arXiv:0911.0473v3 [gr-qc] 12 May 2010

Recovering a spinning inspiralling compact binary waveform immersed in LIGO-like noise with spinning templates

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Abstract. We investigate the recovery chances of highly spinning waveforms immersed in LIGO S5-like noise by performing a matched filtering with 10^6 randomly chosen spinning waveforms generated with the LAL package. While the masses of the compact binary are reasonably well recovered (slightly overestimated), the same does not hold true for the spins. We show the best fit matches both in the time-domain and the frequency-domain. These encompass some of the spinning characteristics of the signal, but far less than what would be required to identify the astrophysical parameters of the system. An improvement of the matching method is necessary, though may be difficult due to the noisy signal.

We report on an attempt to recover a gravitational wave signal $h_{injection}$ immersed in LIGO S5-like noise by a matched filtering with 10^6 randomly chosen templates generated with spinning waveforms [1]. We applied the following process to generate a LIGO S5-like noise sample of N elements: (i) cut out a stretch of 2N elements from an arbitrary sample of real LIGO S5 noise, (ii) cut the stretch into half, resulting in two stretches of N elements, (iii) Fourier-transfom both stretches with an FFT method, resulting in two samples of N complex elements, (iv) combine the magnitude values of the first spectrum with the phase values of the second spectrum, resulting in a complex spectrum of N elements, (v) apply an inverse FFT on the combined spectrum, and use the real part of the resulting array as our LIGO S5-like noise sample. This method has the advantage of preserving the basic spectral and statistical properties of the original LIGO data, while discarding any real gravitational wave signatures that might be present within the original data stretch.

The matched filtering follows the method described in Ref. [2]. Namely, we calculate the
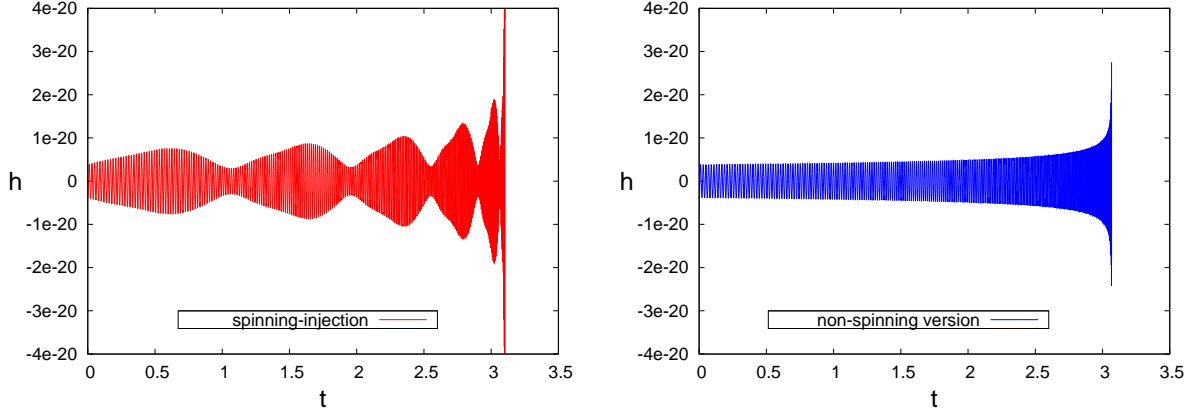
Figure 1. The injected signal (red) and its spinn-less counterpart (blue).

overlap between the noisy injection $h_{n,i}$ and the spinning templates $h_{template}$ as

$$O\left[h_{n,i}, h_{template}\right] = \frac{\langle h_{n,i}|h_{template}\rangle}{\sqrt{\langle h_{n,i}|h_{n,i}\rangle \langle h_{template}|h_{template}\rangle}} \ , \tag{1}$$

where

$$\langle h_1|h_2\rangle = 4Re \int_{f_{\min}}^{f_{\max}} \frac{\tilde{h}_1\left(f\right)\tilde{h}_2^*\left(f\right)}{S_n\left(f\right)} df \ , \tag{2}$$

with $\tilde{h}_i\left(f\right)$ the Fourier transform of $h_i\left(t\right)$ and $S_n\left(f\right)$ the power spectral density of the noise. We choose $f_{\min} = 50\text{Hz}$ and $f_{\max} = 600\text{Hz}$, which lies in the best sensitivity of the LIGO detectors, also the post-Newtonian prediction for the waveform can be considered reasonably accurate. The most lengthy templates in this domain were found to last for approximately 3 sec.
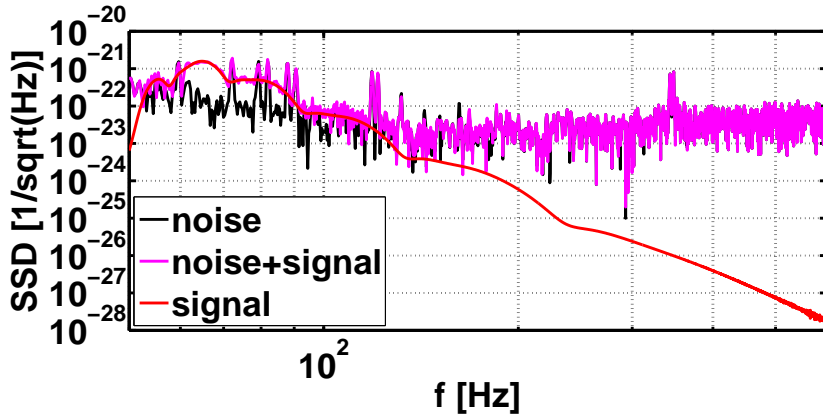

Figure 2. The strain spectral density of the signal (red), noise (grey) and injected signal + noise (magenta).

On theoretical grounds, an infinitely long data series would be required for exact determination of the power spectrum. In order to achieve a stability of the power spectrum of the order of 1%, we would like to have at least 100 periods of all frequencies to be included in the power spectrum, therefore a minimal length of the templates of $100 \times (1/50\text{Hz}) = 2$ sec was imposed. As we know where the injection commences in the noise time sequence, we simplify

Table 1. The parameters of the injection and 5 best fit templates.

name	$m_1(M_\odot)$	$m_2(M_\odot)$	χ_1	χ_2	$\cos\beta_1$	φ_1	$\cos\beta_2$	φ_2
injection	3.553	3.358	0.983	0.902	0.984	1.109	0.978	0.957
560884.wave	4.805	3.336	0.230	0.293	-0.599	1.327	-0.621	0.006
467403.wave	4.092	3.405	0.868	0.891	-0.520	1.275	0.363	3.925
313940.wave	3.569	3.540	0.753	0.413	0.306	1.458	-0.092	2.679
93938.wave	5.012	3.152	0.280	0.424	0.947	2.593	0.888	2.340
80521.wave	4.278	4.360	0.736	0.475	-0.620	5.959	0.945	3.290

our analysis by comparing with templates beginning at the same instant t_0. Further, we also assume identical antenna functions of $\sqrt{2}/2$ both for the injection and templates. Moreover, all parameters of the injection and templates other then the masses m_i and spins (given by their dimensionless magnitude χ_i, polar and azimuthal angles β_i, φ_i, taken in the inertial system with the line of sight on the z-axis) were kept fixed. These parameters were the distance of the binary $d = 1\text{Mpc}$, and the polar angle of the orbital angular momentum $\Theta = 1.4299$. The initial phase $\Phi_S = 0$.

We picked up the injection signal as one of the longests available (see Fig 1). The presence of a high spin induces a strong amplitude modulation, but also a less visible frequency modulation. For comparison, we have also represented on Fig 1 the corresponding non-spinning signal, with the same masses, but the spins switched off.
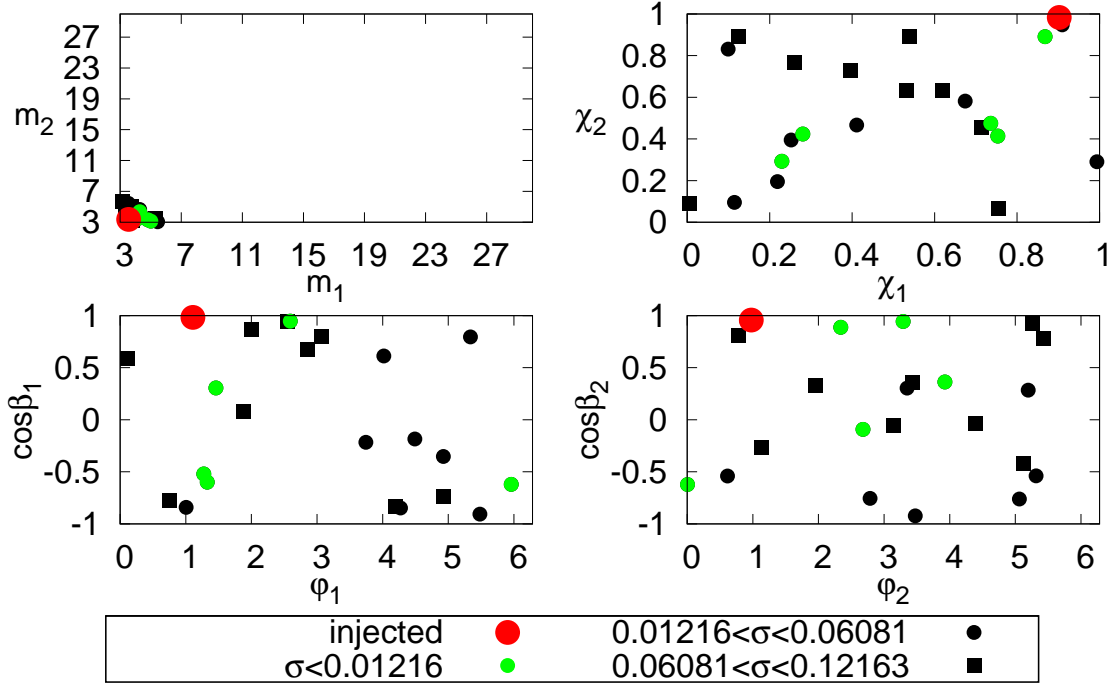

Figure 3. The injection and the best fit matches from 10^6 templates. The mass is roughly recovered, though sligtly overestimated, however the information contained in the spins is not.

The spinning signal is injected in the middle of a finite stretch of LIGO-like data with double the length of the signal. The noise has the basic statistical characteristics (e.g. amplitude distribution, spectral compatibility) of the LIGO 4 km detectors during the 5th science run. The segment to be analyzed is filtered with a zero-phase $50 - 600$ Hz bandpass filter, and a zero-phase notch filter mitigating the effect of narrow insensitivity peaks of detector spectrum. After removing one-fourth of the data segment from both ends due to filter transients, this leaves half the length of the initial noise sequence including the signal for further processing. The strain spectral density, defined as the square root of the periodogram, computed under MatLab [3], is represented on Fig 2 for the signal, noise and noisy signal.
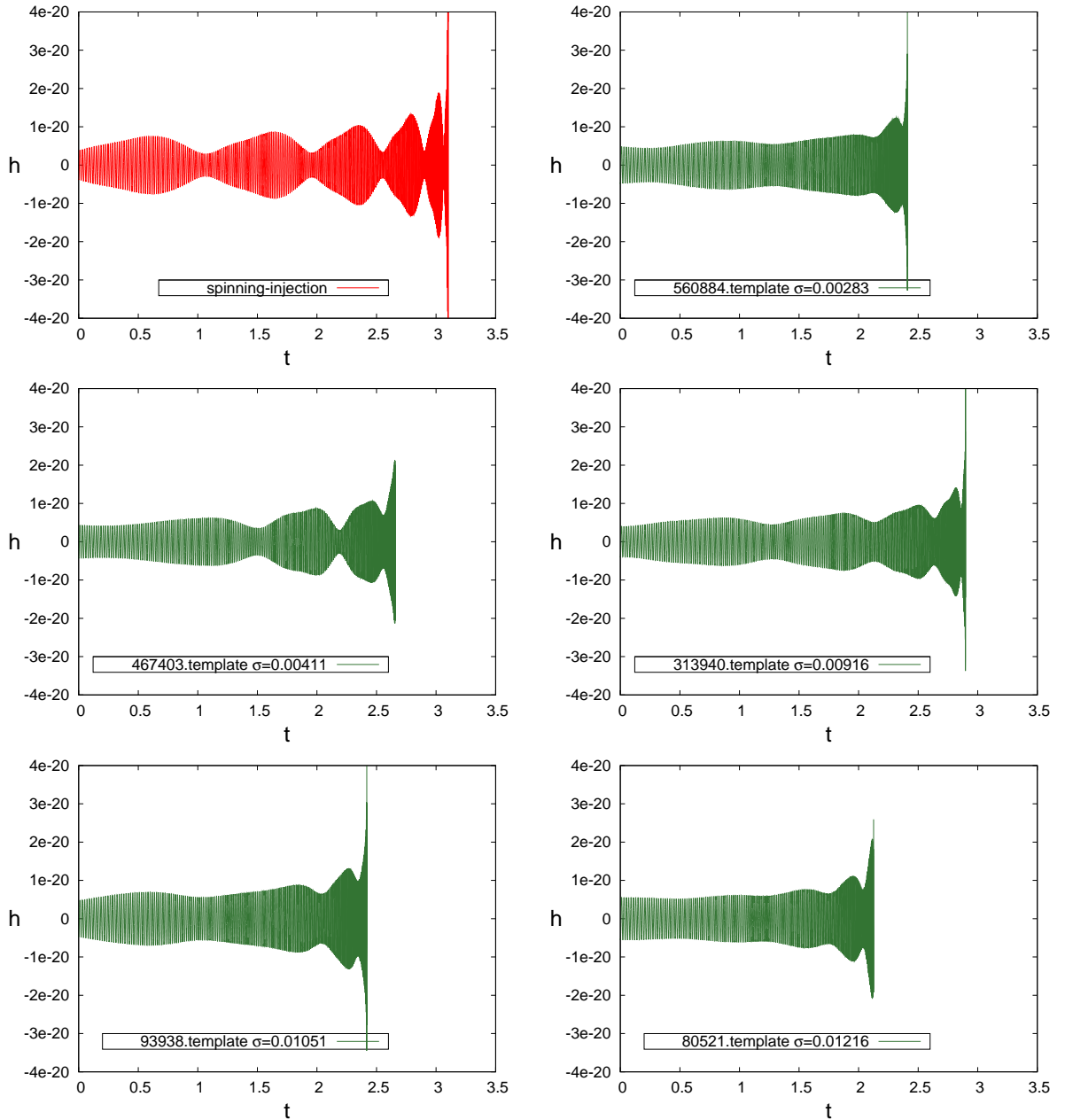

Figure 4. The injected signal and the five best matches. Their serial numbers from among the 10^6 randomly generated templates is also indicated.

The overlap between the noisy injection and the injected signal itself was found to be $O[h_{n,i}, h_{injection}] = 0.83426$. Therefore we define an auxiliary quantity

$$\sigma = \left| 1 - \frac{O[h_{n,i}, h_{template}]}{O[h_{n,i}, h_{injection}]} \right| \tag{3}$$

for characterizing the closeness of the overlap of a template with the noisy injection to $O[h_{n,i}, h_{injection}]$. The parameters of a number of > 20 templates with the lowest values of σ are represented on Fig 3. While it is comforting to realize that (although slightly overestimated) the masses are reasonably well recovered, the spins are not. There is a considerable scatter in both their magnitudes and orientations.
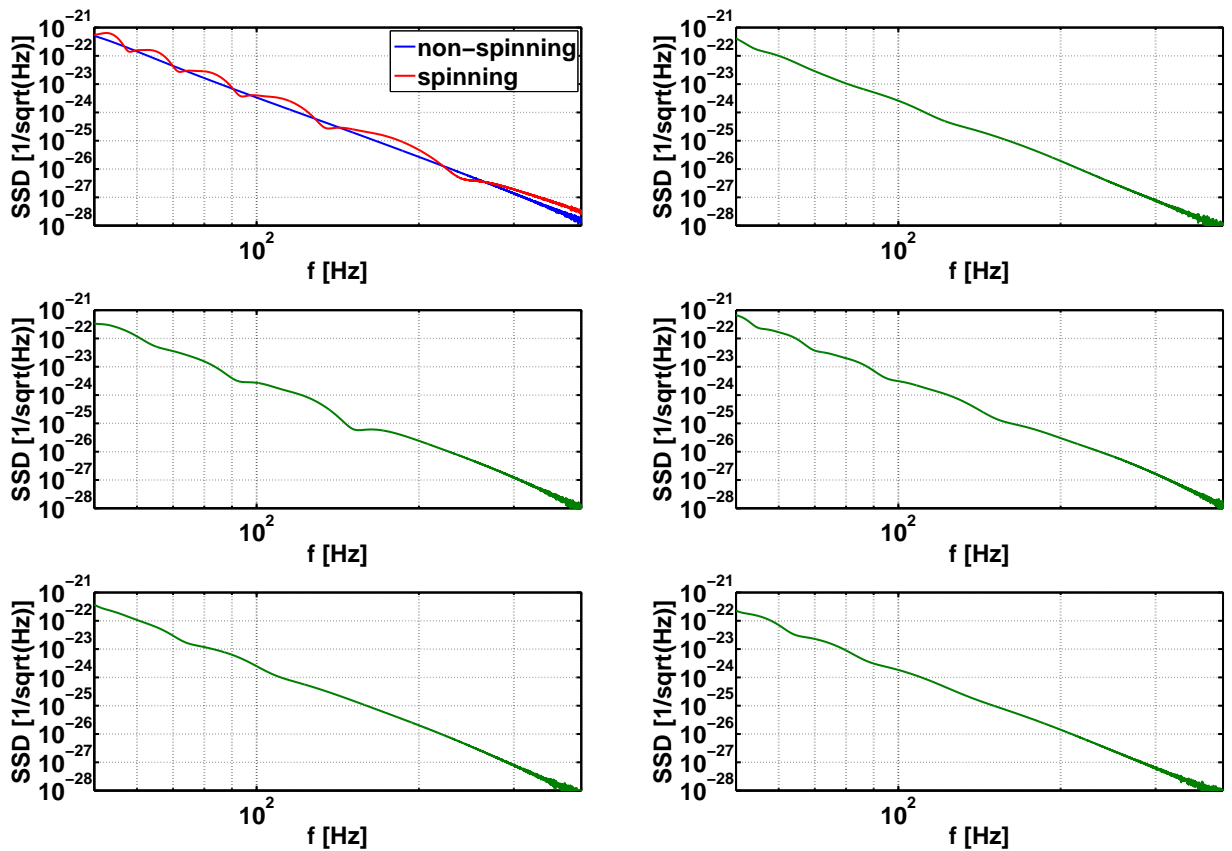

Figure 5. The strain spectral density of the injected signal (red) and its spin-less counterpart (blue) and the five best matches (green).

We picked up the 5 best fits, showed their parameters in Table 1 and represented the respective waveforms on Fig 4; also their strain spectral density on Fig 5. For comparison, the injected signal is also shown.

We conclude that even with all the simplifying assumptions adopted, (a) either the number of 10^6 templates employed was still insufficient or (b) the 6 additional parameters introduced by the spins cause severe degeneracies, which cannot be resolved by this method. In this context we note that the use of a Markov-chain Monte-Carlo technique [4], [5] may turn useful in the recovery of spinning signals. We also plan to investigate how the use of Advanced LIGO-like data would change these conclusions.

References

[1] https://www.lsc-group.phys.uwm.edu/daswg/projects/lal/nightly/docs/html/LALSTPNWaveformTest_8c-source.html
[2] Vaishnav B, Hinder I, Herrmann F, Shoemaker D 2007 *Phys. Rev.* D **76** 084020
[3] http://www.mathworks.com/access/helpdesk/help/toolbox/signal/index.html?/access/helpdesk/help/toolbox/signal/periodogram.html
[4] van der Sluys M, Raymond V, Mandel I, Roever C, Christensen N, Kalogera V, Meyer R, Vecchio A 2008 *Class.Quant.Grav.* **25** 184011
[5] Raymond V, van der Sluys MV, Mandel I, Kalogera V, Roever C, Christensen N, 2009 *Class.Quant.Grav.* **26** 114007