Gravitational-wave astronomy using Markov-chain Monte-Carlo parameter estimation for compact binary inspirals with spinning objects

MARC VAN DER SLUYS[1], VIVIEN RAYMOND[1], ILYA MANDEL[1], CHRISTIAN RÖVER[2],
NELSON CHRISTENSEN[3], VICKY KALOGERA[1], ALBERTO VECCHIO[4]
[1]Northwestern University, [2]AEI Hannover, [3]Carleton College, [4]University of Birmingham

1. Introduction

Stellar-mass compact binaries are amongst the most promising gravitational-wave sources for ground-based laser interferometers. If such a binary contains a black hole (BH), it is believed to be spinning at least moderately [1]. A spinning black hole causes the binary orbit to precess, introducing phase and amplitude modulations to the waveform. Accounting for these effects improves detection efficiency and also improves signal parameter estimation. We developed a parameter-estimation code [2] to extract the source parameters of spinning binary inspirals [3]. The code is based on a Markov-chain Monte-Carlo (MCMC) technique [4] to compute the posterior probability-density functions (PDFs) of the source parameters.

2. The waveform

In this stage of our study, we model the simulated gravitational-wave signal at the restricted 1.5PN approximation [5] and the effect of spins is included in the limit of *simple precession* [6]. The waveform is described by twelve parameters: chirp mass M_c, symmetric mass ratio η, spin magnitude $a_{\rm spin}$, the angle between the axes of spin and orbit $\theta_{\rm SL}$, time (t_c), phase (ϕ_c) and precession phase (α_c) at coalescence, distance d_L, position in the sky (R.A., Dec.), and orientation of the binary (ι, ψ). Here we present the results of the analysis of a selection of hardware injections that were done during the LIGO science run S5.

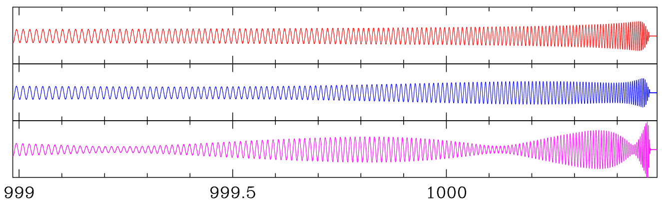

Fig. 1. Inspiral signals for $\theta_{\rm SL} = 20°$ and $a_{\rm spin}$= **0.0**, **0.1** and **0.5**.

3. Hardware injections

The LSC regularly uses hardware injections to add a gravitational-wave signal to the detector data. During the fifth LIGO science run (S5), several hardware injections were performed for compact binary coalescence (CBC) signals, for binaries with different component masses and different signal-to-noise ratios (SNRs).

Most of these hardware injections had non-spinning components, and were done simultaneously for the LIGO interferometers H1, H2 and L1, but not coherently, *i.e.*, there is no specific sky location, orientation or distance for the source. Instead, the non-coherent signal is that of an optimally oriented source, exactly overhead each detector.

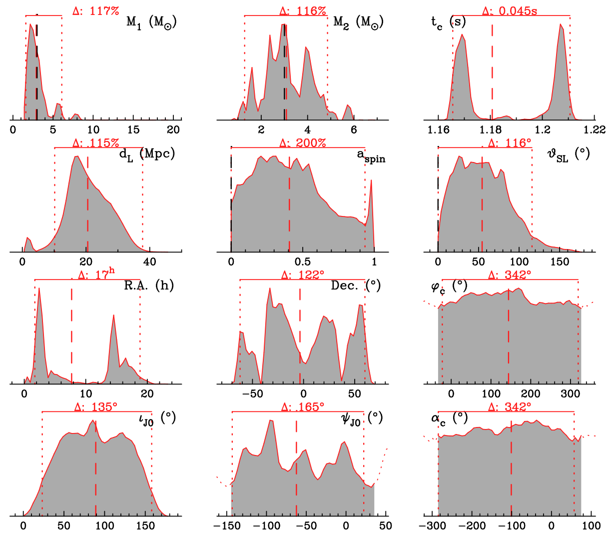

Fig. 2. Posterior PDFs for the source parameters from the analysis of the hardware injection at GPS time 829557331. For each PDF, the **black dashed line** indicates the true value (where available for a non-coherent injection), the **red dashed line** is the median and the **red dotted lines** show the 2σ (95.4%) probability interval, the width of which is indicated by Δ.

4. A black-hole–black-hole inspiral

At GPS time 829557331, a self-blinded hardware injection was done for a 3.0+3.0 $M_\odot$, non-spinning BH-BH inspiral into the LIGO data. The effective distance for the injection was 40 Mpc and the SNR in H1 and L1 10–11. The signal was detected by the compact-binary coalescence (CBC) detection pipeline. We used 8.0 s of data from both H1 and L1 for the analysis and the masses from the detection trigger to start the Markov chains. We ran the analysis both allowing the spin to be determined (spMCMC) and assuming that no spin was present (nsMCMC). The posterior PDFs of the spMCMC analysis are shown in Fig. 2 and the 2σ results for some key parameters are shown in the table below.

	$M_1(M_\odot)$	$M_2(M_\odot)$	spin
Injection	3.0	3.0	0.00
spMCMC	3.85 ± 2.24	3.07 ± 1.78	0.47 ± 0.47
nsMCMC	3.18 ± 1.29	3.29 ± 1.35	—

Figure 3 shows two-dimensional PDFs from the analysis of the BH-BH inspiral. These PDFs are rather narrow and the surface contained in them is much smaller than suggested by the one-dimensional PDFs. For the sky position, the 2D PDF represents a great circle, as expected for a coincident but non-coherent injection.

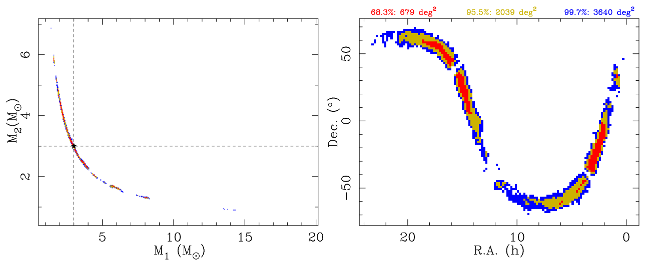

Fig. 3. Two-dimensional PDFs for the two individual masses (left panel) and the position in the sky (right panel) in the spMCMC analysis of the BH-BH inspiral with GPS time 829557331. The different colours show the 1σ (68.3%), 2σ (95.4%) and 3σ (99.7%) probability areas respectively. The star in the left panel denotes the masses of the injected signal, the numbers in the header of the right panel indicate the surface for each probability range in square degrees (the whole sky has a surface of $\sim 41\,253\,{\rm deg}^2$).

5. A neutron-star–neutron-star inspiral

We analysed the self-blinded hardware injection at GPS time 837076903, using 14.0 s of data from H1 and L1. This was the signal of the binary inspiral of two 1.4 $M_\odot$ neutron stars (NSs) at an effective distance of 40 Mpc. This injection had an SNR of $6-7$ in each detector and was found to be consistent with background by the CBC detection pipeline. We started the Markov chains from mass values from a Gaussian distribution with a width of 10 $M_\odot$ around the true masses. The 2σ results for both the spinning and non-spinning analysis are shown in the table below.

	$M_1(M_\odot)$	$M_2(M_\odot)$	spin
Injection	1.4	1.4	0.00
spMCMC	1.52 ± 0.63	1.60 ± 0.67	0.46 ± 0.46
nsMCMC	1.56 ± 0.75	1.57 ± 0.81	—

6. A black-hole–neutron-star inspiral

Finally, we present our analysis of the hardware injection at GPS time 841739297. This was the signal from an inspiral of a 10.0 $M_\odot$ BH and a 1.4 $M_\odot$ NS at an effective distance of 50 Mpc. We used 4.0 s of data from the H1 and L1 interferometers for the parameter estimation. The 2σ results of the main parameters in our MCMC analysis are listed in the table below. Figure 5 shows the posterior PDFs from the analysis.

	$M_1(M_\odot)$	$M_2(M_\odot)$	spin
Injection	10.0	1.4	0.00
spMCMC	7.24 ± 3.78	2.15 ± 0.99	0.47 ± 0.47
nsMCMC	8.19 ± 1.10	1.65 ± 0.19	—

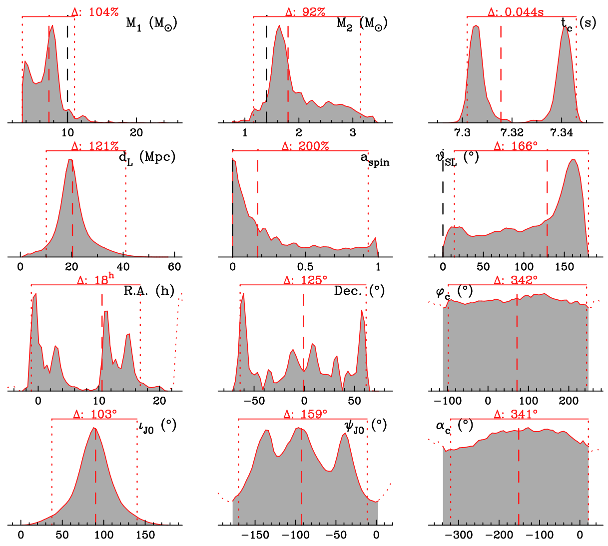

Fig. 5. Posterior PDFs for the source parameters from the analysis of the BH-NS hardware injection at GPS time 841739297. The lines and numbers have the same meaning as in Fig. 2.

7. Conclusions and future work

- Our MCMC code performs reliable and efficient parameter estimation with or without information from the CBC detection pipeline, even at rather low SNR. The true values of the injections are recovered within the 2σ-uncertainty level.
- For S6, coherent hardware injections will be performed in LIGO and Virgo, allowing our coherent analysis to estimate the the sky position and binary orientation of a source with high precision.
- The BH-NS hardware injections in S6 will include spinning signals, which will enable us to fully test our code on such signals in real detector noise.
- We have included more realistic, higher-order waveforms, including the spin of both components (see the poster by Vivien Raymond).
- We have detailed plans to include our MCMC code in the LIGO data-analysis pipeline.

References

[1] Belczynski, K., Taam, R. E., Rantsiou, E., & Van der Sluys, M., ApJ, 682, 474 (2008)

[2] Van der Sluys, M. V., et al., CQG, 25, 184011 (2008)

[3] Van der Sluys, M. V., et al., ApJ, 688, L474 (2008)

[4] Gilks, W. R., Richardson, S., & Spiegelhalter, D. J., Markov chain Monte Carlo in practice. Chapman & Hall / CRC, Boca Raton, (1996)

[5] Blanchet, L., Damour, T., Iyer, B. R., Will, C. M., & Wiseman, A. G., PRL, 74, 3515 (1995)

[6] Apostolatos, T. A., Cutler, C., Sussman, G. J., & Thorne, K. S., PRD, 49, 6274 (1994)

LIGO DCC number: LIGO-G0900014