LIGO SURF Interim Report: Facilitating Multi-Messenger Astronomy with Early Warning Gravitational Wave Detection

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ABSTRACT

Early warning gravitational wave detection pipelines are extremely important tools that could alert astronomers to a gravitational wave event before the event has occurred, facilitating a new frontier for multi-messenger astronomy. The aims of this project are to study the early warning pipeline, specifically GstLAL, and run the pipeline using data from Advanced LIGO and Advanced Virgo's third observing run colored to projected O4 sensitivities. I am varying this data by the upper frequency bound, since early warning detections are concentrated in the lower frequency bands, and comparing the background plots for various frequencies. Once this goal has been completed, I will work on testing various methods for optimizing the pipeline. Specifically, I plan to split the inspiral waveform by time and test to see how the background changes for the full waveform as opposed to various time slices of the waveform. The results of this project will give us insight into how many false alarm events we could detect in O4 and will contribute to making more accurate localization estimates of the events to come.

INTRODUCTION

Gravitational waves, originally predicted by Albert Einstein almost a century ago, are ripples in the fabric of spacetime produced when massive objects such as black holes or neutron stars collide. These waves propagate through spacetime at the speed of light, interacting weakly with matter as they travel through the universe. The Laser Interferometer Gravitational-Wave Observatory, or LIGO, can detect these waves by observing very minute changes in the length of the LIGO detector's 4 kilometer arms. The interferometer process begins when a laser is shone through a beam-splitter, sending light through the arms to mirrors at the ends and back. If there is no change in the length of the arms, no signal is detected through the photodetector. However, a minuscule change in the distance of the arms will result in a signal detection from the photodetector, and data can be obtained from this signal. Indeed, when gravitational waves reach the Earth, they are so small that only a tiny fraction of the original amplitude is detectable; therefore, the change in distance of the arms is also very small.

One way researchers extract a signal from the data collected by LIGO is by using a technique called matched filtering, which correlates the predetermined signal with the observed data. Matched filtering techniques generate thousands of waveforms which are collected into a template bank, used to identify candidate signals. These are then compared to the obtained gravitational wave data in order to observe high similarities. Search pipelines are used to filter through thousands of gravitational waveform templates and pick out the best candidate signals. Pipelines can vary in the following processes, but my project will work with GstLAL, which divides the template bank into subsets, grouping the waveforms together in terms of common factors such as mass or spins. This step is important because this grouping of waveforms by similar parameters will be used in evaluating the likelihood ratio ranking statistic of each event later in the pipeline. [1] [2]

My project will involve working on the GstLAL early warning pipeline, and the problem I am trying to solve deals with improving the technology of gravitational wave detection in order to alert telescopes and observatories of the event as quickly as possible. These results will be worthwhile because decreasing the time between detection and transmission of gravitational wave events will facilitate electromagnetic observations. This topic has already been researched in the past by the group I will be joining, and contains work of many previous papers written by my mentor and others. The results of this research will actively test information that could contribute to the next LIGO observing run. [3]

OBJECTIVES

LIGO's third observing run in 2017 marked a turning point for gravitational wave science: this was the first gravitational wave event detected from a binary neutron star system. Such systems are important in facilitating multi-messenger astronomy because we are able to observe the phenomenon with gravitational waves as well as with the electromagnetic spectrum, and such observations carry insight about short gamma-ray bursts, r-process nucleosynthesis, the final state of the remnant, and many more astrophysical mysteries. In 2017, there was a 4.5 hour window between the gravitational wave's arrival to Earth and sky localization of the event. Reducing this time window will further our knowledge of the early stages of binary neutron star mergers, and is the motivation of early warning gravitational-wave detection pipelines, such as GstLAL. [1]

As discussed previously, early warning detection pipelines, specifically GstLAL, sift through thousands of candidate signals through the process of matched filtering, which matches raw LIGO data to different waveforms. Candidate events are then assigned false alarm rates through comparison to the background, and through these false alarm rates the pipeline can quickly determine whether the signal we have detected is a gravitational wave event or not. The goal of my project is to understand how this pipeline works, and eventually learn enough to run the pipeline using data from LIGO's most recent observing run, which is whitened and recolored to the sensitivities of the next observing run.The aims of this research project are to improve this detection pipeline so that it will more efficiently detect gravitational waves, and therefore shrink the time window between gravitational wave arrival and sky localization. Additionally, the results of this project will give us insight into how many false alarm events we could detect in the next observing run (O4) and will contribute to making more accurate localization estimates of the events to come. [4]

APPROACH

My project is measuring binary neutron star (BNS) and neutron star black hole (NSBH) candidate gravitational waves at different times before the merger event occurs. The goal is to learn how to run the early warning pipeline, test the pipeline using data from O3, and then work with my mentor on different tests to increase the efficiency of the pipeline, improve the pipeline sensitivity, and minimize false alarms, the results of which could actively benefit the next observing run. Before learning how to run the early warning gravitational-wave pipeline, I learned each step in the GstLAL low-latency pipeline and understand what each program within this pipeline will do.

First, I increased my understanding of the GstLAL software and acquired an understanding of the GstLAL workflow for analysis, which leads into my next step of running the analysis. I have been running a few different tests through the GstLAL pipeline for different frequency bounds and have used the results from these runs to create background plots and animations to analyze. Additionally, I recently created some plots which display the probability due to noise for each bin in the GstLAL pipeline. Finally, I will analyze the results of my research and my mentor and I will apply these results to the next observing run. I will be collaborating with my mentor, Ryan Magee, in addition to other GstLAL team members.

CURRENT WORK

Previously, I was working on a Python program which calculated and plotted the number of detections LIGO expects per year in O4 versus the time before the merger (in seconds), with inputs such as chirp mass, signal-to-noise ratio, and various bounds for the frequencies. To calculate the number of detections per year, I multiplied a binary neutron star merger rate of $320\text{Gpc}^{-3}\text{yr}^{-1}$ by a volume function which takes the distance that LIGO can see as an input. This distance function involved interpolating the power spectral density data for specific frequencies, and then integrating through the data with various frequency bounds. This plot is attached below. As binary systems approach merger, their frequencies increase as a power law of $\text{f}^{11/3}$, so varying the bounds of these frequencies allows us to identify candidate binaries before merger. Since the frequency increase is monotonic, we know that the frequency will never decrease before merger, so we can simply look at the lower frequencies if we are attempting to find binaries before merger. Through this process, I have estimated the number of early detections LIGO can hope to achieve every year, as well as the fraction of those detections close enough for observation through the electromagnetic spectrum. With these graphs and equations, we can create a clearer picture of the binaries before they merge, which will facilitate greater understanding of processes we wish to learn more about. [5] [6] [7]

Currently, I have reached the stage of the project where I am running "fake" data through the GstLAL pipeline from a two week segment of O3a, which includes a binary neutron star system, GW190425. I am calling this data "fake" because it is colored data from O3a which is then whitened and recolored to O4 sensitivities. Colored data is data which includes LIGO's frequency dependence, and by whitening this data, we are removing the frequency dependence and adding in the frequency dependence of LIGO's O4 sensitivities. Now, we have "fake" signals with realistic imperfections, such as gravitational wave signals and glitches, hidden inside the noise, and we can treat this like real data to run through the detection pipeline. After running this data through the pipeline and creating a plot of the power spectral density for O4, we observe that the sensitivity of the detectors and the horizon distance (the range which LIGO can observe) is much greater for O4 than it was for O3.

Last week, I completed two runs through the pipeline corresponding with two different upper-limit frequencies: 1024Hz (the full frequency spectrum) and 29Hz (an upper limit corresponding to early warning detection). These runs were each for two days of the two week segment, and were utilized to compare the background plots attached below. We can observe that there is much more noise in the 29Hz run than there is in the 1024Hz run, a factor which hinders early warning detection, and the green dot on the plots (corresponding to an SNR=8 and a chi2=1) is enveloped in noise in the early-warning case. I have also made a few animations which compare the background plots for 29Hz and 1024Hz for each detector. This week, I worked on a run where 56Hz is the frequency upper bound, and from this run I will create more background plots to compare with the previous ones.

This week I have also been working on some new plots and programs which extract the probability densities for different bins from the marginalized likelihood ratio for two different runs: 29Hz and 56Hz. I then created a program and a few plots which shows the difference between probability densities for 29Hz subtracted from 56Hz, and compares this to the bin number, holding SNR=10 and chi2=1.

The next steps for this project will include marginalizing the likelihood ratios for each bin and combining the two runs, and ultimately analyzing the data and plots this will produce. Afterwards, I will continue to work with my mentor and test new hypotheses which we hope will increase the efficiency of the pipeline.

PLOTS AND EQUATIONS

Below is the distance equation that I used when determining the volume function for my program, which led me to create the plot below, seen in Fig.1.

$$D = \frac{1}{8}\left(\frac{5\pi}{24c^3}\right)^{1/2}(\mathrm{GM})^{5/6}\pi^{-7/6}\sqrt{4\int_{flow}^{fhigh}\frac{\mathrm{f}^{-7/3}}{Sn(f)}df}$$

This equation is a measure of the range of LIGO's viewing capabilities. This distance function is used as the radius in the volume function which determines the number of detections LIGO will observe per year. We then multiply the volume function by the BNS merger rate we used earlier, 320Gpc^{-3}yr^{-1}, to determine the detections per year. In this equation, we are assuming that the signal-to-noise ratio is 8, and that both masses are 1.4 solar masses. To find the equation for the red line on the plot, we find the maximum distance by creating a fraction,

$$D = \frac{200Mpc}{MaximumDistance}$$

which measures only the events that could be observed through electromagnetic observers, since 200 Mpc is the upper bound for viewing mergers in the electromagnetic spectrum. The maximum distance involves integrating the previous equation from 10Hz to 1024Hz. Then we use this distance in the volume function to determine the number of multi-messenger astronomy events per year that we could observe; we estimate from this graph that there will be one of these events in O4. [7]

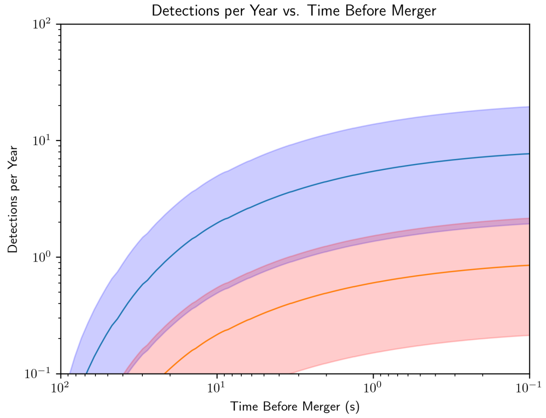

FIG. 1. This is a plot of the detections per year that we anticipate LIGO will receive during O4, the next observing run, plotted against the time before merger in seconds. The orange line corresponds to the events we will detect within 200 Mpc, which is an optimal range for observing binaries through the electromagnetic spectrum. The blue line corresponds to all events LIGO will detect. This plot shows us that we will detect around 8-9 events per year, and one detection per year that is 10-20 seconds early. Additionally, this plot tells us that we will detect one multi-messenger astronomy event in O4.

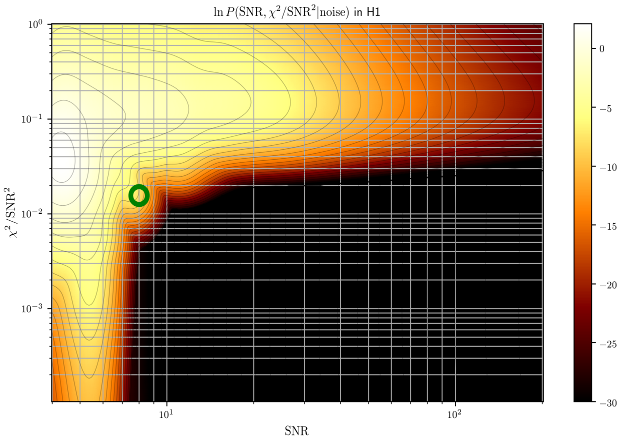

FIG. 2. Here is a background plot of a run through the GstLAL pipeline with a segment of O3a data whitened and recolored to O4 sensitivities, with an upper frequency bound of 29Hz. The orange area corresponds to the noise and background that we expect for O4, and we can see that the green dot (corresponding to an SNR=8 and χ^2=1) is obscured in the background, making early-warning detection very difficult.

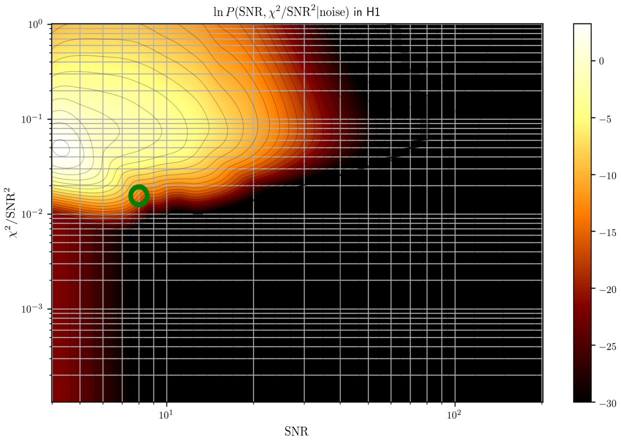

FIG. 3. This plot is similar to Fig 2, but this run took into account the entirety of the frequency spectrum LIGO can detect, with an upper bound of 1024Hz. We can see that the background is much smaller for this plot than the previous one, and that the green dot is located right on the outskirts of the noise, making detection more plausible.

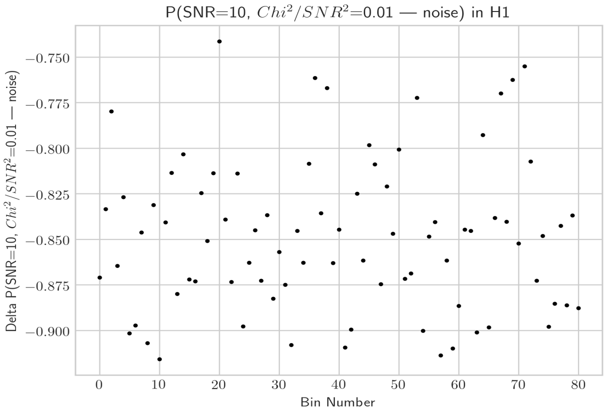

FIG. 4. These are the most recent plots I have created, which show the probability that a signal is due to noise for various bins in the marginalized likelihood ratio, assuming that SNR=10 and χ^2=1. The x-axis of the plot shows the bin number and the y-axis is the difference in probability densities for 29Hz subtracted from the probability densities for 56Hz. This plot measuring Hanford's data only.

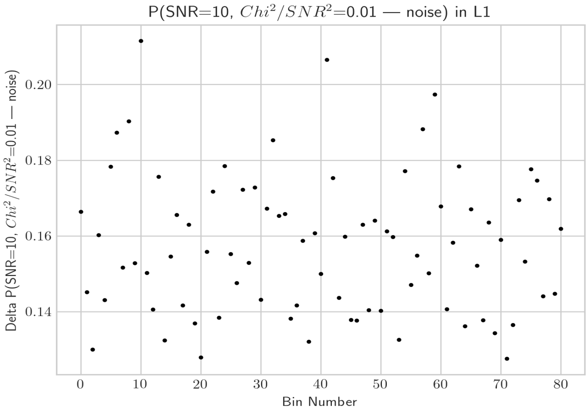

FIG. 5. This plot is the same as the previous one, only using data from Livingston's observatory instead. I'm encountering a problem with the drastically different y-axes, which I am currently looking into.

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