Techniques for gravitational-wave detection of compact binary coalescence

Sarah Caudill for the LIGO Scientific Collaboration and the Virgo Collaboration

Nikhef
Science Park
1098 XG Amsterdam, The Netherlands
caudills@nikhef.nl

Abstract—In September 2015, the Advanced Laser Interferometer Gravitational-wave Observatory (LIGO) came online with unprecedented sensitivity. Now with two observation runs completed, LIGO has detected gravitational waves from five binary black hole mergers and one neutron star merger. The Advanced Virgo detector also recently came online in August 2017, significantly improving the sky localization of two of these events. The identification of these signals relies on techniques that can clearly distinguish a gravitational-wave signature from transient detector noise. With the next LIGO and Virgo observation run expected to begin in the fall of 2018, more detections are expected with the potential for discovery of new types of astrophysical sources.

Index Terms—gravitational waves

I. INTRODUCTION

The Advanced Laser Interferometer Gravitational-wave Observatory (LIGO) is a gravitational-wave detector network composed of two Fabry-Perot-Michelson interferometers with 4-km arms in Hanford, WA and Livingston, LA [2]. The Advanced Virgo detector in Cascina, Italy [19], with 3-km arms, recently joined this network. These detectors measure the effect of a passing gravitational wave as a spacetime strain. This effect results in a varying phase difference between the laser light propagating in perpendicular arms of the interferometers.

During the first observation run (O1) of Advanced LIGO from September 12, 2015 to January 19, 2016, the first direct detection of gravitational waves was made with GW150914 [6] from the inspiral and merger of two black holes with component masses of 36.2±2.3\ M_☉ and 29.1±2.9\ M_☉ (90% credible interval). A second detection of GW151226 from a lighter black hole system [5] as well as the possible third signal LVT151012 further revealed a population of stellar-mass binary black hole systems [3]. At the time of this publication, the second observation run of Advanced LIGO from November 30, 2016 to August 25, 2017 yielded three further binary black hole detections [12]–[14]. Advanced Virgo joined this observation run on August 1, 2017 providing the first triple-detector observation of gravitational waves [14], also from a binary black hole system, as well as the most precisely localized gravitational-wave signal yet, GW170817 [15] from the inspiral of a binary neutron star system. This last event was exceptional due to the association of the gravitational-wave event with the γ-ray burst GRB 170817A [11] and the subsequent identification of counterparts across the electromagnetic spectrum [16].

Detection of gravitational-wave signals from the coalescence of binary neutron star and stellar-mass black hole systems requires an understanding of the detector noise as well as gravitational waveform models. While it is possible for the short signals from heavy stellar-mass black hole binaries to be uncovered by searches for generic gravitational-wave transients [6], [7], longer, lower amplitude signals and subsequent parameter estimation [1], [9] of the sources rely on precise waveform models of the two-body dynamics.

Searches for un-modeled transient gravitational-wave signals employ other methods than those described in this paper. Short-duration transient gravitational-wave searches use minimal assumptions regarding the expected waveform and source direction. More details about these techniques and how they can also detect signals from compact binary coalescence can be found in [8], [10].

II. COMPACT BINARY COALESCEENCE

Advanced LIGO and Virgo are sensitive to gravitational waves that pass through their sensitive frequency band, where the maximum sensitivity occurs near 100Hz. This can be seen in Figure 1 where representative O2 amplitude spectral densities, are plotted estimated using 4096 s of data around the time of GW170814 [14], [27]. Gravitational-wave signals from the coalescence of compact binaries with total masses less than a couple hundred solar masses will be detectable. The types of binaries in this mass range include binary neutron stars, binary stellar-mass or intermediate-mass black holes, or a combination neutron star-black hole system. General relativity provides the model for the inspiral and coalescence of the two compact objects, particularly in the last few seconds that are visible to LIGO and Virgo. The gravitational-wave signal increases in frequency and amplitude, taking the form of a chirp. At early times, the evolution of the chirp frequency is determined primarily by a parameter called the chirp mass:

\[ M = \frac{(m_1m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \]  

(1)

where \( m_1 \) and \( m_2 \) are the component masses. The inspiral phase evolution is also driven by each objects’ angular
momentum, or spin $S_{1,2}$ (magnitude and orientation), and, if the spin is misaligned with respect to the orbital angular momentum, the signal can have amplitude and phase modulations. Right before merger, as the orbit shrinks and the gravitational-wave frequency grows rapidly, the signal is additionally influenced by relativistic effects related to the mass ratio $q = m_2/m_1$ where $m_1 \geq m_2$. If the binary components include a neutron star, tidal effects can also affect the phase. After the objects have merged, a ringdown signal could be seen if a black hole was formed or a more complicated signal might be seen if a short- or long-lived neutron star was formed. The inspiral, merger and ringdown signal for a binary black hole system can be seen in Figure 2.

Matched filtering is the preferred method for extracting modeled signals from Gaussian and stationary detector noise. The correlation of a signal $h(t)$ with detector strain data $s(t)$ can be expressed as

$$\langle s|h \rangle(t) = 4 \int_0^{\infty} \tilde{s}(f) \tilde{h}^*(f) e^{2\pi i f t} df$$

where $\tilde{s}(f)$ is the Fourier transform of $s(t)$ and $S_n(|f|)$ is the one-sided average power spectral density of the detector noise. The square of the matched-filter signal-to-noise ratio (SNR) $\rho(t)$ is defined as

$$\rho^2(t) \equiv \frac{1}{\langle h|h \rangle} |\langle s|h \rangle(t)|^2$$

where $\langle h|h \rangle$ is the autocorrelation of the signal waveform. The SNR in each detector is tracked as a function of time and when there is a peak above a predetermined threshold, a trigger is stored. Each search pipeline determines the SNR threshold independently although values usually range between 4 and 5.5. Typically, a trigger will be defined by its GPS time, the parameters of the signal waveform, or template, that it most closely matched, as well as its SNR.

A. Template Banks

It is not computationally feasible to search for gravitational waves over the continuous mass and angular momentum parameter space that describe the compact binaries accessible to LIGO and Virgo. Instead, we construct a discrete grid of waveforms, or a template bank, and perform matched filtering with these templates. Typically, the template banks are constructed in such a way that the loss in matched-filter SNR is $\leq 3\%$ for any signal with parameters that fall within the boundaries of the template bank. Currently, the gravitational
waveforms are typically represented in a four-dimensional space that includes the two component masses $m_1, m_2$ as well as a measure of the angular momenta $S_{1,2}$ of each component. This measure typically takes the form of the component spin aligned with the direction of the orbital angular momentum $L$ of the binary

$$\chi_{1,2} = \frac{c}{G m_{1,2}} S_{1,2} \cdot \hat{L}. \quad (4)$$

Studies have shown that this simplified parameter space can recover systems with precessing, misaligned spins in the equal mass range [4] but may not provide good coverage for neutron star-black hole systems with large mass ratio and spin magnitude [22]. To refine the system parameters, we use coherent Bayesian analyses in post-processing to derive posterior distributions of the source parameters, including the initial and final masses, final spin, distance, redshift, and tides for neutron star systems [1], [9].

The top panel of Figure 3 shows the template bank used in the O1 search for gravitational waves from compact binary coalescences [4]. Each point represents a unique template waveform represented by four parameters: $\{m_1, m_2, \chi_1, \chi_2\}$. There are 249077 templates in total. The bank covers a total mass between $2M_\odot$ and $100M_\odot$. The range of $\{\chi_1, \chi_2\}$ is represented by the different colored regions: binary neutron stars (green), neutron star-black hole systems (red), and binary black holes (blue). Among binary neutron star systems that will merge within a Hubble time, the most extreme spin has been found to be less than $\sim 0.04$ [23], hence the constraint on the $\chi$ value of the neutron star. The constraints on binary black hole spins are not as strong, hence we allow for near maximal $\chi$ values.

For comparison in the bottom panel of Figure 3, we see the O1 template bank used to search for intermediate-mass black hole binaries [17]. This bank covers a total mass between $50M_\odot$ and $600M_\odot$, mass ratios less extreme than 1:10, and aligned spins $|\chi_{1,2}| \leq 0.99$. There are 44902 templates in total. The higher density of templates at lower masses results from computing the 3% loss in matched-filter SNR from a lower frequency.

**B. Signal-consistency Checks**

Detector data contains many short noise transients, called glitches. These often trigger high SNR output. Thus it is not sufficient to rank gravitational-wave candidates by SNR. Several methods can be employed to combat these glitches. If the glitches arise from known instrumental or environmental issues, it is possible that the data can be removed from the searches. The detector and its environment are carefully monitored with hundreds of sensors. If a coupling can be established between noise visible in a sensor and glitches in the data, then a data-quality veto can be created to exclude the data from the search [18].

Search algorithms may also include an automated gating procedure. For example, if a glitch has an extraordinary amplitude in whitened detector strain data, it can safely be removed. Real gravitational wave signals will not produce such large excursions unless the source is extremely close by.

Finally, signal-consistency tests can also be used to down weight glitch-like triggers. These tests typically consider the unique time-frequency evolution of a chirp signal and penalize any triggers not following this evolution. Examples include a $\chi^2$ time-frequency test for broad-band signals [21] and a matched-filter SNR versus template autocorrelation consistency check [24].

**C. Coincidence**

Requiring coincidence in time and template parameters for the triggers identified in each detector is a powerful tool for identifying real gravitational-wave signals. Events found by both LIGO detectors must fall within the same 15 ms time window. This window is determined by the 10-ms inter site propagation time plus a 5-ms allowance for uncertainty in the arrival time of weak signals. With the inclusion of Virgo and other detectors, the allowed time window will need to be retuned but will still be motivated by the allowed inter site propagation time between all the detectors in the network.

**D. Ranking Statistics**

Coincident triggers that have passed the coincidence test will be ranked by the search algorithms, typically using a
likelihood-ratio-based statistic. Given a set of values that characterize the trigger in each detector (i.e. SNR, signal-consistency checks, timing differences, etc.), we can compute the probability that this set of values came from a signal model and the probability that this set of values came from a background model. For example, the likelihood-based ranking statistic for the LIGO detector network can be generically written as

$$\mathcal{L} = \frac{P\{d_H, d_L\text{ signal}\}}{P(d_H\text{ noise}) P(d_L\text{ noise})}$$

where \(\{d_H, d_L\}\) are the coincident triggers’ characteristic values in the Hanford and Livingston detectors, respectively. The numerator will contain conditional and joint probabilities due to the fact that a signal’s parameters will be strongly correlated in each detector. However, the denominator can be factored since we assume the detectors’ noise distributions are independent of each other. This expression can be expanded to include N-detectors.

The signal model can typically be constructed semi-analytically. However, the noise model must be constructed from the search background. Several methods exist for measuring a matched-filter search background. For example, one can collect statistics from the non-coincident triggers and use them to simulate accidental coincidences. Similarly, the method of time-shifting the triggers in each detector relative to the others provides a way of generating accidental coincidences.

Search background estimation is typically done separately across the target signal space. For example, long signals from binary neutron stars have a lower background than short signals from binary black hole candidates. Thus, candidate and background events are often divided into different search classes based on template length.

It is convenient to express the significance of gravitational wave candidates in terms of how often the noise is expected to yield an event with a ranking statistic \(\mathcal{L}\) larger than some predetermined threshold \(\mathcal{L}^*\). This is the false-alarm rate (FAR). For an experiment of length \(T\), we define this as

$$\text{FAR} = \frac{C(\mathcal{L} \geq \mathcal{L}^* \text{ noise})}{T}$$

where \(C(\mathcal{L} \geq \mathcal{L}^*)\) is a cumulative distribution.

IV. Conclusion

Matched-filter-based searches can detect gravitational-wave signals from the coalescence of binary neutron star and stellar-mass black hole systems as demonstrated by the successes of O1 and O2. Work is ongoing to prepare these searches for the LIGO-Virgo detector network that will begin a third observation run later this year. We also are steadily working towards search algorithms that support N-detectors. Finally, with confident detections becoming a regular occurrence, we will start to explore other parameter spaces, potentially uncovering new types of astrophysical sources.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support of the United States National Science Foundation (NSF) for the construction and operation of the LIGO Laboratory and Advanced LIGO as well as the Science and Technology Facilities Council (STFC) of the United Kingdom, the Max-Planck-Society (MPS), and the State of Niedersachsen/Germany for support of the construction of Advanced LIGO and construction and operation of the GEO600 detector. Additional support for Advanced LIGO was provided by the Australian Research Council. The authors gratefully acknowledge the Italian Istituto Nazionale di Fisica Nucleare (INFN), the French Centre National de la Recherche Scientifique (CNRS) and the Foundation for Fundamental Research on Matter supported by the Netherlands Organisation for Scientific Research, for the construction and operation of the Virgo detector and the creation and support of the EGO consortium. The authors also gratefully acknowledge research support from these agencies as well as by the Council of Scientific and Industrial Research of India, Department of Science and Technology, India, Science & Engineering Research Board (SERB), India, Ministry of Human Resource Development, India, the Spanish Agencia Estatal de Investigación, the Vicepresidencia i Conselleria d’Innovació, Recerca i Turisme and the Conselleria d’Educació i Universitat del Govern de les Illes Balears, the Conselleria d’Educació, Investigació, Cultura i Esport de la Generalitat Valenciana, the National Science Centre of Poland, the Swiss National Science Foundation (SNSF), the European Commission, the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, the Hungarian Scientific Research Fund (OTKA), the Lyon Institute of Origins (LIO), the National Research Foundation of Korea, Industry Canada and the Province of Ontario through the Ministry of Economic Development and Innovation, the Natural Science and Engineering Research Council Canada, Canadian Institute for Advanced Research, the Brazilian Ministry of Science, Technology, and Innovation, International Center for Theoretical Physics South American Institute for Fundamental Research (ICTP-SAIFR), Russian Foundation for Basic Research, the Leverhulme Trust, the Research Corporation, Ministry of Science and Technology (MOST), Taiwan and the Kavli Foundation. The authors gratefully acknowledge the support of the NSF, STFC, MPS, INFN, CNRS and the State of Niedersachsen/Germany for provision of computational resources.

This research has made use of data, software and/or web tools obtained from the LIGO Open Science Center (https://losc.ligo.org), a service of LIGO Laboratory, the LIGO Scientific Collaboration and the Virgo Collaboration.

REFERENCES


