Recovery of hardware injections in the S5R3 Einstein@Home run for continuous wave searches

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Abstract

This technical report refers to the recovery of hardware injections in the S5R3 Einstein@Home run, widely discussed in Ref. [1], where we refer the reader to for more details and for the definition of some code names used here.

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I. RECOVERY OF HARDWARE-INJECTED SIGNALS IN S5R3

The situation for the hardware injections in S5R3 is somewhat more complicated than in S5R5. Unlike in S5R5, there were *two* sets of hardware injections relevant for S5R3, each including ten signals. As in S5R5, of the ten hardware-injected continuous wave (CW) signals, labeled fake pulsar 0, 1, 2,..., 9, only eight had frequencies covered by the S5R3 search frequency band of [50, 1 200] Hz: the fake pulsars 4 and 7 have frequencies outside this band and thus have not been considered in this analysis.

The first set of hardware injections is the same as described in Sec. VI and listed in Table III of Ref. [1]. For this set of simulated signals, the duty cycle in S5R3 data is $\sim 32\%$ and $\sim 39\%$ of the time in H and L detectors, respectively. The other set consists of CW signals injected from the GPS epoch 819 336 132 s until 827 606 816 s. The physical parameters corresponding to the signals included in this set are the same as those shown in Table III of Ref. [1], except for the gravitational wave amplitude h_0. This is equal to 1.34×10^{-24}, 4.07×10^{-24} and 3.97×10^{-24} for the fake pulsars 2, 3 and 8, respectively. The duty cycle for this set is $\sim 8\%$ of the time in both H and L detectors.

Given the different values of h_0 associated with the fake pulsars 2, 3, 8 in the two sets of hardware injections, it turns out that within 7 of the S5R3 data segements, h_0 is reduced by a factor 3 for the fake pulsar 2 and by a factor 4 for the fake pulsars 3 and 8 with respect to the values shown in Table III of Ref. [1].

For each hardware-injection, the expected value of number count has been computed as follows:

$$E[n_c] = \sum_j \eta_j + p\, N_l, \qquad (1)$$

where j runs on the number of data segments where the hardware injections were active and N_l is the number of remaining segments, representing the noise contribution; η and p represent the probabilities that the $2\mathcal{F}$-value, computed for a given data segment, crosses the threshold $2\mathcal{F}_{\rm th} = 5.2$ in presence and absence of signal, respectively. It is worth noting that Eq. (46) in Ref. [1] reduces to Eq. (1) when the Hough weights w_j are all set to unity, as it is the case for the S5R3 search. Following the usual search and post-processing pipeline described in Ref. [1], we find in the end that the only hardware injection recovered in the S5R3 post-processing analysis is the fake pulsar 3. This can also be noticed from the high $\langle 2\mathcal{F}_{\rm HL}\rangle$-value in Table I, greater than 6.5 and corresponding to the candidate that in the final set is closest [2] to fake pulsar 3. In contrast to what happened in S5R5, the fake pulsar 5 is not recovered in S5R3 due to the reduced sensitivity of this search. The fake pulsar 2 has not been retrieved mainly because of the reduced value of gravitational wave amplitude on some data segments, as said before. The fake pulsar 8 is not recovered because its spindown value, -8.65 nHz/s, is outside the S5R3 spindown search range $[-160, -3.2] \times 10^{-11}$ Hz s^{-1} (as it is also the case for Pulsar 6).

Table I shows, for all the hardware injections, their expected number count $E[n_{\rm c}]$, computed using Eq. (1) and the observed number count $n_{\rm c}$ of the S5R3 candidates that, in the final set, are closest to such hardware-injections; $n_{\rm c}$ is computed using Eq. (18) in Ref. [1] with weights all set to unity and $N_{\rm seg} = 84$. The $\langle 2\mathcal{F}_{\rm HL}\rangle$-values associated with these candidates are also shown. The standard deviation is equal to ~ 4.06 for all the candidates, since no weights have been used.

TABLE I: Comparison between the expected values of number count $E[n_{\rm c}]$ for the hardware injections and the observed number count $n_{\rm c}$ of the S5R3 candidates that, in the final set, are closest to the hardware-injections; $E[n_{\rm c}]$ and $n_{\rm c}$ are computed using respectively Eq. (1) and Eq. (18) in Ref. [1] with weights all set to unity and $N_{\rm seg} = 84$. The $\langle 2\mathcal{F}_{\rm HL}\rangle$-values are also reported in the fourth column. The standard deviation is equal to ~ 4.06 for all the candidates. We remind that the fake signals labeled fake pulsar 4 and 7 have frequencies outside the search frequency range and therefore they were excluded from the analysis.

Name	$E[n_{\rm c}]$	$n_{\rm c}$	$< 2\mathcal{F}_{\rm HL} >$
Fake pulsar 0	34	53	5.657
Fake pulsar 1	33	55	5.808
Fake pulsar 2	53	54	5.818
Fake pulsar 3	53	55	33.21
Fake pulsar 5	48	51	5.702
Fake pulsar 6	46	52	5.525
Fake pulsar 8	53	53	5.619
Fake pulsar 9	35	54	5.605

The frequency, right ascension, declination, spindown and the number count values for the fake pulsar 3 and for the candidate that in the final set is closest to it, referred to as Cand 3, are shown in Table II. The recovered parameters of Cand 3 agree well with the injected signal parameters of fake pulsar 3, in spite of the considerable mismatch in spindown. However, the injection was found at the nearest spindown template. Moreover, the number count values show a consistency much smaller than 3 times the standard deviation.

TABLE II: Hardware injection recovery in the S5R3 run. Code names and $(f, \dot{f}, \alpha, \delta)$-parameters for the hardware injection fake pulsar 3 and for the recovered signal, denoted as Cand 3.

Name	f (Hz)	α (rad)	δ (rad)	$\dot{f}$ (Hz/s)	n_c
Fake pulsar 3	108.857159	3.113189	-0.583579	-1.46×10^{-17}	53
Cand 3	108.857161	3.063681	-0.604713	-3.17×10^{-11}	55

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[1] J. Aasi *et al.* (The LIGO Scientific Collaboration and the Virgo Collaboration), *Einstein@Home all-sky search for periodic gravitational waves in LIGO S5 data*, **LIGO-P1200026**; `https://dcc.ligo.org/cgi-bin/private/DocDB/ShowDocument?docid=88496`.

[2] The distance used to judge closeness between candidates is a Euclidean distance expressed in bins in the four dimensions $(f, \dot{f}, \alpha, \delta)$, with f being the signal frequency, $\dot{f}$ the first frequency time-derivative (also called spindown) and (α, δ) the source sky position represented by the right-ascension and declination in equatorial coordinates.