Report on the search for binary black holes inspiral in S3 LIGO data

Thomas Cokelaer¹, for the LIGO Scientific Collaboration

¹School of Physics and Astronomy, Cardiff University, Cardiff CF 24 3YB, UK
E-mail: Thomas.Cokelaer@astro.cf.ac.uk

Abstract. We report on the search for gravitational waves emitted by non-spinning binary black hole inspirals in the data taken during the third LIGO science run (S3). We give an overview of the data acquired during S3 and the target waveforms that we are searching for in this analysis. We briefly describe how the data was filtered using a BCV detection template family (using an hexagonal template bank placement in the mass parameter plane). Finally, we report on preliminary estimates of the sensitivity of the three LIGO detectors using software injections of effective one-body waveforms with component masses in the range 3–40 $M_\odot$ and total mass $M \leq 40 M_\odot$. We show that during S3, the three LIGO detectors have a detection efficiency of 50% up to several Mpc for L1 and H2, and up to 30 Mpc for H1.

1. Introduction

The Laser Interferometer Gravitational Wave Observatory (LIGO) consists of three Fabry-Pérot-Michelson interferometers. Two of them are co-located in Hanford, Washington and are denoted H1 and H2 with arm lengths of 4 and 2 km, respectively. A third detector with arm length 4 km is located in Livingston, Louisiana and is denoted L1.

During the second science run (S2) a low-frequency cutoff of 100 Hz was used, and the analysis showed that the S2 data were sensitive to binary black holes (BBHs) with component masses $m_1$ and $m_2$ between 3 and 20 $M_\odot$ [10]. In the third science run (S3), taken from 31 Oct. 2003 to 9 Jan. 2004, the low-frequency cutoff was set to 70 Hz. The benefit to the S3 analysis was to increase the number of gravitational-wave cycles coming from BBH inspirals and therefore the mass range. Unfortunately, this also increases the computational time needed to perform the analysis.

In this proceeding we report on the preliminary results of the search for gravitational waves emitted by non-spinning BBH inspirals in the S3 data. The rest of the paper is organised as follows. Sec. 2 briefly describes the S3 data. Sec. 3 describes the target population of BBHs we are searching for. The analysis pipeline used to perform the BBH search in S3 is based on the binary neutron star pipeline [11] and S2 BBH search [10]. However, the S3 BBH pipeline has some improvements which are emphasised in Sec. 4. Section 4 also covers some of the template bank issues. In Sec. 5 we describe software injections of effective one-body (EOB) waveforms and finally show the detection efficiency of the different detectors.
2. The S3 data
The LIGO science runs are done in coincidence between the different interferometers. Although
we report here only on preliminary results related to a single detector analysis, we analyse only
data which are in double or triple coincidence since the final analysis is based on a coincidence
analysis. The amount of double coincidence data in S3 is 806, 243 and 200 hours, respectively
for H1-H2, H1-L1 and H2-L1. There are 178 hours of triple coincidence. In Fig. 1 we show the
strain equivalent noise amplitude spectral density of the three detectors as well as the design
gain sensitivity curve.

The S3 data has a sensitivity to BBH inspirals up to tens of Mpc. For instance, Fig. 1 shows
the distance at which an optimally oriented and located (5,5) $M_\odot$ solar mass binary gives a SNR
of 8. The sensitivity is constant for H2 with an average distance of 4.7 Mpc. The sensitivity of
L1 was not stable due to ongoing commissioning (absence of active seismic isolation, partially
commissioned angular stabilization systems and variations in alignment). The H1 has the best
sensitivity with a large variation from 15 to 30 Mpc due to improvements in the alignment
variations during the run.

![Figure 1. Overview of S3 data. The left plot shows the detector sensitivities of the three
detectors and their design sensitivity curve [12]; the right plot shows the evolution on the range
at which an optimally oriented (5,5) $M_\odot$ system can be detected during the entire S3 run.]

3. Target waveforms
The target sources for the BBH search are binary systems that consists of two black holes with
component masses in the range 3-40 $M_\odot$ with a total mass $M \leq 40M_\odot$. Using a lower frequency
cutoff of 100 Hz, the duration of BBH systems is approximately 1.5 seconds for a (3,3)$M_\odot$
system and 30 ms for a (20,20)$M_\odot$ system which contains only a few cycles, which explains our
choice on constraining the total mass. Nonetheless we allow individual masses up to 40$M_\odot$
in order to incorporate asymmetric systems in our analysis.

Although in Sec. 5 we uses only EOB waveforms [5, 6, 7] we also plan to use different software
injections based on the different physical models available in the literature [4, 1, 2]. These include
the standard post-Newtonian (PN) expansion model [3] and models using Padé resummation.

Recent work in [8] derived a detection template family referred to hereafter as BCV templates.
It is motivated by the fact that the amplitude and phase of the standard PN, EOB and Padé
waveforms at different order differ from each other in the last stages of inspirals, and that the true gravitational wave signals might be "in between" the model we search for. A detailed motivation and description for such a method is fully described in [8], and has been used in [10]. The S3 analysis uses a similar approach.

4. Pipeline
The detection method is based on the well-known matched filtering technique, which involves a detection template family as well as a template bank.

4.1. Filtering method
The templates used in the analysis are based on the BCV template family [8], which are phenomenological templates. Like the stationary phase waveforms based on the standard models, these templates incorporate a phase depending on two mass parameters. The templates are computed in the frequency domain:

$$\tilde{h}(f) = f^{-7/6} (1 - \alpha f^{2/3}) \theta(f_{\text{cut}} - f) e^{i(2\pi f t_0 + \phi_0 + \psi_0 f^{-5/3} + \psi_3 f^{-2/3})}.$$  \hspace{1cm} (1)

The amplitude component $f^{-7/6}$ is the standard restricted Newtonian amplitude. The parameters $\psi_0$ and $\psi_3$ are phenomenological parameters which mimic the phase evolution of the binary inspiral phase. The component $(\alpha f^{-1/2})$ is designed to capture the possible post-Newtonian amplitude corrections and possibly the merger part of the inspiral.

The filtering, similarly to the matched filtering in quadrature, implicitly maximises over the unknown orbital initial phase $\phi_0$ and time of arrival $t_0$, and explicitly maximises over the extrinsic parameter $\alpha$. Moreover, using the metric in the two parameters $\psi_0$ and $\psi_3$ allows the design of a bank with a specified minimal match as described in the next section.

The main differences between the S3 and S2 analyses cannot be fully described here but the main issues are worth mentioning. First, we use the initial constraint on the $\alpha$ parameter $(0 < \alpha < f_{\text{cut}}^{2/3})$ in order to compute the signal-to-noise ratio (SNR); it decreases the number of triggers significantly. Second, the S3 search is not a triggered search as in [10, 11]: it analyses the data from each detectors with its own template bank. Finally, a new template bank has been used as we briefly describe below.

4.2. Template Bank design
The BCV template bank is a three-dimensional template bank in $(\psi_0, \psi_3, f_{\text{cut}})$. We will not fully describe all the details of template placement but concentrate instead on the most important issues. First, the metric coefficients can be derived analytically in the parameters $\psi_0$, $\psi_3$ and appear to be constant over the parameter space. It is a nice feature which can be used to place a first layer of templates. We used a hexagonal grid placement which is laid along the eigenvectors of the metric. Since the exact correspondence between the physical mass components of the injected systems and the pair $\psi_0$, $\psi_3$ is not known exactly, the range of $\psi_0$ and $\psi_3$ is set by performing Monte-Carlo simulations. These injections use different physical models and are described in more detail in Sec. 3. For each pair of $\psi_0$ and $\psi_3$, we also need to set the ending frequency $f_{\text{cut}}$ of the templates. Ideally if the correspondence between $\psi_0$, $\psi_3$ and the total mass was well defined, $f_{\text{cut}}$ could be set as the ending frequency of the target system. However, in practice different models lead to different definitions of the ending frequency. Therefore, we place several layers of templates in the $f_{\text{cut}}$ dimension in order to be sensitive to inspirals which stop at the innermost stable circular orbit (standard PN models) as well as the ringdown part (EOB models).

In the template bank design, the minimal match (MM) has to be set in order to insure that any incoming signal can be detected [9]. In the S3 analysis, we chose a minimal match
$MM = 95\%$. Figure 2 shows an example of the template bank as well as the evolution of the template bank size during the S3 run. We can see that the number of templates changes significantly at the end of the run in H2 due to an increase of the flatness of the equivalent noise amplitude spectral density. Conversely, in H1 and L1 that effect is reversed.

![Figure 2. Template placement in the 3 dimensional parameter space $\psi_0$, $\psi_3$ and $f_{\text{cut}}$ (left plot) and the evolution of the BCV template bank size during S3 (right plot).](image)

5. Efficiency of the LIGO detectors
Software injection is an essential part of the pipeline.

- It allows one to test the template bank using real data.
- It gives the efficiency of the detectors to gravitational wave signals.
- The triggers from the injection can be used to optimise the efficiency of the search (clustering, coincidence window on the time of arrival, ...) and to obtain the coincidence parameters between the three detectors.

We performed EOB injections in a subset of the S3 data which corresponds approximately to 10% of the data set. The systems are generated with random orbital-plane orientations and isotropically distributed over the total mass. The distance of injection is set between 1 and 10 Mpc. We performed approximately 2000 injections into the data from the three detectors. The minimal match of the template bank is set to 95% and the SNR threshold of the filtering code was set to 7.

After the data was processed through the template bank, we looked for triggers in a coincidence window of 10 ms around the time of injection. In Fig. 3 we show which of the injected signals were found and which were missed. We plot the effective distance of both the found and missed events versus the total mass for the three detectors.

The separation between found and missed injections do not drop for high masses as we could have expected. The reason could be that the injection is performed uniformly in total mass while the range of the asymmetric parameter $\eta = m_1 m_2 / M^2$ is not constrained. Therefore on the efficiency plots, large masses includes both symmetric and asymmetric systems (for example, a 40
solar mass system can be either a \((3,37)M_\odot\) or a \((20,20)M_\odot\). Further injections will increase the statistics and allow us to plot efficiency for the asymmetric parameter \(\eta\) as well.

Finally, we plot in Fig. 4 the efficiency \(\mathcal{E}\) of the three detectors to EOB waveform injections. This is the ratio of the number of injections found to the total number of injections in a given range of effective distance:

\[
\mathcal{E}(d_1 < d < d_2) = \frac{\text{event}_{\text{found}}(d_1 < d < d_2)}{\text{event}_{\text{found}}(d_1 < d < d_2) + \text{event}_{\text{missed}}(d_1 < d < d_2)}
\]  

We can see that the efficiency of 50\% is reached at 32, 6.5 and 8 Mpc in H1, H2 and L1 detectors, respectively. However, those number have to be taken with care. Indeed, efficiencies are estimated by using injections throughout the run which includes large fluctuations as shown in Fig. 1 and the masses of the binary systems covers a wide range. Nevertheless it gives a good estimation of the range of the detectors and allows to test performance of the analysis.

**Figure 3.** Efficiency of the detectors to EOB injections in the S3 data. The effective distance of the found and missed injections is shown for the individual detectors H1, H2 and L1, respectively.
6. Conclusion
The search for BBH inspiral signals in the LIGO S3 data is nearly complete. The initial phase of pipeline tuning has been performed using Monte Carlo simulations both on Gaussian and real detector noise to test the different parameters of the search. Injections have been performed in triple coincidence S3 data in order to get the efficiency of the S3 data. We show that the detectors are sensitive to 32, 6.5 and 8 Mpc for H1, H2 and L1 detectors, respectively with an efficiency of 50%.

Acknowledgments
The authors gratefully acknowledge the support of the United States National Science Foundation for the construction and operation of the LIGO Laboratory and the Particle Physics and Astronomy Research Council of the United Kingdom, the Max-Planck-Society and the State of Niedersachsen/Germany for support of the construction and operation of the GEO600 detector. The authors also gratefully acknowledge the support of the research by these agencies and by the Australian Research Council, the Natural Sciences and Engineering Research Council of Canada, the Council of Scientific and Industrial Research of India, the Department of Science and Technology of India, the Spanish Ministerio de Educacion y Ciencia, the John Simon Guggenheim Foundation, the Leverhulme Trust, the David and Lucile Packard Foundation, the Research Corporation, and the Alfred P. Sloan Foundation.

References
[1] L. Blanchet 2003 Living Rev. Rel. 5 Preprint gr-qc/0202016.
[2] L. Blanchet, B. R. Iyer, C. Will and A. Wiseman 1996 Class. Q. Grav. 13 575
[3] L. Blanchet, T. Damour, G. Esposito-Farese and B.R. Iyer 2004 Phys. Rev. Lett. 93 091101
[4] T. Damour, B. R. Iyer and B. S. Sathyaprakash 1998 Phys. Rev. D 57 885
[5] A. Buonanno and T. Damour 1999 Phys. Rev. D 59 084006
[6] A. Buonanno and T. Damour 2000 62 064015
[7] T. Damour, P. Janowski and G. Schäfer 2000 Phys. Rev. D 62 084011
[8] A. Buonanno, Y. Chen and M. Vallisneri 2003 Phys. Rev. D 67 024016
[9] B. Owen, B. S. Sathyaprakash 1998 Phys. Rev. D 60 022002
[10] B. Abbott et. al. (in preparation).
[11] B. Abbott et. al. Preprint grqc/0505041
[12] A. Lazzarini, S3 Best Strain Sensitivities, LIGO document G040023-00-E