NINJA Data Analysis

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August 4, 2008

Work completed at Cardiff University
Funding from NSF, University of Florida, and Cardiff University

Abstract

In this paper we outline the work done at Cardiff University in the Numerical Injection Analysis (NINJA) project. The purpose of NINJA is to evaluate the effectiveness of current and new inspiral search methods using numerical relativity binary inspiral waveforms injected in simulated Gaussian noise. This paper focuses on efficiency tests of the standard LSC inspiral pipeline using effective one-body (EOB) and stationary phase approximate (SPA) waveform templates. The program BankEfficiency was used to determine useful parameters and basic template bank behaviors. The NINJA data was then run through the LSC inspiral pipeline with various parameters.

1 Background

When it comes to black holes, observational data is very limited. Due to the very properties that define a black hole, observation through electromagnetic radiation limits itself to accretion discs, and the effects of black holes on their surroundings. Gravitational waves however, provide a much more direct means of observing black holes. As a binary black hole system progresses, gravitational waves are continuously radiated. This radiation causes the system to slowly lose energy, eventually resulting in the merger of the black holes. The gravitational waves emitted during this process are rich with information, including masses, spin, etc. Several ground-based detectors have been constructed for the sole purpose of detecting these gravitational waves, including the LIGO sites in Livingston and Hanford, and the VIRGO detector in Cascina. These detectors all work in the same general fashion by using interferometry to measure the small changes in distance between test masses. Since these detectors are ground-based, and gravitational waves are very low in magnitude, noise is a significant issue. At lower frequency, the noise spectrum is dominated by seismic activity, middle frequencies by thermal noise in the test mass suspension, and high frequencies by shot noise. Due to low signal-to-noise ratios, GW signals can not be found simply by examining detector output. There are several methods used to analyze LIGO data, but this paper will only discuss matched filtering. In this process, the expected shape of the waveform is used to search through the data, and because waveforms are dependent upon several parameters, a bank of templates must be generated for each search.

2 The Pipeline

The LSC inspiral pipeline consists of five main processes. First a template bank spanning the specified parameter space is generated. Matched filtering is then conducted for each of the detectors. For every instance where the signal-to-noise ratio (SNR) surpasses a given threshold, a trigger is produced[1]. These triggers are then checked for consistency in timing and masses between detectors during coincidence testing[2]. The remaining triggers for each detector are then run through signal based vetoes to eliminate glitches and other artifacts, including the χ^2 [3] and r^2 [4] tests. Lastly a final coincidence test is run.

The template bank is typically generated at the beginning of each search. The bank covers a specified parameter space dependent on the input values from the user. One of the most significant variables is the choice of approximate, which determines how the shape of the waveform is generated. Other important parameters include upper cutoff frequency, mass range, and minimal match. The minimal match mainly affects the density of the template bank, by setting the minimum amount a randomly generated waveform must match with the closest template in the bank[5].

The χ^2 test is run in between coincidences. This test is very important in separating non-Gaussian noise glitches from actual signals. Most noise encountered with LIGO is Gaussian, so when artifacts such as Poisson-like glitches are encountered, they are capable of driving high detection output. The χ^2 test breaks the detector strain into frequency bands, with smaller bandwidths in more sensitive regions of the detector. The χ^2 value is then calculated through the relation:

$$\chi^2 = p \sum_{j=1}^{p} \left(z_j - \frac{z}{p} \right)^2 , \tag{1}$$

where p is the number of frequency bands, and z is the SNR calculated for a given template T is given by:

$$z\left(t_0\right) = \int \frac{\widetilde{s}(f)\widetilde{T}}{S_n(f)} e^{2\pi i f t_0} df. \tag{2}$$

Low χ^2 values are representative of a linear combination of Gaussian noise and possible signal waveforms. High χ^2 values show a mismatch of template and waveform, or significant non-Gaussian noise in the signal.

3 Waveforms and Approximates

A binary inspiral waveform can be broken into three main phases. The inspiral phase is what the system is in until the bodies begin their collision. At this point, the inspiral enters the merger phase, where the black holes begin to combine. The final stage is the ringdown, where the system settles after merger into a single black hole. The two approximates evaluated in this paper are TaylorF2, or stationary phase approximation (SPA), and effective one-body (EOB). The TaylorF2 approximate is that typically used for LSC inspiral searches. This approximate constructs templates of just the inspiral phase. The EOB approximate produces similar waveforms, but extends slightly into the merger region. Recently a new approximate has been developed that attempts to produce waveforms containing all three phases. The EOBNR approximate adds the final section of the waveform to EOB by approximating the merger and ringdown phases based on results from numerical simulations. The EOBNR waveforms were not completed in time for this publication, but we hope to run our analysis with this approximate in the future. In Fig. 1 the blue

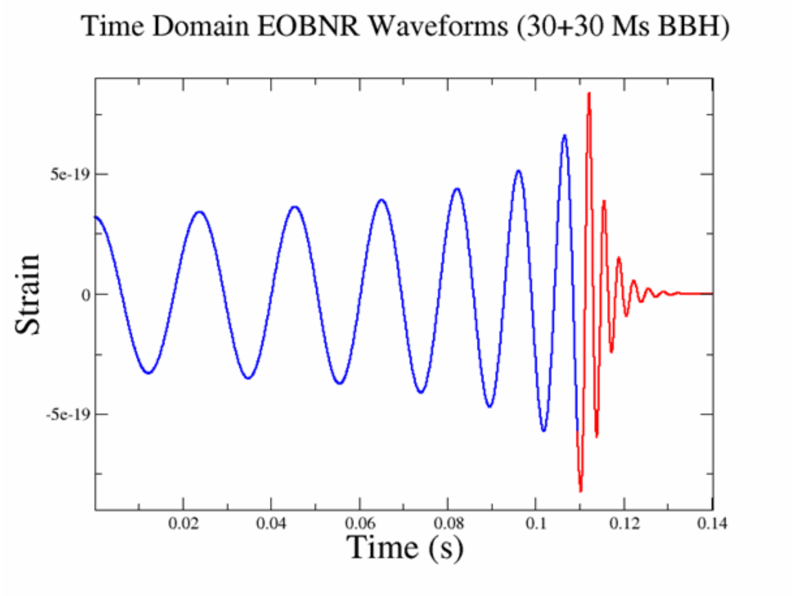


Figure 1: EOBNR – Extension of EOB

section of the waveform shows the extent of the EOB approximate. The red shows the extension provided by EOBNR.

4 Bank Efficiency

The effectiveness of these templates is difficult to determine. Since gravitational waves have never been detected, these templates are constructed purely on a theoretical basis. Currently numerical simulations of binary mergers provide what we assume to be the most realistic and complete waveforms available. These waveforms cannot be used for inspiral search due to the need of full template banks, and the computational cost to produce NR waveforms makes them very impractical for template bank construction. These waveforms can be used to construct better approximates, and test current search methods however. The EOBNR approximate is the first to use NR results to produce more elaborate waveforms, and because of this was used with a program called BankEfficiency to run initial tests of template banks. Using EOBNR, inspirals waveforms were generated and injected into noiseless data streams. Various template banks were then constructed using different approximates and parameters.

4.1 TaylorF2

The TaylorF2 approximate is a stable but limited approximate. Consisting of only the inspiral phase, the template is not favorable for detecting inspirals where merger occurs in the sensitivity region, and as a result would not be expected to perform well at high masses. In Fig. 2, the performance of the TaylorF2 approximate can be seen using EOBNR injections.

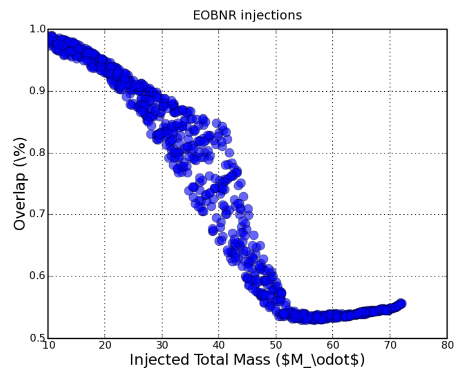


Figure 2: TaylorF2 Bank Efficiency

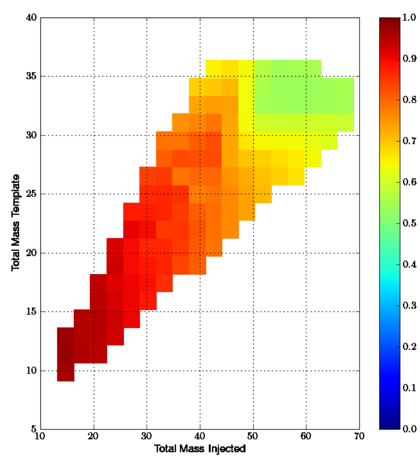


Figure 3: TaylorF2 Bank Efficiency

As expected, TaylorF2 performs quite well at lower masses, and falls steadily as the total mass of the system increases. It can also be shown that the recovered masses using TaylorF2 seem to agree reasonably well with the injected masses. Fig. 3 shows the mass accuracy and SNR decrease at higher masses.

4.2 EOB

The EOB approximate was originally expected to act in a similar fashion, with decreasing SNR at higher masses. When analyzed however, SNR values over 95% were still found at total masses of approximately $275M_{\odot}$. These high SNR values occure in spikes centered on template locations, as seen in Fig. 4. Furthermore, the

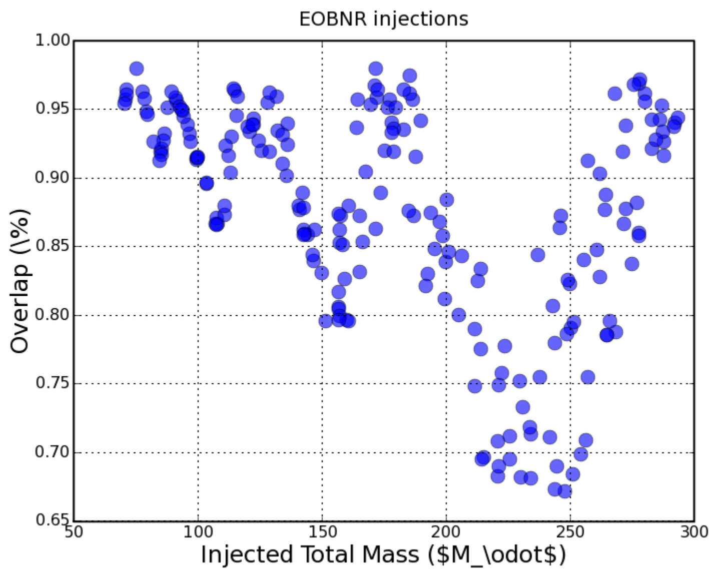


Figure 4: EOB Bank Efficiency

recovered mass is found to be very inaccurate. Fig. 5 shows the significance of the template mismatch, yet SNR remains high.

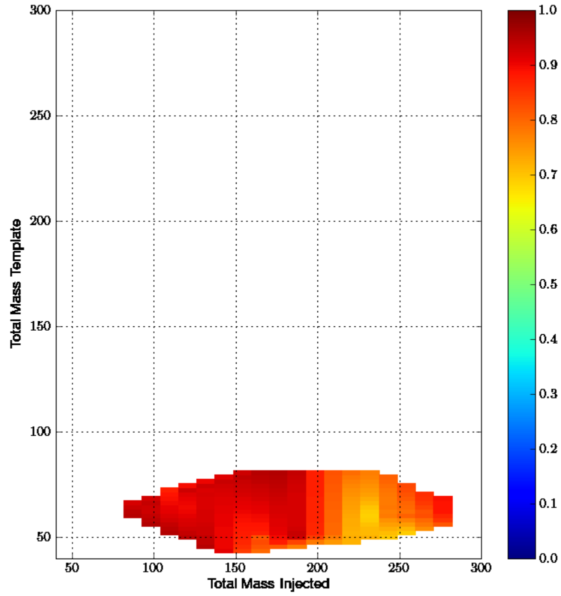


Figure 5: EOB Bank Efficiency

5 LSC Inspiral Pipeline Tests

Using the results from the BankEfficiency tests, the effectiveness of TaylorF2 and EOB approximates were tested using the inspiral pipeline on the NINJA data. We will first define the parameters used for comparison. The chirp mass $\mathcal{M}$ is a combination of independent black hole masses going as (3).

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \tag{3}$$

The symmetric mass ratio η is given by (4)

$$\eta = \frac{m_1 m_2}{(m_1 + m_2)^2} \tag{4}$$

Due to peculiar bank efficiency results with EOB, the recovered mass using the search was of particular interest with the NINJA data analysis. With the inspiral search, both approximates seem to have mismatch of templates at higher masses. Both approximates seem to return reasonable masses up to chirp masses of roughly

$35M_{\odot}$, after which accuracy begins to fall sharpy. Where the two approximates seem to differ was in recovered effective distance and χ^2 values.

5.1 Effective Distance

TaylorF2 proved to return accurate values of effective distances for all detected inspirals. EOB however seems to consistently underestimate effective distance. In Fig. 6 one can see how the results deviate from the expected diagonal.

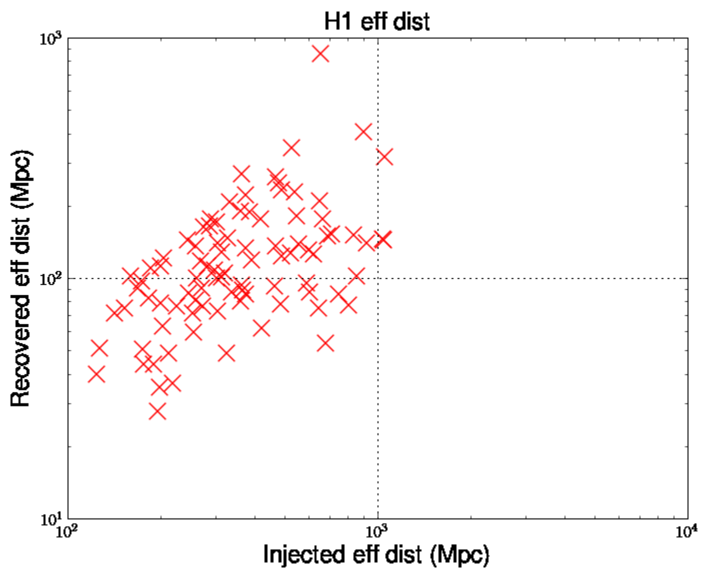
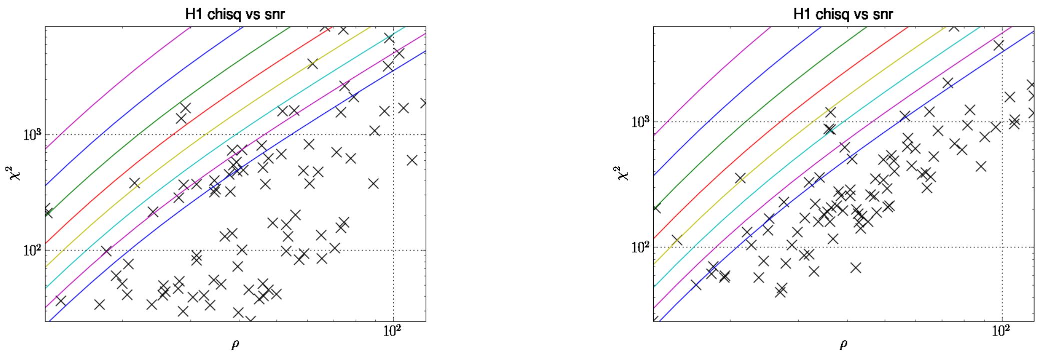


Figure 6: EOB – Effective Distance

While EOB is inaccurate with effective distance, it does seem to return lower χ^2 values, though neither were significantly high. It should also be noted that detections do not seemed to be killed by coincidence, even though the templates which are detecting the high mass injections are very different from the injections themselves.

5.2 χ^2 Comparison

Since the χ^2 value of a given trigger reflects how well the closest template matches each ejection, it is a decent indicator of template performance. Both TaylorF2 and EOB templates seemed to perform comparably, with some subtle differences. Looking at Figs. 7(a) and 7(b), the difference in χ^2 can be seen.



(a) TaylorF2 (b) EOB

Figure 7: Comparison of χ^2 values.

The colored lines show curves of constant effective χ^2, which decreases as one progress down and to the right of the area shown. These plots make it evident that EOB produces consistently lower χ^2 values than TaylorF2.

5.3 Parameters

Using TaylorF2 the effects of minimal match, cutoff frequency, and post-Newtonian order were evaluated. The most significant increase in detections came with an increase in upper cutoff frequency. An increase in PN order also tends to increase detection.

Template	TaylorF2	TaylorF2	TaylorF2	TaylorF2
Minimal Match (%)	97	97	97	99
Freq Cutoff	SchwarzISCO	ERD	ERD	ERD
Post-Newtonian Order	2	2	pseudo 4	pseudo 4
Single Detector (H1,H2,L1)	91,90,84	92,93,86	93,93,89	93,93,88
Coincidence	73	86	90	90
Coincidence & Vetoes	72	86	92	92

There were 160 total injections intended to be in the NINJA data. Due to issues with file generation however, it was found that approximately half of the injections were not actually made. In order to survive coincidence testing, the injections must be in a at least two of the detectors. Out of the 94 total injections present in two or more detector strains, the inspiral pipeline was able to detect up to 92 after coincidence and signal veto. The pipeline's ability to recover such a range of NR waveforms shows it to be a very stable and reliable search tool for gravitational wave searches.

6 Conclusions and Remaining Work

The NINJA calaboration is having a conference in Syracuse, NY. The author will be presenting the results discussed in this paper at the conference. The calaboration also hopes to have released a revised data set containing all injections. We hope to run a full analysis on this data using TaylorF2, EOB, and EOBNR templates (if ready) for the conference. Once this analysis has been run on a data set sure to contain all expected injections, it will be possible to determine exactly what characteristics of merger cause problems within the pipeline.

From what analysis was able to be done with the partial injections, it seems that spin and other properties do not pose significant obstacles to the analysis. We were not able to determine precisely how the distance of the system affects detection, since most of the distant mergers were the ones not properly injected. The parameters with greatest effect on detection were the cutoff frequency and post-Newtonian order. Optimum values for these variables seem to be a cutoff frequency at effective ringdown (ERD), and pseudo 4 post-Newtonian order. It should also be noted that the injection window for coincidence testing needed to be varied slightly. By giving this variable a bit of freedom, we prevent elimination of good detections during coincidence due to slight differences in overlap between the templates. A window of 10ms was settled upon as good balance of allowing acceptable matches, while eliminating poorly matching triggers.

References

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