We describe directed searches for continuous gravitational waves in data from the sixth LIGO science data run. The targets were nine young supernova remnants not associated with pulsars; eight of the remnants are associated with non-pulsing suspected neutron stars. One target’s parameters are uncertain enough to warrant two searches, for a total of ten. Each search covered a broad band of the remnants’ spectral energy distributions, for a few of the pulsars searched, thereby marking the point at which the Laser Interferometer Gravitational-wave Observatory (LIGO) and Virgo began revealing new information about these pulsars. Other continuous GW searches have surveyed the whole sky for neutron stars not seen as pulsars, using great computational power to cover wide frequency bands and large ranges of spin-down parameters (Abbott et al. 2005a, 2007a, 2008a, 2009a, 2013b, 2014a, b, d). The four most recent of these papers have set direct upper limits on GW emission stricter than the indirect “spin-down limits” derived from energy conservation, for a few of the pulsars searched, thereby marking the point at which the Laser Interferometer Gravitational-wave Observatory (LIGO) and Virgo began revealing new information about these pulsars. Other continuous GW searches have surveyed the whole sky for neutron stars not seen as pulsars, using great computational power to cover wide frequency bands and large ranges of spin-down parameters (Abbott et al. 2005a, 2007a, 2008a, 2009a, b, d, Abadie et al. 2012, Aasi et al. 2013b, 2014a, d) and recently possible binary parameters too (Aasi et al. 2014d). Several of the recent all-sky searches have set direct upper limits competitive with indirect upper limits based on the galactic neutron-star...
population [Knispel & Allen 2008].

Between these two extremes of computational cost and sensitivity are the directed searches, where the sky location (and thus the detector-frame Doppler modulation) is known but the frequency and other parameters are not. The first directed search was for the accreting neutron star in the low-mass X-ray binary Sco X-1 (Abbott et al. 2007a; Abadie et al. 2011b). This type of search must cover a range of GW frequencies since no pulsations are observed, and a range of orbital parameters since there are substantial uncertainties. Direct upper limits from searches for Sco X-1 have not beaten the indirect limit derived from accretion torque balance, but may with data from interferometers upgraded to the “advanced” sensitivity [Harry 2010; Sammut et al. 2014].

The search of the fifth LIGO science run (S5) data for the central compact object (CCO) in the supernova remnant (SNR) Cas A (Abadie et al. 2010) inaugurated a new type, directed searches for young non-pulsing neutron stars. Such a search is motivated by the idea that young neutron stars might be the best emitters of continuous GW. It is made possible by the fact that a known sky direction allows for searching a wide band of frequencies and frequency derivatives with much less computing power than the all-sky wide-band searches (Wette et al. 2008), and for isolated neutron stars no search over binary parameters is needed. The Cas A search [Abadie et al. 2010] set upper limits on GW strain which beat an indirect limit derived from energy conservation and the age of the remnant [Wette et al. 2008] over a wide frequency band. Upper limits on the fiducial ellipticity of the neutron star were within the range of observational predictions, as were upper limits on r-mode amplitude (the first ever set in a GW search). Since then similar searches, using different data analysis methods, have been performed for supernova 1987A and unseen stars near the galactic center (Abadie et al. 2011b; Aasi et al. 2013a).

In this article, we describe searches of data from S6 for Cas A and eight more supernova remnants with known or suspected young isolated neutron stars with no observed electromagnetic pulsations. These targets were chosen so that a computationally feasible coherent search similar to [Abadie et al. 2010] could beat the age-based indirect limits. Therefore each search had a chance of detecting something, and non-detections could constrain the star’s GW emission, provided that emission is at a frequency within the band searched. No search found a plausible GW signal, and hence the main result is a set of upper limits similar to those presented in Abadie et al. (2010).

The rest of this article is structured as follows: In Sec. 2 we present the methods, implementation, and results of the searches. The upper limits set in the absence of a credible signal are presented in Sec. 3, and the results are discussed in Sec. 4. In the Appendix we describe the performance of the analysis pipeline on hardware injected signals.

2. SEARCHES

2.1. Data selection

S6 ran from July 7 2009 21:00:00 UTC (GPS 931035615) to October 21 2010 00:00:00 UTC (GPS 971654415). It included two interferometers with 4-km arm lengths, H1 at LIGO Hanford Observatory (LHO) near Hanford, Washington and L1 at LIGO Livingston Observatory (LLO) near Livingston, Louisiana. It did not include the 2-km H2 interferometer that was present at LHO during earlier runs. Plots of the noise power spectral density (PSD) curves and descriptions of the improvements over S5 can be found, for example, in Aasi et al. (2014b). A description of the calibration and uncertainties can be found in [Bartos et al. 2011]. The phase calibration errors at the frequencies searched were up to 7° and 10° for H1 and L1 respectively, small enough not to affect the analysis. The corresponding amplitude calibration errors were 16% and 19% respectively. For reasons discussed in Aasi et al. (2014a) we estimate the maximum amplitude uncertainty of our joint H1-L1 results to be 20%.

Concurrently with the LIGO S6 run, the Virgo interferometer near Cascina, Italy had its data runs VSR2 and VSR3. Although Virgo noise performance was better than LIGO in a narrow band below roughly 40 Hz, it was not as good as LIGO at the higher frequencies of the searches described here, and hence the searches described here used only LIGO data.

Like many other continuous-wave searches, those reported here used GW data in the Short Fourier Transform (SFT) format. The (discontinuous) series of science-mode data, minus short segments which were “category 1” vetoed [Aasi et al. 2014b] was broken into segments of T_{SFT} = 1800 s. There were a total of 19268 of these segments for H1 and L1 during the S6 run. Each 30-minute segment was band-pass filtered from 40–2035 Hz, Tukey windowed in the time domain, and Fourier transformed to produce an SFT. The power loss due to windowing was of order 0.1%. The power lost below 40 Hz is unimportant for most searches because the LIGO noise PSD rises steeply below that frequency. Also, for the searches described here, astrophysical constraints dictated higher frequencies (see below).

Although a directed search is computationally more tractable than an all-sky search, computational costs nonetheless restrict us to searching a limited time span T_{span} of the S6 data. The data selection criterion was the same as in Abadie et al. (2010), maximizing the figure of

<table>
<thead>
<tr>
<th>SNR</th>
<th>Other name</th>
<th>RA+dec</th>
<th>D</th>
<th>a</th>
</tr>
</thead>
<tbody>
<tr>
<td>(G name)</td>
<td>(J2000)</td>
<td>(kpc)</td>
<td>(kyr)</td>
<td></td>
</tr>
<tr>
<td>1.9+0.3</td>
<td>174846.9–271016</td>
<td>8.5</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>18.9–1.1</td>
<td>182913.1–125113</td>
<td>2</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td>93.3+6.9</td>
<td>DA 530</td>
<td>205214.0+551722</td>
<td>1.7</td>
<td>5</td>
</tr>
<tr>
<td>111.7–2.1</td>
<td>Cas A</td>
<td>232327.9+584842</td>
<td>3.3</td>
<td>0.3</td>
</tr>
<tr>
<td>189.1+3.0</td>
<td>IC 443</td>
<td>061705.3+222127</td>
<td>1.5</td>
<td>3</td>
</tr>
<tr>
<td>266.2–1.2</td>
<td>Vela Jr.</td>
<td>058214.0–461753</td>
<td>0.2</td>
<td>0.69</td>
</tr>
<tr>
<td>266.2–1.2</td>
<td>Vela Jr.</td>
<td>058214.0–461753</td>
<td>0.75</td>
<td>4.3</td>
</tr>
<tr>
<td>291.0–0.1</td>
<td>MSH 11–62</td>
<td>111148.6–603926</td>
<td>3.5</td>
<td>1.2</td>
</tr>
<tr>
<td>347.3–0.5</td>
<td>171328.3–394953</td>
<td>0.9</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>550.1–0.3</td>
<td>172054.5–372652</td>
<td>4.5</td>
<td>0.6</td>
<td></td>
</tr>
</tbody>
</table>

Values of distance D and age a are at the optimistic (nearby and young) end of ranges given in the literature, except for the second search for Vela Jr. See text for details and references.
and orientation angles, as well as on the parameters of
with the earth. It depends on the source’s sky location
including of the beam patterns as the interferometer rotates
strain response
covered. The precise expression for the interferometer
frequency, based on the time spans and ranges of \( \dot{f} \)
in the observation. We also
glitched (had abrupt frequency jumps) or had significant
quency band. The sum was evaluated over SFTs only,
 frequency band. Maximizing this figure of merit
roughly corresponds to optimizing (minimizing) the de-
strains. This figure of merit also neglects
Turing noise (additional, perhaps stochastic, time depen-
dal effect was at most a few percent, less than the amplitude
comparable amounts of H1 and L1 data, the declination
ruled by LLO is better for low (Jaranowski et al.
that LHO is better for high declina-
runtional cost the same for all searches resulted in some
The primary detection statistic was the multi-
interferometer \( F \)-statistic (Cutler & Schutz 2005). This is based
on the single-interferometer \( F \)-statistic
Jaranowski et al. [1998], which combines the results of
matched filters for the four sinusoids of the signal in
a way that is computationally fast and nearly optimal
(Prix & Krishnan 2009). In Gaussian noise \( 2F \) is drawn
from a \( \chi^2 \) distribution with four degrees of freedom, and
hence \( F/2 \) is roughly a power signal-to-noise ratio.
We used the implementation of the \( F \)-statistic in the
LALSuite package, tag S6SNRSearch, publicly
available at https://www.lsc-group.phys.uwm.edu/
daswg/projects/lalsuite.html. In particular most
of the computing power of the search was spent in
the ComputeFStatistic_v2_SSE program, which unlike
the version used in the preceding search of this type
(“mismatch” or maximum loss of \( 2F \))
due to discretization of the frequency and derivatives
(Owen 1990; Brady et al. 1998) was 0.2, again the same as
in Abadie et al. (2010). Choosing to keep the computa-
tional cost the same for all searches resulted in some
variation of the total number of templates per search, 3–
12×10^{12} compared to the 7×10^{12} in
Abadie et al. (2010).

2.3. Target objects

The goal of these searches was to target young non-
pulsing neutron stars. Starting with the comprehensive
catalog of SNRs (Green 2009, 2014), augmented by a
search of the recent literature, we narrowed the list to
remnants with confirmed associated non-pulsing point
sources (central compact objects or small pulsar wind
nebulae or candidates). We also included SNR G1.9+0.3,
although a point source is not visible (and may not exist
since the supernova may have been Type Ia), because
this remnant is the youngest known and is small enough
to search with a single sky location.

The final selection of target objects and search param-

<table>
<thead>
<tr>
<th>SNR (G name)</th>
<th>( f_{\text{min}} ) (Hz)</th>
<th>( f_{\text{max}} ) (Hz)</th>
<th>( T_{\text{span}} ) (s)</th>
<th>( T_{\text{span}} ) (days)</th>
<th>Start of span (UTC, 2010)</th>
<th>H1 SFTs</th>
<th>L1 SFTs</th>
<th>Duty factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9+0.3</td>
<td>141</td>
<td>287</td>
<td>788</td>
<td>9.1</td>
<td>Aug 22 00:23:45</td>
<td>356</td>
<td>318</td>
<td>0.77</td>
</tr>
<tr>
<td>18.9–1.1</td>
<td>132</td>
<td>298</td>
<td>2 186</td>
<td>25.3</td>
<td>Aug 13 02:02:24</td>
<td>786</td>
<td>912</td>
<td>0.70</td>
</tr>
<tr>
<td>90.3+6.9</td>
<td>109</td>
<td>373</td>
<td>2 012</td>
<td>23.3</td>
<td>Aug 10 18:49:49</td>
<td>770</td>
<td>813</td>
<td>0.71</td>
</tr>
<tr>
<td>111.7–2.1</td>
<td>91</td>
<td>573</td>
<td>730</td>
<td>8.4</td>
<td>Aug 22 10:27:49</td>
<td>332</td>
<td>298</td>
<td>0.77</td>
</tr>
<tr>
<td>189.1+3.0</td>
<td>101</td>
<td>464</td>
<td>1 553</td>
<td>18.0</td>
<td>Aug 13 07:55:32</td>
<td>650</td>
<td>634</td>
<td>0.74</td>
</tr>
<tr>
<td>266.2–1.2</td>
<td>46</td>
<td>2034</td>
<td>456</td>
<td>5.3</td>
<td>Jul 30 06:17:12</td>
<td>218</td>
<td>186</td>
<td>0.80</td>
</tr>
<tr>
<td>266.2–1.2</td>
<td>82</td>
<td>846</td>
<td>1 220</td>
<td>14.1</td>
<td>Aug 17 02:58:47</td>
<td>525</td>
<td>503</td>
<td>0.76</td>
</tr>
<tr>
<td>291.0–0.1</td>
<td>124</td>
<td>315</td>
<td>1 487</td>
<td>17.2</td>
<td>Aug 14 00:53:35</td>
<td>629</td>
<td>615</td>
<td>0.75</td>
</tr>
<tr>
<td>347.3–0.5</td>
<td>82</td>
<td>923</td>
<td>903</td>
<td>10.5</td>
<td>Aug 20 22:00:05</td>
<td>397</td>
<td>370</td>
<td>0.76</td>
</tr>
<tr>
<td>350.1–0.3</td>
<td>132</td>
<td>301</td>
<td>1 270</td>
<td>14.7</td>
<td>Aug 16 13:10:34</td>
<td>538</td>
<td>519</td>
<td>0.75</td>
</tr>
</tbody>
</table>
eters was based on beating the indirect upper limit on GW emission due to energy conservation. This upper limit is based on the optimistic assumption that all of the star’s (unobserved) spin-down is due to GW emission, and has been since the supernova. In terms of the distance $D$ to the source and the age $a$ of the source, this indirect limit is

$$h_0 < 1.26 \times 10^{-24} \left(\frac{3.30 \text{ kpc}}{D}\right) \left(\frac{300 \text{ yr}}{a}\right)^{1/2}. \quad (3)$$

This assumes a moment of inertia $10^{45} \text{ g cm}^2$ and (spherical harmonic $m = 2$) mass quadrupole GW emission, the usual assumption in the literature. For current quadrupole ($r$-mode) emission, it is slightly higher (Owen 2010), but we used the mass quadrupole value. The “intrinsic strain” $h_0$ is generally a factor 2–3 greater than the actual strain amplitude response of a detector; it is defined precisely in Jaranowski et al. (1998) and related to standard multipoles and properties of the source in Owen (2010). In order to beat the limit (3) over as wide a frequency band as possible, we generally used the most optimistic (lowest) age and distance estimates from the literature, corresponding to the highest indirect limit, with exceptions noted below. The algorithm for that final selection is described in the next subsection.

The resulting target list and astronomical parameters are shown in Table 3. The individual SNRs and the provenance of the parameters used are:

- **G1.9+0.3**—Currently the youngest known SNR in the galaxy (Reynolds et al. 2008). Nothing is visible inside the remnant, which although more than an arcminute across is small enough to be searched with one sky position for the integration times used here (Whitbeck 2006). Several arguments favor it being a Type Ia (Reynolds et al. 2008), but this is not definite and the remnant’s youth makes it an interesting target. We used the position of the center of the remnant from the discovery paper (Reich et al. 1984). The age and distance are from the “rediscovery” paper (Reynolds et al. 2008).

- **G18.9—1.1**—The position is that of the *Chandra* point source discovered by Tullmann et al. (2010). Age and distance estimates are from Harrus et al. (2004).

- **G347.3+6.9**—Also known as DA 530. The position and age are from Jiang et al. (2007). No true sub-arcsecond *Chandra* point source is seen, but the e-folding scale of X-ray intensity at the center of the putative pulsar wind nebula is 6", which qualifies as a point source for the GW search. The distance estimate is from Foster & Routledge (2003).

- **G11.7—2.1**—Also known as Cas A. The point source was discovered with *Chandra*’s first light (Tananbaum 1999). The position is from that reference, the distance from Reed et al. (1995), the age from Fesen et al. (2001). In this search we used 300 years rather than 330 years as in Abadie et al. (2010), reflecting the idea of using optimistic ends of ranges given in the literature, which also corresponds to broader parameter space coverage.

- **G18.9+3.0**—Also known as IC 443. The position is that of the *Chandra* point source found by Gilbert et al. (2001). This object is often studied, with a wide range of distance and age estimates in the literature. We used Petre et al. (1988) for an optimistic age estimate. We did not use the most optimistic distance quoted, but

<table>
<thead>
<tr>
<th>Search</th>
<th>Job min. and max. frequency (Hz)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>G18.9—1.1</td>
<td>192.470 192.477</td>
<td>Pulsar 8</td>
</tr>
<tr>
<td>G18.9+3.0</td>
<td>393.167 393.176</td>
<td>H1 &amp; L1 clock noise</td>
</tr>
<tr>
<td>G18.9+3.0</td>
<td>399.264 399.272</td>
<td>L1 clock noise</td>
</tr>
<tr>
<td>G266.2—1.2 wide</td>
<td>441.004 441.212</td>
<td>H1 geophone</td>
</tr>
<tr>
<td>G266.2—1.2 wide</td>
<td>1397.720 1397.780</td>
<td>Pulsar 4</td>
</tr>
<tr>
<td>G266.2—1.2 wide</td>
<td>1408.100 1408.170</td>
<td>H1 electronics</td>
</tr>
<tr>
<td>G347.3—0.5</td>
<td>108.790 108.920</td>
<td>Pulsar 3</td>
</tr>
<tr>
<td>G347.3—0.5</td>
<td>192.448 192.522</td>
<td>Pulsar 8</td>
</tr>
<tr>
<td>G350.1—0.3</td>
<td>192.465 192.472</td>
<td>Pulsar 8</td>
</tr>
<tr>
<td>G350.1—0.3</td>
<td>192.472 192.479</td>
<td>Pulsar 8</td>
</tr>
</tbody>
</table>

Search jobs that produced non-vetoed candidates above the 95% confidence Gaussian threshold, along with the most likely causes. Notes of the form “Pulsar N” refer to hardware-injected signals (see the Appendix). The others are described in the text. Frequencies are shown in the solar system barycenter frame at the beginning of each observation span.

The final selection of targets involved estimating GW search sensitivities and computing costs to determine which objects could feasibly be searched well enough to beat the energy conservation limits on GW emission—see Eq. (3). The sensitivity of each search was worked out in two iterations.
The first iteration made an optimistic sensitivity estimate using the noise PSD harmonically averaged over all S6 and both LIGO interferometers. Writing the 95% confidence upper limit on intrinsic strain $h_0$ as

$$h_{0,\text{95\%}} = \Theta \sqrt{\frac{S_h}{T_{\text{data}}}}, \tag{4}$$

where $T_{\text{data}}$ is the total data live time, the first iteration used a threshold factor $\Theta$ of 28 to ensure that it was too optimistic and thus did not rule out any targets that the second iteration would find feasible. The second iteration results are not sensitive to the precise $\Theta$ chosen in the first iteration, as long as the first iteration value is slightly lower than the true values, which are in the 30s as was seen in [Abadie et al. (2010)] and in the results of the second iteration.

For a given frequency, we chose the range of first and second frequency derivatives in the same manner as [Abadie et al. (2010)]. That is, we assumed a range of braking indices $n = jf/\dot{f}^2$ from 2–7, so that

$$-\frac{f}{(n_{\text{min}} - 1)a} \leq \dot{f} \leq -\frac{f}{(n_{\text{max}} - 1)a} \tag{5}$$

at each frequency. For each $(f, \dot{f})$ the second derivative satisfied

$$n_{\text{min}}\dot{f}^2 \leq \ddot{f} \leq n_{\text{max}}\dot{f}^2. \tag{6}$$

Note that the range of $\dot{f}$ does not extend up to zero. This might seem to be an issue as it would not include "anti-magnetars", or young neutron stars which are observed to spin down very slowly and hence must have small surface magnetic fields (e.g. Gotthelf & Halpern 2008). However, these are stars we would not detect anyway—any star with GW emission close enough to the indirect limit to be detected would have a high spin-down due to that emission, even if it had a low surface magnetic field.

The computational cost is a function of the parameter space covered. The product of the ranges on $f$, $\dot{f}$, and $\ddot{f}$ suggests that the size of the parameter space and the computational cost should scale as $f_{\text{max}}^{-2}a^{-3}T_{\text{span}}^{-2}$ (Wette et al. 2008). In the limit that only one value of $\dot{f}$ is used, the range of that parameter should be eliminated from the product, the parameter space should be two dimensional rather than three, and the scaling should be $f_{\text{max}}^{-2}a^{-1}T_{\text{span}}^{-2}$. By setting up several searches with different parameters perturbed from those of the Cas A search, we observed that the computational cost scaled roughly as $f_{\text{max}}^{2.2}a^{-1.1}T_{\text{span}}^{-2}$. Comparing this to [Wette et al. 2008] shows that the effective dimensions of the template banks were nearly 2 rather than 3, as confirmed by the fact that the number of different $\dot{f}$ values in the template banks was typically more than one but small.

Assuming a 70% duty factor, and the empirical scaling for computational cost above, we determined the three unknowns $(f_{\text{min}}, f_{\text{max}}, T_{\text{span}})$ by setting the sensitivity (1) equal to the indirect limit on $h_0$ (3) at both ends of the search frequency band $(f_{\text{min}}$ and $f_{\text{max}})$. The third condition to fix the three unknowns was to keep the computational cost per search at roughly the same nominal value as [Abadie et al. 2010], although because of hardware and software improvements the total computational time was less (see below).

The second iteration involved running the analysis pipeline on small bands to get true template densities, the noise PSD of the optimal data stretch for each search, upper limits, and thus a better estimate of each $\Theta$. For at least a 10 Hz band near each $f_{\text{min}}$ and $f_{\text{max}}$, we ran the search (without looking at detection candidates) to get upper limits. We then read off the value of $\Theta$ [from the observed upper limits and inverting Eq. (4)] at frequencies near $f_{\text{min}}$ and $f_{\text{max}}$. These values were spot checked beforehand to verify that upper limits were comparable to indirect limits. This second iteration was good enough, considering calibration uncertainties and other errors. The lowest (best) values of $\Theta$ were comparable to the 31.25 predicted by averaging the calculation of [Wette (2014)] over declination, but in some bands $\Theta$ could be more than 40 because of narrow noisy and/or non-stationary bands. In general $\Theta$ rose slightly at higher frequencies because of the increasing density of templates (per Hz).

Table 2 lists the targets and other GW search parameters determined by the sensitivity algorithm. The span reported is the final one, including the possible extension to the end of an SFT in progress at the end of the originally requested span. The duty factor reported is total SFT time divided by $T_{\text{span}}$ divided by the number of interferometers (two).

These parameters were confirmed by several consistency checks:

For each search we checked that $\dot{f}$ was the highest frequency derivative needed for the resulting $T_{\text{span}}$ using the parameter-space metric of Whitbeck (2006). Specifically, we computed the diagonal metric component for the third frequency derivative and verified that the $2\mathcal{F}$ lost by neglecting that derivative in the worst corner of parameter space searched was much less than the 20% template bank mismatch. In the worst case, the Vela Jr. wide search, it was just under 1%.

For each search we also checked the “pixel size” obtained from the metric on the sky position parameters to verify that more than one sky position was not needed. The position error ellipses for a 20% mismatch were roughly 0.5–2 arcminutes across the minor axis for $T_{\text{span}}$ of two weeks, and that width scaled as the inverse of $T_{\text{span}}$. Most of the target positions are known to sub-arcsecond accuracy. The location of the object in SNR G93.3+6.9 is known to a few arcseconds. SNR G1.9+0.3 has no known object inside, but the remnant itself is barely an arcminute across; and given the age and distance any neutron star would have moved only a few arcseconds from the center of the remnant even at transverse kick velocities of order 1000 km/s. Since the integration time for that SNR was short, the error ellipse was several arcminutes across.

We also confirmed that the standard 1800-second SFTs do not cause problems. The $\mathcal{F}$-statistic code requires that signals not change more than a frequency bin over the duration of an SFT. The maximum $\dot{f}$ feasible is then $1/(1800 s)^2 \approx 3 \times 10^{-7}$ Hz/s. The strongest $\dot{f}$ from orbital motion in these searches is $2 \text{kHz} \times 10^{-4} \times 2\pi/1 \text{yr} \approx 4 \times 10^{-8}$ Hz/s, where the $10^{-4}$ is the Earth’s orbital velocity in units of $c$. The strongest intrinsic spin-
down is 2 kHz/690 yr ≈ 9 × 10^{-8} Hz/s. (Both of these figures come from the Vela Jr. wide search.)

2.5. Implementation

All searches ran on the Atlas computing cluster at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) in Hanover, Germany using the Condor queuing system. Most searches used 140 000–150 000 computational core-hours, except the Vela Jr. wide search which used about 110 000. The load-balancing algorithm became less accurate for that search because the effective dimensionality of the parameter space was closer to 3 than to 2, as the range of \( f \) searched was more than usual. The number of matched filtering templates used in each search was about 3–12 \( \times 10^{12} \), comparable to the 7 \( \times 10^{12} \) used in Abadie et al. (2011). The latter cost about 420 000 core-hours; the factor of 3 speed-up was due mainly to the SSE2 floating-point extensions used in the new code.

Each search was split into nominal 5-hour Condor jobs, typically 28 000–30 000 jobs per search, except the Vela Jr. wide search which was about 22 000. In order to keep the search jobs at roughly the same computational cost, the frequency band covered by each job varied with frequency. The Vela Jr. wide search had jobs covering bands from 35 mHz to nearly 2 Hz at low frequencies, while the other searches had search job bands on the order of a few mHz to tens of mHz. Each search job recorded all candidates with \( F > 2 \) above about 33.4, or 1 per million in stationary Gaussian white noise. In bands with “clean” noise, typical jobs with a few times \( 10^8 \) templates thus recorded a few hundred candidates. This choice of recording (which was different from the S5 search which recorded the loudest 0.01% of events) was needed because of the “dirtier” nature of the S6 noise and housekeeping issues associated with excessive disk space and input/output. The searches recorded a total of about 800 GB of candidates.

2.6. Vetoes

A high value of \( 2F \) is not enough to claim a detection, since instrumental lines lead to non-Gaussian and/or non-stationary noise in many narrow frequency bands. Hence we vetoed many candidates before further investigating a few survivors.

First, we used an “Fscan veto” similar to the one used in Abadie et al. (2011). An Fscan is a normalized spectrogram formed from the SFTs. First it normalizes SFTs by scaling the power to the running median over 50 frequency bins, correcting for the bias between the finite-point running median and the mean. (While more complicated than simply normalizing to the mean, this procedure is more robust to fluctuations in the time or frequency domain.) Then the Fscan time-averages the normalized power in each SFT frequency bin. In stationary Gaussian white noise the Fscan power for \( N_{\text{SFT}} \) SFTs is

\[
\chi^2 \sim N_{\text{SFT}}
\]

Therefore deviations from a \( \chi^2 \) indicate nonstationarity, spectral lines, or both.

In Abadie et al. (2011), the Fscan veto was triggered at a threshold of 1.5 times the expected power, which was about 11 standard deviations for H1 and 10.5 for L1. When triggered, it vetoed all signals overlapping a region 16 frequency bins on either side of the central frequency (the number of terms kept in the Dirichlet kernel) since those could be contaminated as well. Since the SSE2 code used here kept only 8 terms, we changed the window to 8 frequency bins.

In the present searches we also changed the threshold of the Fscan veto because we found that the S5 threshold was too lenient: S6 data had many more instrumental noise artifacts. Since the highest number of SFT frequency bins (in the Vela Jr. wide search) was about 4 \( \times 10^8 \), an Fscan power threshold of six standard deviations above the mean and five below would be unlikely to veto any Gaussian noise. We increased the S6 threshold further to \( \pm 7 \) standard deviations to allow for a roughly 3% bias (at most one standard deviation for these searches) observed in the Fscan power due to the effect of estimating the PSD with a running median over a finite number of bins (Prix 2009).

The second veto was based on the \( F \)-statistic consistency veto introduced in Aasi et al. (2013a), which uses the fact that an astrophysical signal should have a higher joint value of \( 2F \) (combining data from the two interferometers) than in either interferometer alone. Recorded candidates that violate this inequality were vetoed. This is a simpler and more lenient version of the more recent line veto (Keitel et al. 2014). In clean noise bands we found that it vetoed less than 1% of the candidates.

We extended the consistency veto to limited frequency bands as follows: For each search job’s frequency band (minus any Fscan vetoed bands), if the number of candidates vetoed for consistency was greater than the number of templates not vetoed, the entire search job was vetoed as being contaminated by a broad feature in one interferometer. Since we kept candidates at the 1 per million level for Gaussian noise, search jobs in clean noise bands recorded hundreds of templates, and hence this veto was only triggered if the number of consistency-vetoed candidates was about two orders of magnitude greater than usual.

The combination of these vetoes, although each was fairly lenient, greatly reduced the number of candidates surviving for human inspection. The vetoes also proved to be safe, in the sense that they were not triggered by the hardware-injected signals, with the exception of a few injections that were so loud that they distorted the data PSD and made it nonstationary (i.e. triggered the Fscan veto). It was easy to check that no astrophysical signals were vetoed this way by verifying that the small number of bands vetoed in both interferometers were due to the loud hardware-injected signals described in the Appendix or to known instrumental artifacts. The total frequency band vetoed was just over 1% of the frequency band searched, for all searches. We also checked with a full pipeline run of several hundred software injections and confirmed that, for \( 2F \) less than about 230, about 1% went undetected due to vetoes.

2.7. Detection criteria and results

For each search, we computed the \( 2F \) value corresponding to a 5% false alarm probability assuming Gaussian noise, and gave a further look to search jobs with nonvetoed candidates passing this threshold. Because
of potential correlations between templates, we checked for an effective number of independent templates $N_{\text{eff}}$. The distribution of loudest nonvetoed event per search job for each target was nearly Gaussian. Therefore we determined $N_{\text{eff}}$ by minimizing the Kolmogorov-Smirnov distance between the observed and expected cumulative distributions. For all searches this produced $N_{\text{eff}}$ roughly 90% of the true number of templates and resulted in a further-look threshold of $2F \approx 71–73$.

The search jobs that produced outliers surviving the automatic vetoes and thus warranting manual investigation are listed in Table 3. For all investigations it sufficed to make two plots of the results of the search job, demonstrated in Fig. 1 for the last outlier in Table 3 (top panels) and the first (and barely detected in 10 days’ integration) hardware injection, “Pulsar 0” (bottom panels, see the Appendix for more on the hardware injections).

Examples of the first plot, of $2F$ vs. frequency, are shown in the left-hand panels of Fig. 1. Injected signals showed up as near-\(\delta\)-functions in this plot, as in the bottom left panel of Fig. 1, while noise outliers had broader structures as in the top left panel. In most cases the outliers are clearly leaking past the edges of a vetoed band. Most of the outliers were near those hardware-injected signals that were loud enough to trigger the Fscan veto.

The second plot used in each investigation was a histogram of the probability density function of the recorded candidates, exemplified in the right-hand panels of Fig. 1. All jobs with outliers surviving the veto process clearly showed the tail of a \(\chi^2\) distribution with the wrong normalization, as in the top right panel, indicating that the estimator of the noise PSD was off because of a narrow spectral feature or nonstationarity. Injected signals in clean data showed a correctly normalized \(\chi^2\) tail with a relatively small number of outliers extending to high $2F$ values, which was visibly distinguishable from the candidates caused by noisy data, as can be seen in the bottom right panel.

We also tracked down the instrumental sources of the outliers in Table 3. (This was done after the outliers had already been dismissed by the inspections above, and was directed toward improving future searches rather than adding confidence to the results of this one.) In all cases the search jobs producing outliers were adjacent in frequency to Fscan vetoed bands or consistency-vetoed search jobs, and the outliers were apparently produced

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**Figure 1.** Inspection of the last outlier (top) and hardware-injected Pulsar 0 (bottom). Top left: $2F$ vs. frequency for the search job. The higher line is the 95% confidence Gaussian threshold for the whole search; the lower line is the same for that search job. Top right: Histogram (tail) of $2F$ for the search job. The line is for Gaussian noise, a \(\chi^2\) with four degrees of freedom. Bottom left: $2F$ vs. frequency for the hardware injection search job; the line is the 95% confidence Gaussian threshold for that job. Bottom right: Histogram (tail) of $2F$; the line is a \(\chi^2\) with four degrees of freedom.
by strong lines (including some very strong hardware injections) leaking past the vetoes (which were fairly lenient). Six of the outliers were associated with strong hardware injections, which appeared as broad spectral features rather than δ-functions due to residual Doppler modulation (since their sky positions did not match the positions being searched). Of the other outliers, the first two were associated with digital clock noise lines in both interferometers which drifted around bands of a few Hz. In the former outlier, the lines happened to coincide at the time of the observation; the latter outlier was just contributed by L1. In addition, there was an outlier associated with a 441 Hz calibration signal in a geophone prefilter in H1. The last non-injection outlier was part of a very stable and wide-ranging structure with dozens of sidebands seen in H1, identified also as digital electronic noise.

3. UPPER LIMITS

3.1. Methods

The method for setting upper limits was essentially the same as in Abadie et al. (2010). We divided each search into 1 Hz bands. For each of these upper limit bands, we recorded the loudest 2F which passed the automated vetoes. We then estimated the intrinsic strain h0 at which 95% of signals would be found, if drawn from a population with random parameters other than h0, with a louder value than the loudest 2F actually recorded for that upper limit band.

This 95% confidence limit was first estimated for each upper limit band with a combination of analytical and computationally cheap Monte Carlo methods. Then, in the more computationally intensive step (in some cases 20–30% of the cost of the original search), we software-injected 6 000 signals into the band at that h0 to test that the confidence level was truly 95%. The frequencies of these software injections were randomly chosen within the band, and the polarization and inclination angles were chosen randomly. The upper limit injection runs have some safety margin built in, and in fact the confidence level was typically 96–97%. For a few upper limit bands—less than 1% of the total for each search—this test showed that the confidence level was actually lower than 95%. These typically corresponded to bands known...
to contain significant numbers of instrumental lines, and rather than iterate the computationally expensive procedure we chose not to present upper limits for these bands.

3.2. Results

The resulting upper limits on \( h_0 \), in 1 Hz bands, are plotted in Figs. 2 and 3. They closely follow the shape of the joint noise PSD, although with an overall scale factor and slight shape distortions. The best (lowest) upper limits on \( h_0 \) generally occur for each search around 170 Hz, where the noise PSD is lowest. Several searches achieved upper limits on \( h_0 \) of about \( 4 \times 10^{-25} \) in that band, as can be seen in Table 2 (which also includes the indirect limits from energy conservation). Table 3 lists data for our observational upper limits on \( h_0 \) for all searches, i.e. the black points in Fig. 2 and the top panel of Fig. 3 in machine-readable form.

In all these plots, the main set of points does not include bands where more than 5% of the 1 Hz upper limit band is vetoed or where the injection-checked false dismissal rate was more than 5%. Most of these frequencies correspond to known instrumental disturbances, such as calibration lines or clock noise. We also removed 2 Hz bands centered on the electrical mains frequency of 60 Hz and its harmonics up to 300 Hz, as well as the band 339–352 Hz which is full of the extremely strong “violin modes” of the test mass suspension system. While a few upper limit bands containing these lines did pass the false dismissal and vetoed-band tests, the upper limits were much higher (weaker) on account of the increased noise; and upper limits on bands where the noise PSD varies greatly within the band are not so informative. Hence all these bad bands are removed from the main set of points, but are plotted near the top of each plot (in red on-line, at a constant \( h_0 \) in each plot) so as to give an idea of their numbers (5–10% of the total for each search) and locations (clustered around suspension violin modes, etc).

The strain upper limits can be converted to upper limits on the fiducial ellipticity \( \epsilon = |I_{xx} - I_{yy}|/I_{zz} \) of each neutron star using (e.g. Wette et al. 2008)

\[
\epsilon = 3.9 \times 10^{-4} \left( \frac{h_0}{1.2 \times 10^{-24}} \right) \left( \frac{a}{300 \text{ yr}} \right)^{1/2} \left( \frac{100 \text{ Hz}}{f} \right)^2,
\]

assuming a fiducial value of \( I_{zz} = 10^{45} \text{ g cm}^2 \). We used this equation to convert both the energy-conservation limit and the direct 95% confidence limits obtained here. The results are plotted in the middle panel of Fig. 3 for the Vela Jr. wide search. This and the similar plots for the other searches are all tilted, curved versions of the plot for \( h_0 \), and therefore we display only this one as an example. For all of the searches we summarize the ranges of ellipticity upper limits in Table 4.

Table 4.

<table>
<thead>
<tr>
<th>Search</th>
<th>Indirect ( h_0 )</th>
<th>Direct ( h_0 )</th>
<th>Direct ( \epsilon )</th>
<th>Direct ( \alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lowest (best)</td>
<td>at ( f_{\text{min}} )</td>
<td>at ( f_{\text{max}} )</td>
<td>at ( f_{\text{min}} )</td>
</tr>
<tr>
<td>G1.9+0.3</td>
<td>( 8.4 \times 10^{-22} )</td>
<td>( 6.4 \times 10^{-22} )</td>
<td>( 2.9 \times 10^{-4} )</td>
<td>( 7.6 \times 10^{-5} )</td>
</tr>
<tr>
<td>G18.9–1.1</td>
<td>( 5.4 \times 10^{-25} )</td>
<td>( 4.2 \times 10^{-25} )</td>
<td>( 5.9 \times 10^{-5} )</td>
<td>( 1.2 \times 10^{-5} )</td>
</tr>
<tr>
<td>G93.3+6.9</td>
<td>( 6.0 \times 10^{-25} )</td>
<td>( 3.7 \times 10^{-25} )</td>
<td>( 8.1 \times 10^{-5} )</td>
<td>( 6.8 \times 10^{-6} )</td>
</tr>
<tr>
<td>G111.7–2.1</td>
<td>( 1.3 \times 10^{-24} )</td>
<td>( 5.8 \times 10^{-25} )</td>
<td>( 4.6 \times 10^{-4} )</td>
<td>( 1.2 \times 10^{-5} )</td>
</tr>
<tr>
<td>G189.1+3.0</td>
<td>( 8.7 \times 10^{-25} )</td>
<td>( 4.6 \times 10^{-25} )</td>
<td>( 1.2 \times 10^{-4} )</td>
<td>( 5.7 \times 10^{-6} )</td>
</tr>
<tr>
<td>G266.2–1.2 wide</td>
<td>( 1.4 \times 10^{-23} )</td>
<td>( 6.8 \times 10^{-25} )</td>
<td>( 1.1 \times 10^{-3} )</td>
<td>( 2.3 \times 10^{-7} )</td>
</tr>
<tr>
<td>G266.2–1.2 deep</td>
<td>( 1.5 \times 10^{-24} )</td>
<td>( 4.4 \times 10^{-25} )</td>
<td>( 1.4 \times 10^{-4} )</td>
<td>( 1.4 \times 10^{-6} )</td>
</tr>
<tr>
<td>G291.0–0.1</td>
<td>( 5.9 \times 10^{-25} )</td>
<td>( 4.2 \times 10^{-25} )</td>
<td>( 1.3 \times 10^{-4} )</td>
<td>( 2.0 \times 10^{-5} )</td>
</tr>
<tr>
<td>G347.3–0.5</td>
<td>( 2.0 \times 10^{-24} )</td>
<td>( 5.6 \times 10^{-25} )</td>
<td>( 2.0 \times 10^{-4} )</td>
<td>( 2.0 \times 10^{-6} )</td>
</tr>
<tr>
<td>G530.1–0.3</td>
<td>( 6.5 \times 10^{-25} )</td>
<td>( 5.1 \times 10^{-25} )</td>
<td>( 1.6 \times 10^{-4} )</td>
<td>( 3.1 \times 10^{-5} )</td>
</tr>
</tbody>
</table>

Note that this fiducial ellipticity is really a dimensionless version of the (spherical harmonic \( m = 2 \) part of the mass quadrupole moment, not the true shape of the star. Conversion factors to these other quantities can be found in Owen (2010) and Johnson-McDaniel (2013), respectively. The quantity truly inferred from the measurement of \( h_0 \) (and the measured frequency and assumed distance) is a component of the mass quadrupole. The conversion factor to ellipticity can have uncertainties of a factor 5 or more (Johnson-McDaniel 2013) depending on the neutron star mass, which has an observed range of about a factor 2, and the equation of state, which is significantly uncertain.

Strain upper limits can also be converted to limits on the r-mode amplitude \( \alpha \) (Lindblom et al. 1998) via

\[
\alpha = 0.28 \left( \frac{h_0}{10^{-24}} \right) \left( \frac{100 \text{ Hz}}{f} \right) \left( \frac{D}{1 \text{ kpc}} \right),
\]

for a typical neutron star, with about a factor 2–3 uncertainty depending on the mass and equation of state—see Eq. (24) of Owen (2010) and the discussion preceding it for details. We used this equation to convert both the energy-conservation limit and the direct 95% confidence obtained here. The results are plotted in the bottom panel of Fig. 3 for the Vela Jr. wide search. Like the plots of upper limits on fiducial ellipticity, the \( \alpha \) upper limit plots are tilted, curved versions of the \( h_0 \) upper limit plots. Thus we do not display them for the other searches, although we do summarize all of the ranges in Table 4. Similarly to the case of fiducial ellipticity, the...
upper limits on fiducial ellipticity and wide search. The middle and bottom plots are the corresponding Figure 3. The top plot is the analog of Fig. 2 for the Vela Jr. quantity most directly inferred from $h_0$ here is the ($m = 2$ part of the) current quadrupole. While $\alpha$ is a convenient dimensionless measure, the conversion factor—like that for $\epsilon$—is uncertain by a factor of a few.

4. DISCUSSION

<table>
<thead>
<tr>
<th>Search</th>
<th>Frequency (Hz)</th>
<th>$h_0$ upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1.9+0.3</td>
<td>141.5</td>
<td>$7.38 \times 10^{-25}$</td>
</tr>
<tr>
<td>G1.9+0.3</td>
<td>142.5</td>
<td>$7.08 \times 10^{-25}$</td>
</tr>
<tr>
<td>G1.9+0.3</td>
<td>143.5</td>
<td>$7.09 \times 10^{-25}$</td>
</tr>
<tr>
<td>G1.9+0.3</td>
<td>144.5</td>
<td>$7.44 \times 10^{-25}$</td>
</tr>
</tbody>
</table>

This table lists data for our observational upper limits on $h_0$ for all searches, i.e. the black points in Fig. 2 and the top panel of Fig. 3. Frequencies are central frequencies for the upper limit bands. Only a portion of this table is shown here to demonstrate its form and content. A machine-readable version of the full table is available.

Our searches improved sensitivity and parameter space coverage over previous searches, and reached theoretically interesting sensitivities as well.

The best direct (observational) upper limits on $h_0$ and the indirect (theoretical) upper limits on $h_0$ from energy conservation are shown in Table 4. The S5 search for Cas A (Abadie et al. 2010) obtained a best upper limit on $h_0$ of $7 \times 10^{-25}$. Our best S6 limit on Cas A was $6 \times 10^{-25}$, less of an improvement than the improvement in noise would indicate because we reduced the integration time. This in turn was because we searched a broader parameter space, including more than doubling the frequency band. Several of the S6 searches described here obtained upper limits on $h_0$ as strong (low) as $4 \times 10^{-25}$, nearly a factor of two better than Abadie et al. (2010), in spite of aiming in general for broad parameter space coverage. Several searches beat their corresponding indirect limits on $h_0$ by a factor of two, and the Vela Jr. wide search beat its indirect limit by about a factor of 20.

It is also interesting to compare our upper limits on neutron star fiducial ellipticities and $r$-mode amplitudes to the maximum values predicted theoretically.

The most up-to-date numbers for elastically supported quadrupoles are in Johnson-McDaniel & Owen (2013): They correspond to maximum fiducial ellipticities of order $10^{-5}$ for normal neutron stars, $10^{-3}$ for quark-baryon hybrid stars, and $10^{-1}$ for quark stars. Many of our upper limits, summarized in Table 4 get well into the range for normal stars. For instance the Vela Jr. wide search beat a fiducial ellipticity of $10^{-5}$ over almost all of its frequency band.

Corresponding values for magnetically supported quadrupoles are more complicated, as they depend on details of the field configuration such as the relative strengths of the poloidal and toroidal components as well as the hydrostatic structure of the star. Although the literature on the problem grows rapidly, the highest ellipticities predicted remain, as in Abadie et al. (2010), on the order of $10^{-4} (B/10^{15} \text{ G})^2$—see Ciolfi & Rezzolla (2013) for a recent example and summary. Unlike the case of elastic deformations, where only maximum possible values are calculated, magnetic deformations must reach a certain value for a certain average field, configuration, etc.; and thus our upper limits on $h_0$ correspond to upper limits on an average internal magnetic field—for example, about $10^{14}$ G for the Vela Jr, wide search over much of its frequency band. From the lack of detected pulsations, it is likely that the surface magnetic fields of these
objects are orders of magnitude lower. Hence the remaining question is whether such a discrepancy between internal and external fields is possible in young neutron stars. Currently it most likely is under some conditions internal and external fields is possible in young neutron this work. They, and the detailed waveforms, are explained in detail in Jaranowski et al. (1998). The incl ination angle did not include second derivatives. The inclination angle \( \epsilon \) was constant, i.e. the injections did not include second derivatives. The inclination angle \( \epsilon \), polarization angle \( \psi \), and signal phase offset \( \phi_0 \) were not used in this work. They, and the detailed waveforms, are explained in detail in Jaranowski et al. (1998).

It is also interesting to compare to the largest \( r \)-mode amplitudes predicted by theory. This is also a complicated subject, depending on the history as well as the composition of the star. As at the time of Abadie et al. (2010), the most detailed calculation of nonlinear hy drodynamical saturation of the \( r \)-mode remains that of Bondarescu et al. (2009), and the answer is an amplitude of order \( 10^{-3} \) in the units used here. Thus, as seen in Fig 3, the Vela Jr. wide search reached interesting values over most of its frequency band. And as seen in Table 3 most of the searches reached interesting values at least at the high end of their frequency bands.

In the near future, the Advanced LIGO and Virgo interferometers will come on-line and take data with strain noise amplitude reduced from S6 values by a significant factor, which by the end of the decade will reach an order of magnitude. Re-running the analysis pipeline used here on such data would result in better sensitivity to \( h_0 \), \( \epsilon \), and \( \alpha \) by the same factor. Improved analysis methods are likely to improve the sensitivity even more, making it interesting (i.e. possible to detect a signal or at least to set upper limits that beat indirect limits) for many more supernova remnants and other targets.

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APPENDIX

S6 featured a suite of hardware-injected continuous-wave signals, similar to previous science runs. Their nominal parameters (i.e. not allowing for calibration errors), in the notation of Jaranowski et al. (1998), are listed in Table 6. They are used by most searches, including those described here, for basic sanity checks of the analysis pipeline. For each of the first ten, called Pulsars 0–9, we searched a 1 Hz wide band around the injected frequency for a \( T_{\text{span}} \) of 

<table>
<thead>
<tr>
<th>Pulsar No.</th>
<th>RA+dec (J2000)</th>
<th>Base frequency (Hz)</th>
<th>( -f ) (Hz/s)</th>
<th>( h_0 )</th>
<th>( \epsilon ) (rad)</th>
<th>( \psi ) (rad)</th>
<th>( \phi_0 ) (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>04:46:12.5–56:13:03</td>
<td>265.576308874</td>
<td>4.15 × 10^{-12}</td>
<td>2.47 × 10^{-24}</td>
<td>0.652</td>
<td>0.770</td>
<td>2.66</td>
</tr>
<tr>
<td>1</td>
<td>02:29:34.5–29:27:09</td>
<td>849.029489519</td>
<td>3.00 × 10^{-10}</td>
<td>1.06 × 10^{-24}</td>
<td>1.088</td>
<td>0.356</td>
<td>1.28</td>
</tr>
<tr>
<td>2</td>
<td>14:21:01.5+03:26:38</td>
<td>575.163548428</td>
<td>1.37 × 10^{-11}</td>
<td>4.02 × 10^{-24}</td>
<td>2.761</td>
<td>-0.222</td>
<td>4.03</td>
</tr>
<tr>
<td>3</td>
<td>11:53:59.4–33:26:12</td>
<td>108.857159397</td>
<td>1.46 × 10^{-17}</td>
<td>1.63 × 10^{-23}</td>
<td>1.652</td>
<td>0.444</td>
<td>5.53</td>
</tr>
<tr>
<td>4</td>
<td>18:35:57.0–12:28:00</td>
<td>1398.60769871</td>
<td>2.54 × 10^{-8}</td>
<td>4.56 × 10^{-23}</td>
<td>1.290</td>
<td>-0.648</td>
<td>4.83</td>
</tr>
<tr>
<td>5</td>
<td>20:10:30.4–83:50:21</td>
<td>52.8083243593</td>
<td>4.03 × 10^{-18}</td>
<td>8.45 × 10^{-24}</td>
<td>1.089</td>
<td>-0.364</td>
<td>2.23</td>
</tr>
<tr>
<td>6</td>
<td>23:55:00.2–62:52:21</td>
<td>147.5119602499</td>
<td>6.73 × 10^{-9}</td>
<td>6.92 × 10^{-25}</td>
<td>1.725</td>
<td>0.471</td>
<td>0.97</td>
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<tr>
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<td>14:34:21.0–29:27:02</td>
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<td>2.20 × 10^{-24}</td>
<td>0.712</td>
<td>0.512</td>
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<tr>
<td>8</td>
<td>23:25:33.5–33:25:07</td>
<td>192.756899543</td>
<td>8.65 × 10^{-10}</td>
<td>1.59 × 10^{-23}</td>
<td>1.497</td>
<td>0.170</td>
<td>5.89</td>
</tr>
<tr>
<td>9</td>
<td>13:13:52.5+75:14:23</td>
<td>763.847316497</td>
<td>1.45 × 10^{-17}</td>
<td>8.13 × 10^{-23}</td>
<td>2.239</td>
<td>-0.009</td>
<td>1.01</td>
</tr>
<tr>
<td>10</td>
<td>14:46:13.4+42:52:38</td>
<td>26.358743499</td>
<td>8.50 × 10^{-11}</td>
<td>2.37 × 10^{-24}</td>
<td>2.935</td>
<td>0.615</td>
<td>0.12</td>
</tr>
<tr>
<td>11</td>
<td>19:00:23.4–58:16:20</td>
<td>31.428459701</td>
<td>5.07 × 10^{-13}</td>
<td>1.80 × 10^{-23}</td>
<td>1.906</td>
<td>0.412</td>
<td>5.16</td>
</tr>
<tr>
<td>12</td>
<td>22:07:24.6–16:58:22</td>
<td>39.7247753175</td>
<td>6.25 × 10^{-9}</td>
<td>2.66 × 10^{-25}</td>
<td>1.327</td>
<td>-0.068</td>
<td>2.79</td>
</tr>
</tbody>
</table>
10 days, and for Pulsar 0 we also did a 20 day search (see below). We did not search for Pulsars 10–12 since they were out of the frequency band of the SFTs we used. For each pulsar we ran the analysis pipeline using $f/|\dot{f}|$ as the age so that the search would cover the injected spin-down parameter in roughly the middle of the range.

With these searches we were able to detect all ten hardware injections above the “further look” threshold (95% confidence in Gaussian noise). Since Pulsar 0 was just barely above threshold in the first search, we made a first follow-up by doubling the integration time to 20 days to verify that $2\mathcal{F}$ doubled, similar to what would have been done in the early stages of following up a plausible non-injected candidate. The loudest injections (Pulsar 3 and Pulsar 8) triggered the Fscan veto, which had to be switched off to complete this exercise. Although this might cause concerns about the safety of the veto, these injections are unreasonably loud, with $2\mathcal{F} \approx 2 \times 10^4$. Real signals that would have been detected in earlier LIGO data runs. Also, very few frequency bands triggered an Fscan veto in both detectors, and we checked that (other than the loud hardware injections) these bands corresponded to known instrumental artifacts. By contrast, Pulsar 4 had $2\mathcal{F} \approx 2 \times 10^4$ and was not Fscan-vetoed, apparently because of its large $|f| > 2.5 \times 10^{-8}$ Hz/s spreading the power over several SFT bins.

The recovered parameters of the hardware injections were typically off by the amount expected from template parameter discretization and the fact that the injections did not include a second spin-down parameter while the search templates did. In a real potential detection scenario, candidates would have been followed up in a more sophisticated way, such as a hierarchical search or the gridless method of Shaltev & Prix (2013).

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