Connecting Numerical Relativity and Data Analysis of Gravitational Wave Detectors

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Abstract Gravitational waves deliver information in exquisite detail about astrophysical phenomena, among them the collision of two black holes, a system completely invisible to the eyes of electromagnetic telescopes. Models that predict gravitational wave signals from likely sources are crucial for the success of this endeavor. Modeling binary black hole sources of gravitational radiation requires solving the Einstein equations of General Relativity using powerful computer hardware and sophisticated numerical algorithms. This proceeding presents where we are in understanding ground-based gravitational waves resulting from the merger of black holes and the implications of these sources for the advent of gravitational-wave astronomy.

1 Introduction

During the GR 1 conference held on January 1957 at the University of North Carolina, Chapel Hill, Charlie Misner famously said, “... we assume that we have a computer machine better than anything we have now, and many programmers and...”

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a lot of money, and you want to look at a nice pretty solution of the Einstein equations. ... Now, if you don’t watch out when you specify these initial conditions, then either the programmer will shoot himself or the machine will blow up (Misner, 1957).” From that date in 1957 to Frans Pretorius’ landmark paper in 2005 (Pretorius, 2005) that successfully followed an orbit and merger of two black holes (BHs), many programmers and money tackled the problem that Misner so eloquently points out. With two other groups following the Pretorius paper within a year (Baker et al., 2006; Campanelli et al., 2006), a new age of numerical relativity (NR) was begun. Progress was being made over the intervening decades (Brandt and Bruegmann, 1997; Bruegmann, 1999; Abrahams et al., 1998; Cook et al., 1998; Gomez et al., 1998; Brandt et al., 2000; Alcubierre et al., 2001; 2003; Bruegmann et al., 2004; Gundlach et al., 2005) to reference just a few of the many pivotal papers during that time.

Arguably the driving force behind the decades of work on solving Einstein’s equations for the coalescence of compact binary systems has been and continues to be the imminent detection of gravitational waves (GWs). The world-wide network of detectors is coming online with Advanced LIGO (Harry, 2010) and Advanced Virgo (Acernese et al., 2009) leading the way and KAGRA (Somiya, 2012) on the way. The era of gravitational wave astronomy is upon us (Aasi et al., 2013a) and NR has an important role to play. Just some of the important issues currently being addressed by NR for GW astronomy are

- determining where approximations to full solutions to the Einstein equation break down as we approach merger (Ohme et al., 2011; MacDonald et al., 2013),
- detecting the difference between NS and BH sources (Foucart et al., 2013; Han- nam et al., 2013),
- creating template banks that cover the complete parameter space (Kumar et al., 2014; Privitera et al., 2014),
- determining the impact of higher harmonics on detection and parameter estimation,
- settling down to final state of the black hole, and
- investigating mergers as GW transients.

This proceeding focuses on that last three items in the above list. First, we discuss a historical perspective of NR and GWs in §2 and a more detailed look into BBH mergers in NR §3 before discussing the role of harmonics §4 the approach to the final state §5 and mergers as transients §6 Conclusions are presented in §7.

2 Historical Perspective on NR and GWs

While NR was struggling to capture the spacetime and dynamics of a merging compact binary on computers, the gravitational wave community was preparing for initial LIGO and VIRGO. Ref. (Cutler et al., 1993) lays out the case for a deep understanding of the theoretical waveforms, called templates, from compact binary coa-
lescence in preparation for the GW detectors. These theoretical templates are needed to unearth the signal within the noisy data using matched filtering, the optimal choice for detecting a signal in Gaussian noise where the template is known (Thorne 1987). Although at the time NR had not yet produced waveforms from BBH mergers, post-Newtonian theory was making progress in producing waveforms that work well for binary neutron stars and low mass BH binaries. Low-mass objects, a couple of solar masses to tens of solar masses, have long inspirals in the LIGO frequency band well modeled by post-Newtonian approximations. In fact, neutron star binaries may merge outside of the band making NR less useful in predicting these signals.

BBH signals that are more massive could be the first detected (Brady et al., 1998) motivating several methods to bridge the gap between post-Newtonian inspiral and ringdown. Energy conditions were studied (Flanagan and Hughes, 1998a,b) and approximations were developed to produce waveforms that would cover the full inspiral, merger, ringdown (Buonanno and Damour, 1999; Khanna et al., 1999; Baker et al., 2002). Fortunately, NR was on the brink of success culminating in the series of papers in 2005-2006 (Pretorius, 2005; Campanelli et al., 2006; Baker et al., 2006).

### 3 Binary black hole mergers

Post 2005, NR groups world wide began an assault on the BBH parameter space, focusing primarily on gravitational recoil and the spin of the final black hole. A few turned their attention to the ramifications of these new NR waveforms on data analysis efforts to detect BBHs (Baumgarte et al., 2008; Buonanno et al., 2007; Baker et al., 2007; Ajith et al., 2007; Pan et al., 2008; Vaishnav et al., 2007). This culminated in three collaborations:

1. NINJA (Aylott et al., 2009b,a; Ajith et al., 2012; Aasi et al., 2014): the Numerical INJection Analysis project whose goal is to use NR waveforms as signal and test the detection and parameter estimation pipelines for the ground-based GW detectors,

2. SAMURI (Hannam et al., 2009): this was a one-time project that did a consistency check of several NR codes; and,

3. NRAR (Hinder et al., 2014): Numerical Relativity and Analytical Relativity Collaboration whose goal is to use NR waveforms to produce the next generation of waveform models.

For more details on these collaborative efforts in the numerical relativity and gravitational wave community, see the paper by Sascha Husa in this collection.

Figure 1 is a figure from the NINJA 2 paper (Ajith et al., 2012) where a catalog of NINJA waveforms were publicly released. The figure depicts one hybrid waveform at three different total masses. The merger is at the extremum of the waveform.

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1 To understand matter’s effect on neutron star waveforms see Ref. (Read et al., 2013) for binary neutron stars and Ref. (Andersson and Kokkotas, 1998) for isolated neutron stars.
The triangles represent the region where we created hybrids by stitching together the post-Newtonian NR waveforms. As mass increases, the signal-to-noise ratio increases and the number of cycles in band decreases at a fixed distance for an optimally oriented binary with the parameters held fixed; however, at some point, the reduction in the number of cycles will result in a drop of signal-to-noise ratio. The figure illustrates the impact of merger on the BBH signals for masses above $20M_\odot$ where the merger sits in the most sensitive region of the detector. As the masses grow higher than a couple of hundred solar masses, we begin to only detect the merger and ringdown addressed in §6.

![Fig. 1](image)

**Fig. 1** A Ninja 2 Collaboration [Ajith et al., 2012] figure. Here we see the GW from a NINJA2 waveform versus frequency against two predictions of the advanced LIGO noise curve. A single NR waveform is represented at three different total masses. The waveform is a hybrid, non-spinning, 2 to 1 mass ratio waveform scaled to three different total masses. The triangles represent the starting and ending frequencies of the hybridization region where the NR and post-Newtonian waveforms were stitched together. The waveform is scaled such that it is optimally oriented at a distance of 1 Gpc from the detector. The signal-to-noise ratios, $\rho$, were computed at that distance with the early aLIGO sensitivity.

One of the challenges in NR is covering the full parameter space of the binary black hole (BBH) system. There are no stringent constraints on the initial spins of the black hole, although there are some expectations [Gerosa et al., 2013; Kesden et al., 2010; Schnittman, 2004]; and, in fact, we expects GWs to be the main method for observing BH parameters. A similar scenario holds for the mass ratio, $q = m_1/m_2$.
where \( m_1 \) and \( m_2 \) are the BH masses, and total mass, \( M = m_1 + m_2 \). Recent work points to the possibility of higher mass BHs than expected \cite{Dominik2014} and see the proceedings by Thomas Bulik in this collection. Simulating extreme spins \cite{Lovelace2012} and mass ratios \cite{Lousto2011} is still a challenge, especially in producing quality waveforms from such simulations. Despite these challenges, several groups are running generic, precessing BBH systems. The SXS collaboration has a published catalog of 174 BBH waveforms \cite{Mroue2013} including spins of 0.99 and mass-ratios of 1:10 \cite{Lovelace2014}, RIT has generic runs \cite{Lousto2010} and GT \cite{Pekowsky2013} has several hundred shown here in fig. 2.

![Graph](image)

**Fig. 2** The left figure is GT’s non-precessing runs and the right the precessing runs. The left plot indicates our set of runs, one for each circle, corresponding to the mass ratio, \( q = m_1 / m_2 \) where \( m_1 \) and \( m_2 \) are the BH masses, and the initial spin of each black hole, \( a_1 = S_1 / m_1 \) and \( a_2 = S_2 / m_2 \). The figure on the right, again depicts each run now by a square bot plots versus mass ratio on the vertical axis, \( q \), and the angle between the total spins \( S_{\text{tot}} = S_1 + S_2 \) and \( L \), the total momentum and the angle between \( S_1 \) and \( S_2 \).

The open problem and important challenge for NR and GW data analysis is in preparing to detect and characterize the parameters from a precessing BBH system, see Ref \cite{Hannam2013} and references therein.

# 4 Role of Higher Harmonics on BBH Mergers and GWs

Gravitational waves encode the dynamics and history of the compact binary coalescence. When the GW reaches the detector, the radiation also encodes the position of the binary on the sky and its inclination with respect to the detector(s). In NR, we choose to represent the GWs extracted from our simulations via spin-weighted
spherical harmonics that map the waveform from a function of angles to a function of modes, or harmonics, labeled by $\ell$ and $m$. This mode description can be very useful theoretically since inspiralling binaries will have the quadupolar mode dominating, given by $\ell = |m| = 2$. However, as the black holes inspiral, merge and settle down to its final BH, the information about the system is radiated in those harmonics. In addition, the sky position also mixes in with these parameters as seen in fig. 3 where we plot a BBH system at two different lines of site with respect to the detector. The binary in this figure has a mass ratio 1:10 and is non-spinning. To the left, you see that the binary was optimally oriented and the $\ell = |m| = 2$ mode, given by $h_{22}$, overlaps with the full waveform, $h$, containing all the non-zero modes well. The overlap is the scalar product between $h$ and $h_{22}$ normalized to one. To the right, we place the binary at a non-optimal position and now see that $h_{22}$ no longer as good of a representation of the full waveform along that line of site.

Fig. 3 The upper figures show the location of the $q = 10$ binary with respect to the detector. The lower plots are of the strain of the $\ell = |m| = 2$ waveform and the full waveform plotted on top of each other. In the left, the binary is optimally oriented and the right, randomly oriented. The strains are scaled to be one at the peak.

The question then is, for the current set of detectors, how important is this information? Can we detect binaries of generic initial states without accounting for the modes? If so, how does it bias the extracted parameters? This topic is addressed in a recent set of papers [Healy et al., 2013; Pekowsky et al., 2012; Capano et al., 2013] that are reviewed here. First we can look back at fig. 3 and see which modes are needed to optimize our sky coverage. We know that for highly precessing binaries or binaries with moderately large mass ratios, the energy in the radiation is spread out among the modes. In fig. 4 we see the relative amplitudes of higher modes in comparison with the $\ell = |m| = 2$ mode for both an equal mass (left) and unequal (right). Clearly, as the mass ratio increases, the higher modes gain in amplitude. In fact, the relative importance of the modes also increases towards merger, which makes these modes and hence NR potentially more important for BBH systems. However, when we looked
at sky coverage, defined as the percent of sky in a source-centric frame that a template will match with nature, which modes were important could deviate from a ranked list of amplitudes. To cover the entire sky to some measure, as mass ratio increases beyond \( q = 7 \), more than 4 modes are necessary. In the absence of precession, increasing spin magnitude reduces the number of needed modes. Precessing systems required up to 12 modes for the cases studies in Ref. (Healy et al., 2013).

We then computed how the reach of a single detector would be impacted by not including all the relevant modes in Ref. Pekowsky et al. (2012). Figure 5 is a plot from that paper that shows the energy radiated per run in both the \( \ell = |m| = 2 \) only and all the modes versus the volume of the detector for that system. The energy radiated in these systems corresponds to the amplitude of the waveform. The actual values in Gpc are not to be used literally since these numbers do not incorporate event-loss and other important aspects of the real detector pipeline. We see that the fact the more modes are required for higher mass-ratio systems is diluted by the fact that these systems radiated less in total output; and, therefore, are reduced in volume. Likewise, the higher modes are less important as the spin increases, seen here as the points on the right that radiate the largest amount of energy. Precessing systems will depend on the parameters but the largest deviation between all the modes and just the quadrupolar is seen.

A further step was taken to understand the role of the sub-dominant modes for mass ratios of \( q < 4 \) in ref (Capano et al., 2013). They found that the higher modes did not improve detection rates for advanced LIGO when using a re-weighed SNR (Abadie et al. 2012b; Aasi et al. 2013b) and in fact including the modes increases the false-alarm rate. We may conclude, that for unequal-mass binaries of \( q < 4 \), higher modes should not be included in the detection pipeline, although a definitive answer would require a all-mode injection into the real detector noise.

**Fig. 4** Figure from Healy et al. (2013) shows the strain amplitude relative to the \( \ell = |m| = 2 \) mode. The left panel shows the case of an equal mass binary, and the right panel that of a 1:4 mass ratio system. In both figures the systems have been scaled to total mass \( M = 100M_\odot \) and neither have spin.
Fig. 5 Figure from (Pekowsky et al., 2012) shows the correlation between the total energy radiated and the detector reach measured in volume using just the $|m| = 2$ waveform or the full waveform labeled here as $h_{\text{ideal}}$. Circles label non-spinning systems, squares are spinning but non-precessing systems, and triangles are precessing systems.

Whether or not that will remain the case for generic runs with precessing spins is an open question, as is the potential for parameter bias in the unequal-mass case which we are addressing in a future work (Pekowsky et al., 2014).

5 End State of BBH Merger

We’ve studied how the initial data of the binaries is imprinted on the harmonics of the waveforms. In these final moments of the coalescence, the two BHs merge into a perturbed Kerr BH, whose gravitational radiation rings down like a struck bell. With the BH’s mass and spin known, perturbation theory provides the quasi-normal modes (QNMs) that describe ringdown (Press and Teukolsky, 1973; Leaver, 1985; Berti et al., 2007); however, perturbation theory cannot inform us of the amplitudes of each mode. Recent studies have used NR waveforms to correlate the QNM excitation amplitudes with initial parameters (Berti et al., 2007; Kamaretsos et al., 2012a,b; Kelly and Baker, 2013; London et al., 2014). Figure 6 depicts the end state of our GT runs with the final BH’s spin versus its mass.

In ref (London et al., 2014), we studied the QNMs excited by a series of NR simulations that focused on non-spinning, unequal mass binaries. We found a rich variety of fundamental QNMs, as well as overtones, and evidence for 2nd order QNMs. Rather than the spin-weighted spherical harmonics used in NR extraction, we represent the waveforms in terms of the spheroidal harmonics which are natural to perturbation theory. It has been an open question whether or not such a differ-

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Note that the final mass is constrained to be less than one. The mass and spin are computed using isolated horizons (Dreyer et al., 2003).
Fig. 6 Plotted are the spin and mass for the final, merged BH at the end of our NR simulations. Each point represents a different simulation from unique initial data. The squares are precessing runs and the circles are non-precessing.

ence would make an impact on the modes. Inner-products between spherical and spheroidal harmonics suggest that for the $\ell = m$ modes, very little difference should be expected (Berti et al., 2006). For the $\ell \neq m$ modes we expect “beating” that arises in the QNMs when found using spherical harmonics which are combinations of the spheroidal harmonics used in perturbation theory (Kelly and Baker 2013). As the final spin magnitude increasing deviates from 0, the difference between spherical and spheroidal harmonics is more pronounced, as expected (London et al., 2014).

We find that the mass-ratio dependence of quasi-normal mode excitation is very well modeled by a Post-Newtonian like sum for most but not all QNMs. We presented new fitting formulas for the amplitudes versus the mass ratio in Ref. (London et al., 2014). Figure 7 plots the amplitudes of the fundamental QNMs versus $q$ and include our fits.

The modes would be difficult to detect for current GW detectors. However, there is the possibility that future detectors might be able to see them, as seen in fig. 8 which depicts both Einstein Telescope and advanced LIGO noise predictions. It seems possible to do gravitational-wave astronomy with QNMs, if not as simply as first laid out in Refs. (Kamaretsos et al., 2012a,b).
6 Mergers as Transient GW Events

The LIGO and Virgo Collaborations search for gravitational wave transients, or bursts, without templates for sources like supernova or the unknown (Abadie et al., 2012a; Andersson et al., 2013). Recently, several groups have begun to explore the merger of BHs as a transient event (Fischetti et al., 2011; Clark et al., 2014; Klimenko, 2014; Cornish, 2014). This is a very interesting development that focuses on intermediate-mass BBH systems that may only have a few cycles in band. See (Clark et al., 2014) in this volume for a discussion of one such approach to mergers as transients.

7 Conclusions

Undoubtedly, numerical relativity, analytical relativity and gravitational wave data analysis have made great strides in the last few years. With the advanced LIGO scheduled to begin taking data next year and her sister detectors soon after, the theoretical efforts are focusing down on the crucial open questions for detecting GW sources and estimating their parameters. This proceeding highlighted just a few of those questions.

Clearly, the parameter space of generic BH binaries is large and the NR community continues its efforts to provide waveforms for the full space and to turn these
NR waveforms into viable GW templates. One avenue of research that is still open is using tools like principal component analysis (Clark et al., 2014) to predict where we need a new NR run that will make the most impact on the template bank.

Over the last couple of years, work has been done to measure the impact of higher modes on detection. We are optimistic that for lower mass-ratios and non-precessing spins, the dominate mode will be enough for detection. The problem is still open for a verification of this statement as mass ratio increases over the full BBH total mass range. As is the question of higher modes for highly precessing binaries where the $\ell = |m| = 2$ mode is not always dominate.

NR runs result in the BBH system ringing down to the final BH. We have found a rich and fascinating regime during this epoch, revealing a variety of QNMs. While it is still questionable whether these modes will be detectable by the current generation of GW detectors, it does hint at the tantalizing possibility of conduction GW astronomy with BH ringdown waveforms.

NR still has a story to tell GW astronomy. New and exciting work is being done in BH-neutron star and binary neutron stars. BBHs as transients are being seriously investigated. At the end of the day, it will be GW astronomy that will excite new work in NR as we learn about how general relativity is manifested in the Universe.
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