

First loosely coherent search for continuous gravitational wave sources with substellar companions in the Orion spur

Vladimir Dergachev^{1,*} and Maria Alessandra Papa^{1,2,†}

¹*Max Planck Institute for Gravitational Physics (Albert Einstein Institute),
Callinstrasse 38, 30167 Hannover, Germany*

²*Leibniz Universität Hannover, D-30167 Hannover, Germany*



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We report on the first loosely coherent search for continuous gravitational waves from neutron stars in binary systems. We searched ≈ 0.01 sr in the Orion spur, a high stellar density region close to Earth. We covered gravitational wave frequencies from 100 to 700 Hz and frequency derivatives in the range $\pm 10^{-11}$ Hz/s. An atlas of results from the search is made publicly available. A follow-up was performed, on a subset of the released results, which found no outliers.

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I. INTRODUCTION

All-sky searches for continuous gravitational waves from isolated stars over extended observation periods are computationally demanding. As optimal search methods are prohibitively expensive, suboptimal methods are employed, requiring trade-offs between search depth, breadth, and robustness. The problem becomes harder when the emitting object, rather than being isolated, is in a binary system, because the orbital parameters now also need to be searched over. The result is that, with the same computational budget, an all-sky search for emission from a star in a binary system is less sensitive than an all-sky search from an isolated object over the same set of possible signal frequencies.

Previous wide parameter searches for binary systems [1–5] have employed various techniques [6–8]. Loosely coherent algorithms [9–11] analyze patches of parameter space, gaining efficiency as the patch size increases. One would therefore expect that loosely coherent methods would be particularly suitable to tackle binary searches because of the larger dimensionality of the waveform manifold compared to searches for isolated sources. In this paper, we present the results of the first loosely coherent search for continuous gravitational wave signals from neutron stars in binary systems with substellar companions.

The Falcon pipeline, which employs loosely coherent methods, has enabled very sensitive searches for continuous waves from isolated neutron stars with small ellipticities [12–14]. The search presented here is the first step in extending Falcon’s capabilities to include binary systems, scaling computational performance and internal structures to accommodate the higher-dimensional parameter spaces required.

We conducted a wide frequency-band search for signals from a portion of the sky within the Orion spur, restricting the modulation depth to substellar companions. This is a physically interesting region that Falcon can search with a comparatively small amount of computational resources—less than 1.2×10^6 CPU-thread hours, including follow-up analysis.

The follow-up analysis produced no outliers. No outliers were expected from hardware injected simulated signals because none were present in the searched sky area.

The results of the first analysis stage were compiled into an atlas [12], which we make available with this paper. A summary of the atlas is shown in Fig. 1.

II. SEARCH

Our loosely coherent search method computes an estimate of the power from a signal at a certain frequency, coming from a certain sky direction. We use the Falcon pipeline implementation [12], which allows us to construct this estimate efficiently, combining the data coherently over a so-called coherence length, that is a free parameter, and then summing the results from the various coherent segments. In the follow-ups we re-run the Falcon pipeline with a longer coherence length and/or larger data set while zooming in on interesting parameter space regions.

*Contact author: vladimir.dergachev@aei.mpg.de

†Contact author: maria.alessandra.papa@aei.mpg.de

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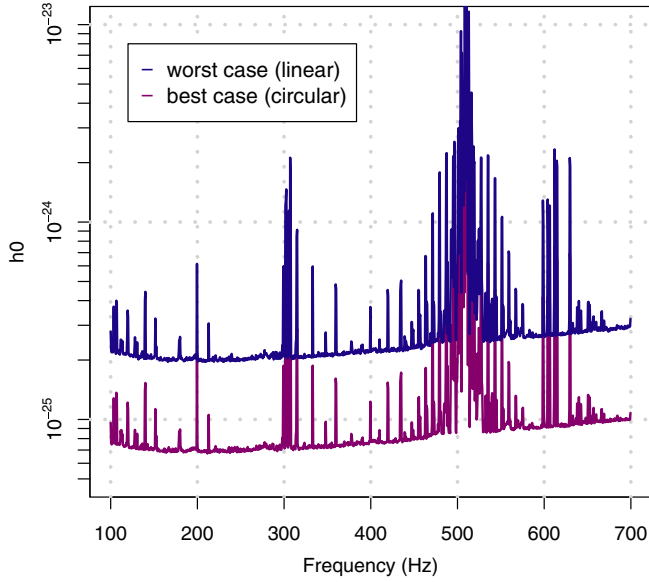


FIG. 1. Gravitational wave intrinsic amplitude h_0 upper limits at 95% confidence as a function of signal frequency. The upper curve shows worst-case upper limits, maximized over sky and polarization parameters. The lower curve shows upper limits maximized over sky for circular polarization only. The sensitivity of interferometers to circular and linear polarization varies in time. That variation is much stronger for linearly polarized signals, where sometimes the amplitude response goes to 0, unlike for circularly polarized signals where it never does. Different weights at different times are hence applied to interferometer data to compute the upper limits for different polarizations. The ratio between worst- and best-case upper limits is thus not constant and can vary significantly due to nonstationary noise and disturbances.

The Falcon pipeline was initially applied to searches for signals from isolated sources. Signals from neutron stars in binary systems are not conceptually different with respect to signals from isolated neutron stars, they are just more complicated due to the additional frequency modulation due to the motion of the source around its companion. Even though the overarching design of Falcon was cognizant of the plan to extend the searches to signals from binary systems, adding infrastructure was still needed and changes were necessary to ensure the scalability of our code and to maintain performance. These modifications are of a technical nature and outside of the scope of this paper. Here we concentrate on the results of the search that demonstrate the successful extension of Falcon to binary systems and the release of such results as the atlas.

The first analysis stage and the first follow-up stage use data from the O3a LIGO public dataset [15]. The final follow-up stage uses the full public data of the O3 run [15,16]. We begin with a coherence length of one hour, which is doubled in the follow-up stages.

The Orion spur is the high stellar density region closest to Earth and therefore constitutes an interesting target for

“spotlight” searches for continuous gravitational waves. In [17] we carried out a search for continuous gravitational wave emission from isolated neutron stars from this region and now we use this region to showcase the performance of the loosely coherent Falcon search to neutron stars in binary systems. Our target region covers 0.0113 sr disk centered at the direction A of [17], that is, toward Cygnus-X 1 and has right ascension and declination coordinates ($20^{\text{hr}}10^{\text{min}}54.715^{\text{s}}, 33^{\circ}33'29.297''$).

We restrict our consideration to binary systems with circular orbits, as the orbits tend to circularize over time. We search binary periods

$$10 \leq P_{\text{orb}} \leq 30 \text{ days} \quad (1)$$

and projected semimajor axes

$$a_p \leq 1 - s \left[\frac{f}{575.25 \text{ Hz}} \right], \quad (2)$$

with f being the signal frequency. Assuming the source of gravitational waves at 575.25 Hz is a neutron star of 1.4 solar masses, this covers the companions with masses from 0 to $\approx 2 \times 10^{-2}$ solar masses. Such binary systems are known to exist [18] and lie in a binary parameter space region that has not been covered by previous searches (see Fig. 2 adapted from Fig. 2 of [3]). We use the binary signal model described in [19].

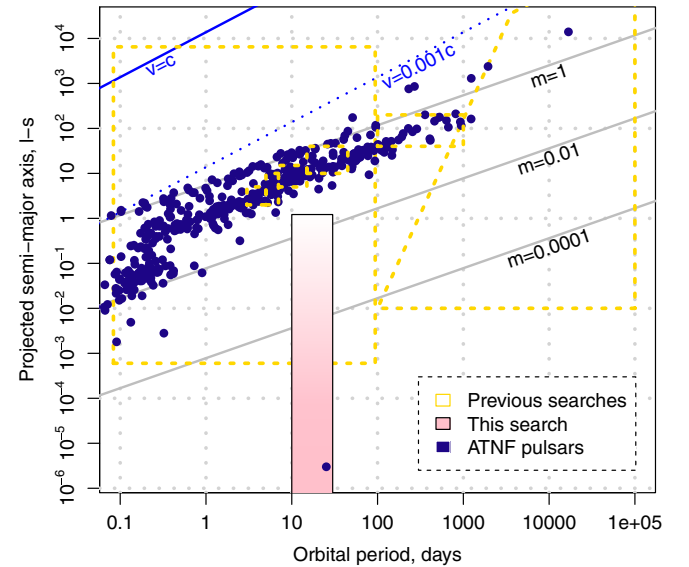


FIG. 2. Orbital parameters of known pulsars (circles), regions of orbital parameter space surveyed so far by continuous wave searches (dashed yellow lines) and by this search (shaded region). The sensitivities of previous searches vary considerably, for example, the search covering the large rectangle was performed on pre-Advanced-LIGO data. We also show contours of constant companion mass m and the contours of companion orbital velocity v , and pulsars from ATNF catalog [18].

TABLE I. Parameters for each stage of the search. Stage 3 refines outlier parameters by using denser sampling of the parameter space and subjects them to an additional consistency check by comparing outlier parameters from analyses of individual interferometer data. Only the first stage was used to construct the atlas, while subsequent stages were used for outlier analysis.

Stage	Coherence length (h)	Minimum SNR	Dataset
1	1	9	O3a
2	2	10	O3a
3	2	12	O3a + O3b

The reference phase of the orbit is taken at $t_0 = 1246070000$ GPS seconds, and we consider ten different values for this parameter in our search.

The frequency and frequency derivative search ranges are

$$100 \leq f \leq 700 \text{ Hz}, \quad (3)$$

$$-10^{-11} \leq \dot{f} \leq 10^{-11} \text{ [Hz/s]}. \quad (4)$$

The upper bound of the frequency range was chosen to be high enough to include the highly contaminated frequency space around 500 Hz as well as the cleaner spectrum above, while not being too high to avoid excessive computational resource requirements. The lower frequency range was set at 100 Hz to avoid the noisier low-frequency bands, which would be better analyzed with finer sky resolution.

Further follow-up analysis was restricted at stage 1 to candidates with signal-to-noise ratio (SNR) of at least 9, and this cutoff threshold increased at later stages as detailed in Table I. Stage 3 consisted of three different searches: based on the use of solely H1 data, solely L1 data, and on the coherent combination of both H1 and L1 data. Consistency in parameters of candidates from these different searches was required for candidates to survive the last stage. The multi-interferometer and single-interferometer candidate frequency and frequency derivative were considered consistent if they differed by no more than 0.5 mHz and 10^{-11} Hz/s, respectively. In stage 1, 25442 survived, 3641 survived stage 2, and none survived stage 3.

III. TESTING

As expected, the Falcon pipeline required modifications to adapt to the higher-dimensional parameter spaces of the binary search. To validate its performance, we carried out several simulations where test signals were added to the O3 data and recovered with the new pipeline. Figure 3 shows the results of an extensive validation study, where we computed polarization-specific upper limits [20] and compared them with the strain of the added test signals. Polarization-specific upper limits were obtained by the

same procedure [21] as used in the actual analysis and contributing to the atlas. As we can see, the upper limits exceed the test signal amplitudes. Worst-case and circularly polarized upper limits were verified as well.

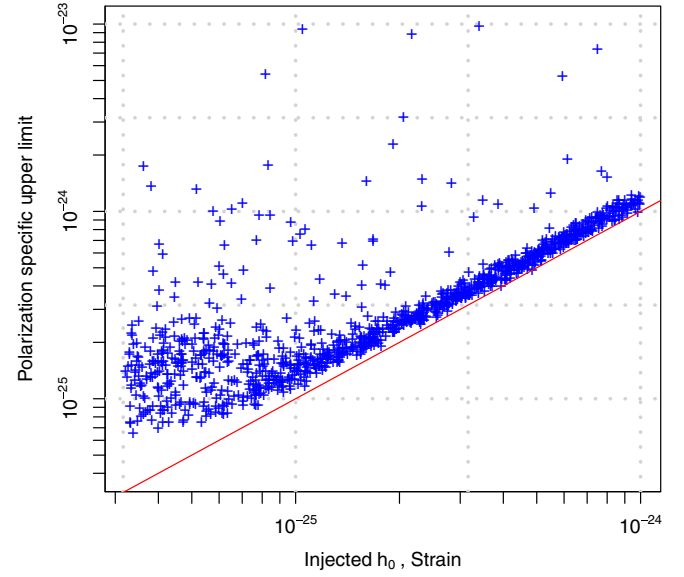


FIG. 3. Polarization-specific upper limits obtained for test signals. The red line at the bottom is a diagonal $y = x$.

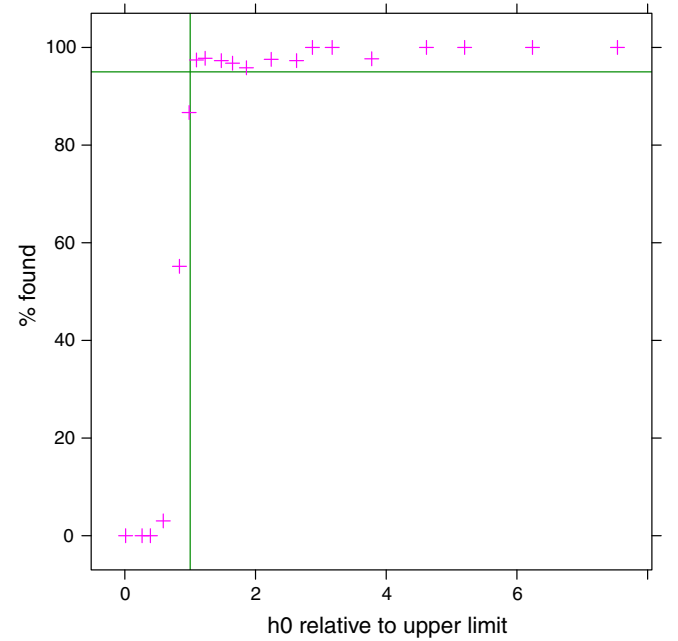


FIG. 4. Recovery of test signals. The X axis shows test signal strain normalized to the worst-case upper limit obtained in absence of test signals. The Y axis shows the percentage of injections recovered. The vertical green line indicates when the test signal strain is equal to the upper limit obtained without test signal. The horizontal green line shows the 95% recovery level.

The test signals were further used to verify follow-up performance. Figure 4 demonstrates that we recover 95% of test signals above the worst-case upper limit level computed for the data without the test signals.

IV. RESULTS

The results obtained from our analysis have been compiled into a gravitational wave atlas [22]. A summary of its data is shown in Fig. 1. In our most sensitive region, we reach worst-case strain upper limit of 2×10^{-25} . This is competitive with the searches in comparable frequency regions [4,23], albeit on different orbital parameters. The follow-up analysis produced no outliers.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [22].

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