3. The sampling rate of the blip was different from the one used for our signal so re-sampling the blip was necessary before it could be added to the signal and noise.

The three simulated events for two 20 solar mass black holes with the glitch injected 0.5s before the signal, directly on the signal, and 0.5s after the signal are shown in Figures 4, 5, and 6, respectively. Q-scans for the other nine events are not pictured because they are very similar to those for the 20 solar mass signals. The notable variations between events of different masses come from the fact that binaries of higher masses coalesce more rapidly, and are louder overall, causing signals to decrease in length and increase in energy as the masses of the system increase. For all 12 events the same three glitch injection times were used to provide a straight-forward comparison.

III. RUNNING BILBY

The most important part of running a Bilby job is choosing the best priors. For the $20M_{Sun}$, $30M_{Sun}$, and

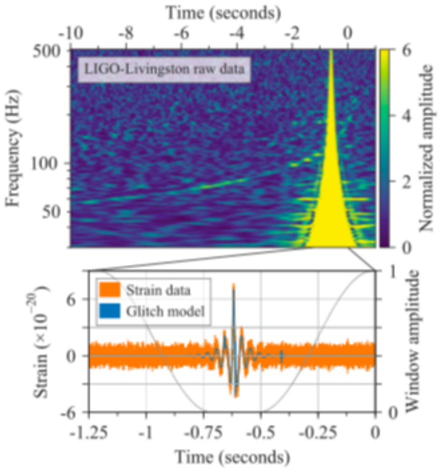

FIG. 2. The detection of the glitch in the LIGO data above with the model of the glitch below for event GW170817 [2]. In the top image we see the glitch as a bright transient which obscures a portion of the signal. Below we have the raw data plotted in orange and the model of the glitch in blue. It is this model that will then be subtracted from the strain data.

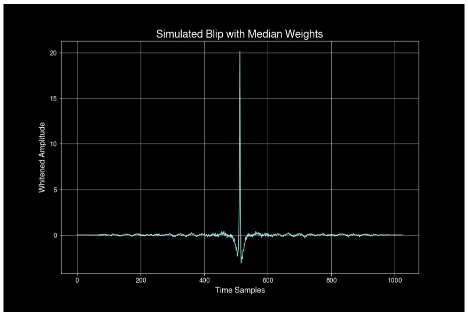

FIG. 3. Example of a randomly generated blip in the time domain.

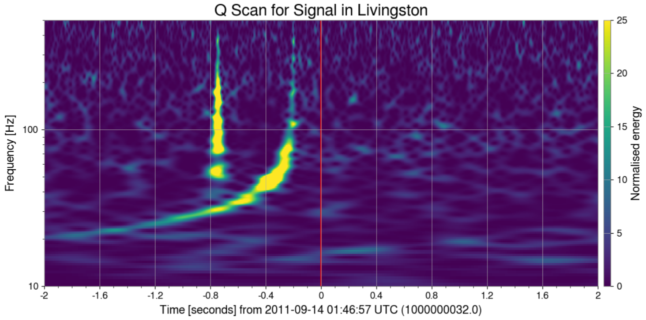

FIG. 4. Simulated event created using two 20 solar mass black holes with the glitch injected 0.5 seconds before the signal.

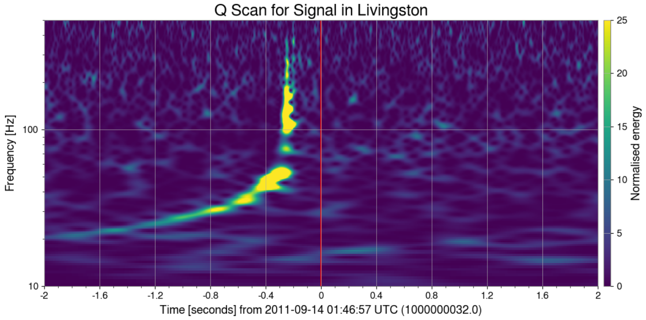

FIG. 5. Simulated event created using two 20 solar mass black holes with the glitch injected directly onto the signal.

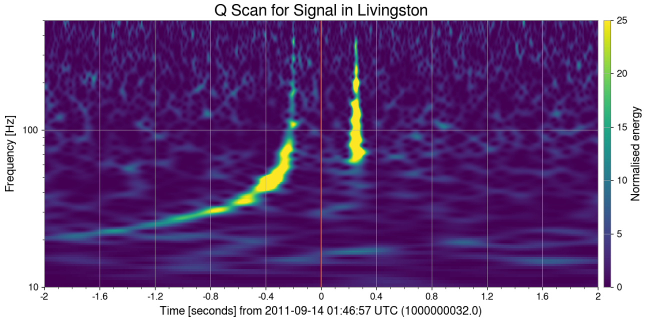

FIG. 6. Simulated event created using two 20 solar mass black holes with the glitch injected 0.5 seconds after the signal.

$40 M_{Sun}$ runs we set the minimum mass prior to 10 and the maximum to 50 for both masses. The chirp mass prior too, had limits of 10 and 50. For the mass ratio we set the lower limit to 0.125 and the upper limit to 1. The phase parameter naturally has limits of 0 to 2 pi, and the geocentric time was given plus or minus 1s on either side of the known merger time. The declination prior was set using the Cosine function from bilby.core.prior, and the right ascension was given a minimum of 0 and a maximum of 2 pi. $Theta_{jn}$ was set using the Sine function from bilby.core.prior, and psi was given a minimum of 0 and a maximum of pi. The luminosity distance had a range of 100 Mpc to 5000 Mpc, and lastly both chi_1 and chi_2 had limits of 0 to 0.99. Any parameter not listed here was set to zero.

IV. RESULTS

Bilby parameter estimation produces posteriors of various parameters. We decided to focus on three parameters that are especially important to recover: mass ratio, chirp mass, and luminosity distance. The mass ratio is simply the ratio m_1/m_2. Every event in our data set should have a mass ratio of 1 but we do not expect to get a posterior histogram centered on 1 because the mass ratio cannot exceed unity and therefore 1 is the upper limit on our mass ratio prior. For the three events using two 20 solar mass black holes with the glitch before, on, and after the signal, we found median mass ratios of 0.813, 0.831, and 0.792 respectively. All of these values fall within their specific 90% confidence intervals. The overlaid posterior plots for the 20 solar mass events can be found in Figure 7. For the three events using two 30 solar mass black holes with the glitch before, on, and after the signal, we found median mass ratios of 0.815, 0.858, and 0.840 respectively. Again all of these values fall within their specific 90% confidence intervals. The posterior plots for the 30 solar mass events can be found in Figure 8. Due to the actual mass ratio value being essentially impossible to recover, we can conclude that Bilby was able to find the mass ratio fairly well, despite the presence of the blip glitch. We can also conclude that the proximity of the glitch to the signal did not significantly impact Bilby's ability to retrieve the mass ratio for systems of either total mass.

The second parameter we investigated is chirp mass, which is given by the equation:

$$M_{chirp} = \frac{(m_1 * m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

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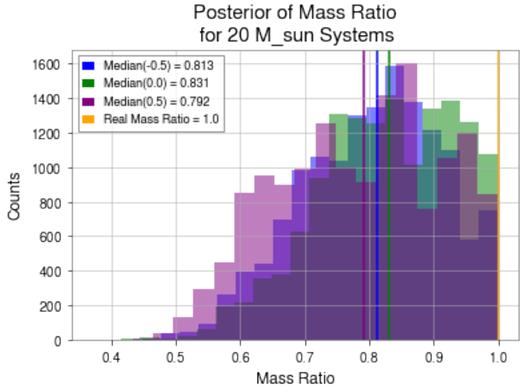

FIG. 7. Posterior of mass ratio for all three events using two 20 solar mass black holes. Medians for the events with the glitch placed before, on, and after the signal are shown with vertical lines in blue, green, and purple respectively. The true mass ratio of one is marked with an orange line at the upper limit of the graph. All three overlaid posteriors agree fairly well, and each produce medians that are within their 90% confidence intervals. This interval is from 0.613-0.970 for the blue event, 0.637-0.977 for the green event, and 0.577-0.972 for the purple event.

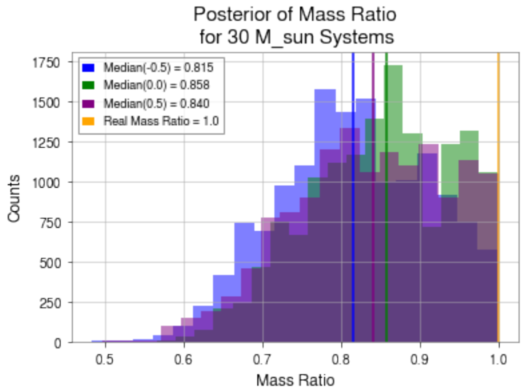

FIG. 8. Posterior of mass ratio for all three events using two 30 solar mass black holes. Medians for the events with the glitch placed before, on, and after the signal are shown with vertical lines in blue, green, and purple respectively. The true mass ratio of one is marked with an orange line at the upper limit of the graph. All three overlaid posteriors agree fairly well, and each produce medians that are within their 90% confidence intervals. This interval is from 0.658-0.967 for the blue event, 0.696-0.984 for the green event, and 0.668-0.983 for the purple event.

From this equation we calculated an actual chirp mass for the system using two 20 solar mass black holes to be $17.411 M_{sun}$ and $26.116 M_{sun}$ for the 30 solar mass system. All posteriors for the chirp mass are well-behaved with medians surprisingly close to the calculated values. The posterior plots of chirp mass for the 20 and 30 solar mass systems can be found in Figures 9 and 10 respectively. The largest deviation between a median and the true chirp mass is between the 30 solar mass event with the glitch placed 0.5 seconds behind the signal, but this is only a difference of 0.043. Based on these posterior distributions and the well recovered chirp mass, we can conclude that the glitch did not have an impact on our ability to recover this parameter for all combinations of masses and glitch times discussed above.

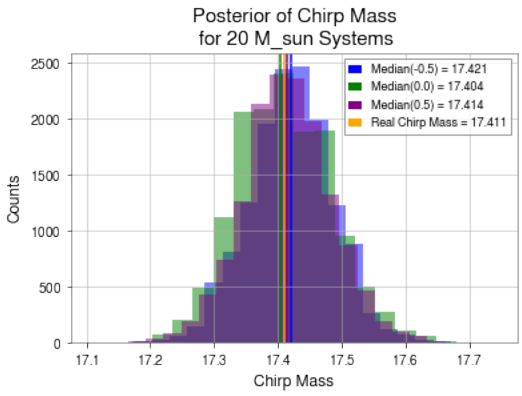

FIG. 9. Posterior of chirp mass for all three events using two 20 solar mass black holes. Medians for the events with the glitch placed before, on, and after the signal are shown with vertical lines in blue, green, and purple respectively. The true chirp mass of 17.411 is marked with an orange line. All three overlaid posteriors are well-centered Gaussians with their peaks aligned approximately on the true value. Each produce medians that are within their 90% confidence intervals. This interval is from 17.311-17.523 for the blue event, 17.296-7.535 for the green event, and 17.302-17.527 for the purple event.

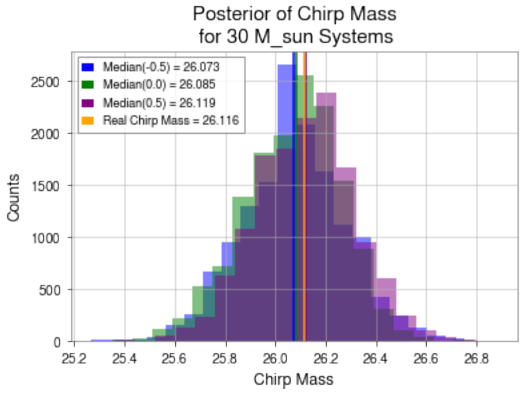

FIG. 10. Posterior of chirp mass for all three events using two 30 solar mass black holes. Medians for the events with the glitch placed before, on, and after the signal are shown with vertical lines in blue, green, and purple respectively. The true chirp mass of 26.116 is marked with an orange line. All three overlaid posteriors are well-centered Gaussians with their peaks aligned close the true value. Each produce medians that are within their 90% confidence intervals. This interval is from 25.750-26.415 for the blue event, 25.730-26.358 for the green event, and 25.799-26.431 for the purple event.

The last parameter we focused on was the luminosity distance which is the distance in mega-parsecs from Earth to the merger. This is another parameter we picked when creating the simulated signal, which we chose to be 1200Mpc. As with the other two parameters, the median luminosity distances for every combination of masses and glitch placements are within their respective 90% confidence intervals. We can conclude that the glitch had no effect on the ability of Bilby to recover this parameter for the combinations of masses and glitch times discussed here.

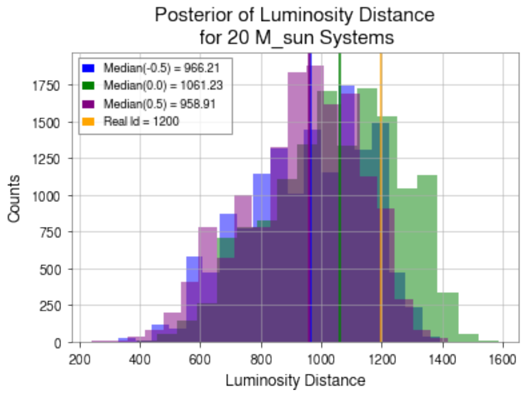

FIG. 11. Posterior of luminosity distance for all three events using two 20 solar mass black holes. Medians for the events with the glitch placed before, on, and after the signal are shown with vertical lines in blue, green, and purple respectively. The true chirp mass of 1200Mpc is marked with an orange line. Each posterior distribution produces medians that are within their 90% confidence intervals. This interval is from 595.906-1228.331 for the blue event, 685.748-1359.787 for the green event, and 596.027-1215.667 for the purple event.

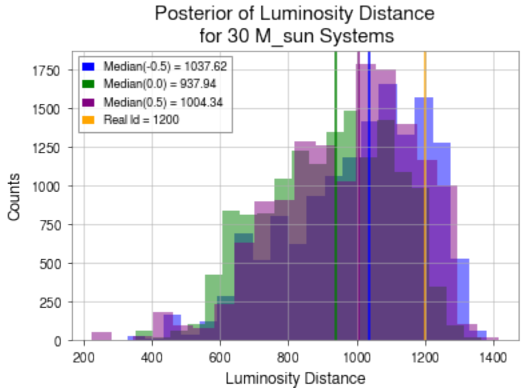

FIG. 12. Posterior of luminosity distance for all three events using two 30 solar mass black holes. Medians for the events with the glitch placed before, on, and after the signal are shown with vertical lines in blue, green, and purple respectively. The true chirp mass of 1200Mpc is marked with an orange line. Each posterior distribution produces medians that are within their 90% confidence intervals. This interval is from 645.343-1271.406 for the blue event, 611.757-1201.746 for the green event, and 642.962-1260.074 for the purple event.

V. FUTURE WORK

To make this study more comprehensive, we could run Bilby on the higher mass systems we simulated. Originally we planned to include results for a system of two

40 solar mass black holes, and a system of two 50 solar mass black holes. We ran into an unexpected problem with Bilby where it quit close to the end of the run for the 40 solar mass system. This happened at the very end of the semester which is why we ultimately decided to leave higher masses out of this study. It would be an interesting project to look at the higher mass systems because GW signals get shorter as the masses increase. It would be useful to know if Bilby is able to differentiate between shorter signals and the blip glitch. Another way to continue this project would be to investigate other parameters outside of the three we focused on here. Alternatively, a similar project could be done with a different type of glitch such as a scatter light glitch which is particularly difficult to model and extract from the data.

VI. ACKNOWLEDGEMENTS

I would like to thank my mentors Jonah Kanner and James Lowenthal for allowing me to continue and expand upon my summer research. Jonah Kanner offered guidance and support throughout, helping me to make sense of my findings and teaching me valuable skills on how to effectively communicate my research. James Lowenthal approved my continuation of the study for the recipt of course credit. I would also like to thank the LIGO organization for the opportunity to learn and grow by working for them.

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