Optimal Settings for Fast Low-Latency Skymaps of Neutron Star Binaries
Second Interim Report

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The detection of gravitational waves is instrumental to our understanding of astrophysical processes and the fate and evolution of the sources of such waves. One source of gravitational waves is compact binary coalescences (CBC)–binary systems which consist of black holes, neutron stars, or both. Specifically for this project, we will be focusing on neutron star binary systems and how to optimize data intake to improve localization of such systems. Longer signal durations increase typical computing effects but maximize relevant information we can extract from the signals. For analyses where prompt results are essential, such as for multimessenger followup, we aim to study the ideal conditions for fast and accurate analysis.

I. INTRODUCTION

Since its inception, the Advanced LIGO and Advanced Virgo detectors have discovered a plethora of gravitational waves. Their first gravitational wave transient catalog includes ten binary black hole coalescences and one binary neutron star coalescence. Additionally, an updated second gravitational wave catalog from a third observing period has yielded dozens more events, with signals encompassing even more compact binary coalescences [1].

The binary neutron star merger was detected through GW170817 [2]; the first signal from this low-mass, compact binary inspiral was detected August 17, 2017, and was inferred by astronomers to be located in the NGC 4993 galaxy. Gravitational waves from binary neutron stars exhibit a chirplike time evolution which depends both on the system's component masses, or chirp mass, and its mass ratio and spins. Also unique to neutron star systems is the influence of their internal structure on its waveform; such properties can be inferred from tidal interactions.

The localization of GW170817 to the NGC 4993 galaxy was aided by the skymap that was computed from gravitational wave data. Once the skymap was constructed, astronomers were able to follow up on this data and were able to localize the source within a few hours after initial detection. Figure 1 demonstrates the improved localization of GW170817 from gravitational wave data alone due to improved calibration of Virgo data. Assuming the previously deduced location in NGC 4993, the 90% localization region was reduced from 28 deg^2 to 16 deg^2.

Aiding in this endeavor of gravitational wave detection is BILBY [3], a Bayesian inference library which infers source properties from individual signals of compact binary coalescences. To date, BILBY has produced reliable results for both simulated and real gravitational wave data from compact binary mergers and coalescences. Using these source properties, in upcoming observing runs BILBY will be used to compute skymaps which will then be utilized by astronomers to localize the gravitational wave signal sources, such as in the case of GW170817.

II. MOTIVATIONS

Gravitational wave data allows for localization of the source signal itself, upon which astronomers may then search to identify the exact location of the CBC event. Ideally, this continuous process of intaking gravitational wave data and computing the subsequent skymap should occur in as minimal a timeframe as possible, since an electromagnetic signal from the CBC event could fade rapidly within the span of a few hours or even minutes. The runtime will vary depending on which parameters are sampled but ideally should last from a few minutes up to half an hour.

Ultimately, many inferred source parameters through gravitational wave data of merging binary neutron will be further improved by and electromagnetic detection and identification of the host galaxy. These include specific properties of the binary system itself, such as its mass, spin, and tidal parameters, which may also better equip our general understanding of binary, stellar evolution. Improved localization may also better our understanding of short gamma-ray burst properties and, on a grander scale, the equation of state of neutron-star matter, the nature of gravity, the value of the cosmological constant, and even allow us to test theories of general relativity.

III. METHODS

We are relying on Bayesian inference for this project. We begin with a posterior probability dis-

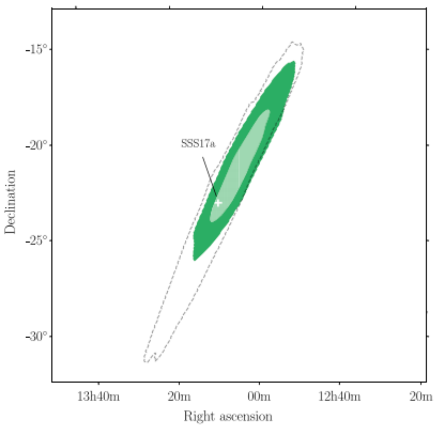

Figure 1. The improved localization of GW170817, with the dotted gray line indicating previous localization of 90% credibility from 2017 and lighter and darker green regions corresponding to increased region credibility of 50% and 90%, respectively, in 2019.

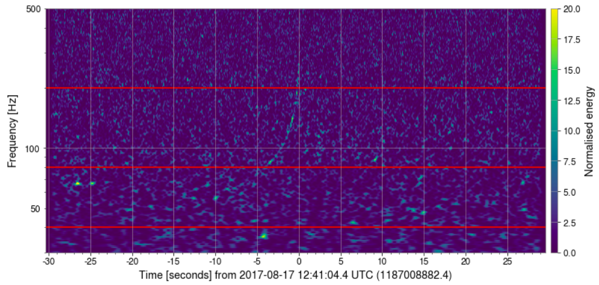

Figure 2. Spectrogram of GW170817 from the LIGO Hanford detector with the merger placed at the 0 second time mark. Horizontal lines denote frequencies of 40, 80, and 200 Hz, respectively, which correspond to various times that different parameters may be inferred.

tribution which is calculated using Bayes' Theorem:

$$p(\theta|d) = \frac{\mathcal{L}(d|\theta)\pi(\theta)}{\mathcal{Z}} \tag{1}$$

Here θ represents the source parameters, $\mathcal{L}(d|\theta)$ is the likelihood function, or probability of the detectors measuring data d assuming a model hypothesis, $\pi(\theta)$ is the prior distribution, which incorporates any prior knowledge about our parameters, and $\mathcal{Z}$ is the normalization factor, or evidence, which is defined as:

$$\mathcal{Z} = \int \mathcal{L}(d|\theta)\pi(\theta)d\theta \tag{2}$$

This evidence indicates how well the data is modeled by the hypothesis, which is vital for model selection. In this case, the posterior probability distributions are calculated by BILBY, and we apply restricted analysis by focusing on restricted parameters and/or timeframes in order to narrow down the posterior distribution area. Ultimately the parameters that we will primarily be interested in are the sky location and the distance to the source.

For every signal analysis, there exists a trade-off between accuracy and computational efficiency. A typical signal may last for a span of around two minutes with a frequency ranging from 20 Hz to 2000 Hz, as shown in Figure 2. Conversely, the duration to compute the associated skymaps may range from a few hours to even months, depending on various factors including models and tools for analyses. This proves problematic when we consider that the electromagnetic signal from the CBC event may last only up to a few hours at most and a skymap must be computed and distributed for astronomical follow-up as soon as possible. As such, we explore how settings such as time duration, sampling frequency, frequency bounds, and the sampler dictionary may be optimized in order to achieve reliable sky localization in a minimal timeframe. We aim to analyze both binary neutron star injections and real data from GW170817.

IV. PROGRESS

Thus far, I have completed both binary black hole and binary neutron star injection runs on BILBY _PIPE, a Python package which automates the process of running BILBY on a computing cluster [3]. I have been analyzing these run results using PESummary, a parameter estimation summary page builder which compiles relevant data, such as the waveform shown in Figure 3, into a user-friendly and comprehensible webpage [4].

A. Binary Black Hole Injections

The most recent binary black hole run proved fairly successful overall with a runtime of a few hours; the injection was set at a duration of 4.0 seconds, sampling frequency of 4096 Hz, and used the waveform model IMRPhenomPv2, which allows for precession (although for the purposes of this project, no injections will demonstrate precession with all spin angles and most spin magnitudes fixed to zero). With the exception of the effective spin as shown in Figure 4, most relevant parameter posterior distributions were centered around the true injected values. We speculate that the inaccuracy for the effective spin could be due to the significant difference in spin

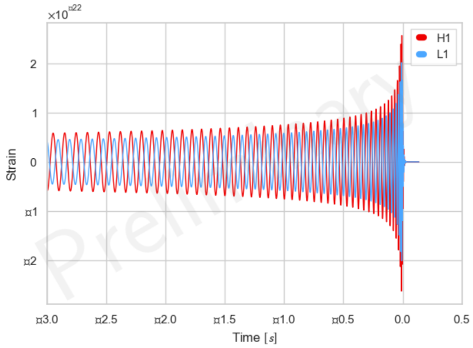

Figure 3. Plot generated by PESummary showing the time domain waveform from Livingston and Hanford detectors of a binary black hole injection, generated from the maximum likelihood samples.

magnitudes for the black holes, at 0.014 and 0.765 respectively.

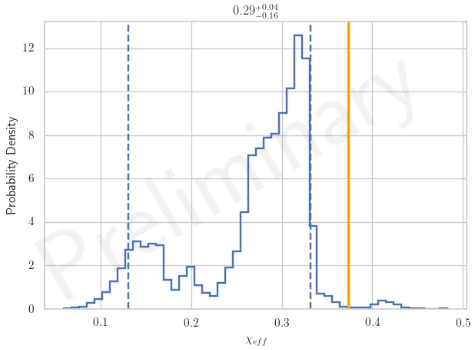

Figure 4. The marginalized posterior distribution for chi_eff (the effective inspiral spin parameter) of a binary black hole injection. The vertical dashed lines show the 90% credible interval and the title gives the median and 90% confidence interval; injected value is marked by the orange vertical line.

In particular, the sky location parameters which we are primarily interested in for this project were closely constrained, although not completely accurate, as shown in Figure 5. Unfortunately, a speculated unidentifiable error in PESummary causes the injected values to not appear in random cases such as this one; nonetheless, when compared to the injected values the posterior distributions seem to center fairly well.

Figure 6 gives the skymap of the binary black hole injection and better visualizes the parameter distributions of the injected signal by plotting the true value along with its sky localization. The signal was localized to a moderately constrained region of 118 deg^2 for the 90% credible region, despite being around 30 deg below the actual source location. This discrepancy could possibly be due to the unusually large distance of the injection at 1434.301 Mpc. I caught this error and reduced it drastically for future runs.

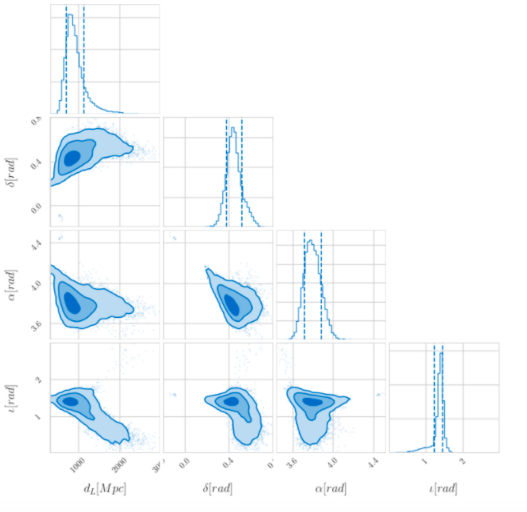

Figure 5. Corner plots showing posterior distributions of location parameters–right ascension, declination, distance, and inclination angle–for binary black hole injection. Injected values unable to be shown due to PESummary glitch.

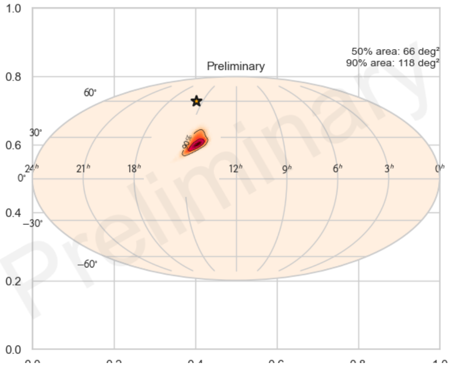

Figure 6. Skymap of binary black hole injection showing the most likely position of the source that generated the gravitational wave, with 50% and 90% credible intervals and injected value given. The black region corresponds to the most likely position and light orange least likely.

B. Binary Neutron Star Injections

In general, binary neutron star runs have proven to be much more complicated than those of binary black holes. While I have kept the sampling frequency at 2048 Hz, the longer signal requires a larger analysis segment which increases runtime. I initially used durations of 64 and 128 seconds, but not only were the runtimes extremely long but the signal was not very well read. I then reduced the duration to 32 seconds which improved the run results. A host of other settings were varied throughout the BNS runs; to start, I increased the minimum frequency from 20 Hz to 32 Hz to better focus on relevant inferred parameters which occur closer to the late inspiral stage of a BNS signal track. As aforementioned, I decreased the distance to 40 Mpc, which would produce a signal about as loud as GW170817 [2], and greatly increased the signal to noise ratio compared to earlier BNS runs as shown in Figure 7.

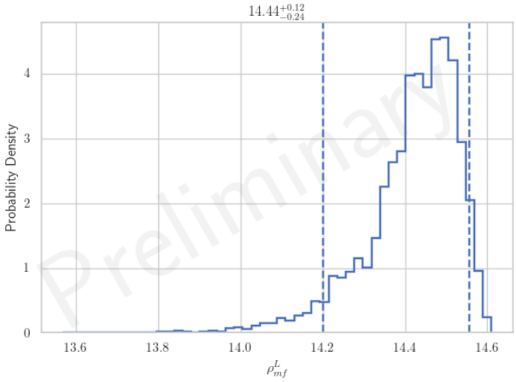

Figure 7. Plot showing probability distribution of matched filter signal to noise ratio (SNR) of binary neutron star injection from LIGO Livingston observatory.

Additionally, I have been experimenting with the sampler dictionary which also affects runtime. BILBY uses the default sampler Dynesty, which utilizes both nested sampling and Markov chain Monte Carlo (MCMC). Some sampler settings I can vary include the number of likelihood live points as well as the maximum number of random walks to use. The length of these runs are still at least a day, and some of the posterior distributions are inaccurate; nonetheless, the sky localization of some more recent runs happened to be closer to the injected value, as shown in Figure 8, and we will continue to try to improve this metric and reduce runtime in the following weeks.

V. CHALLENGES AND FUTURE PROSPECTS

The first problem we will try to overcome is the inaccuracy of the posterior distributions for our BNS runs. Although some parameters have been well constrained, including sky localization, they are still in the wrong region and do not encompass the actual injected values. To fix some prior railings, I made sure to marginalize time, distance, and phase parameters for future runs; I also adjusted the prior settings involving spin by using a single spin parameter, chi_i, instead of separate parameters for the spin magnitudes and angles, which should prevent the effective spin railing that we have been experiencing. We will continue to experiment with current settings to try to reduce the runtime and potentially experiment with parallelization to aid in this endeavor. If these BNS injection runs succeed and time permits, I will attempt to do runs on real data from GW170817.

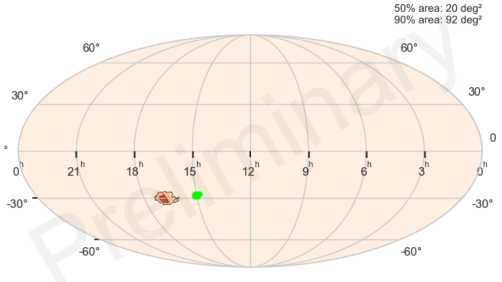

Figure 8. Skymap of binary neutron star injection showing the most likely position of the source that generated the gravitational wave, with 50% and 90% credible intervals given. The black region corresponds to the most likely position and light orange least likely.

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[1] B. Abbott *et al.*, Gwtc-1: A gravitational-wave transient catalog of compact binary mergers observed by Ligo and Virgo during the first and second observing runs, (2019), arXiv:1811.12907.

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[3] I. Romero-Shaw *et al.*, Bayesian inference for compact binary coalescences with BILBY: Validation and application to the first LIGO–Virgo gravitational-wave transient catalogue, (2020), arXiv:2006.00714.

[4] C. Hoy and V. Raymond, Pesummary: the code agnostic parameter estimation summary page builder (2021), arXiv:2006.06639 [astro-ph.IM].