A method for directed searches of continuous gravitational waves in advanced detector data

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Abstract

Continuous waves (CW) are still undetected gravitational-wave signals emitted by rotating neutron stars, either isolated or in binary systems. The estimated number of isolated neutron stars in our Galaxy is $10^8 - 10^9$. Information provided by electromagnetic observations is crucial to constrain the signal parameter space, lower the computational cost of a CW search, and increase the number of potential targets. Several *Directed* search pipelines have been developed to look for CW signals when the only parameter known is the source sky position [1]. In this work we present prospects for the directed search of CW signals, from isolated neutron stars, in the advanced LIGO-Virgo data using the **Band-Sampled-Data-directed search** method [2]. A list of potentially interesting sources, which are present in the publicly available astronomical catalogs, along with some 'young' supernova remnants (SNR), is investigated. **Theoretical indirect upper limits** are also computed when possible.

The CW signal

CWs can be emitted by fast spinning neutron stars (NS), non-axisymmetric with respect to the rotational axis. The emitted signal Eq. (1) is quasi-monochromatic with a frequency proportional to the star rotational frequency. The GW-strain amplitude is given by [1]:

$$h_0 = \frac{4\pi^2 G I_{zz} f^2}{c^4 \; r}\epsilon, \quad I_{zz}: \text{moment of inertia} \quad \epsilon: \text{ellipticity of the star} \tag{1}$$

The signal at the detector is modulated in frequency by two main effects: the Doppler Eq. (2) and the source spin-down Eq. (3). In addition there is an amplitude modulation due to the sidereal motion.

$$f(t) = \frac{1}{2\pi}\frac{d\Phi(t)}{dt} = f_0(t)\left(1 + \frac{\vec{v}\cdot\hat{n}}{c}\right), \quad \vec{v} = \vec{v}_{orb} + \vec{v}_{rot} \tag{2}$$

$$f_0(t) = f_0 + \dot{f}_0(t - t_0) + \frac{\ddot{f}_0}{2}(t - t_0)^2 + \ldots \tag{3}$$

These effects should be properly corrected when we look for a CW signal.

Potential sources of CWs

Sources which are likely hosting a NS are interesting candidates for our searches. Several potential sources are present in the astronomical catalogs like the pre-release of the 8-years Fermi-LAT point sources catalog [3] and the IBIS-INTEGRAL soft gamma-ray source catalog [4]. The Fermi catalog potential CW sources are listed below:

Identified:

Source	#	Frequency	position	CW search
Pulsar (PSR)	184	well known	well known	targeted
Pulsar Wind Nebula (PWN)	8	not known	known	directed
Supernova remnant (SNR)	22	not known	known	directed

Associated:

Source	#	Frequency	position	CW search
Pulsar (psr)	34	not well known	known	Narrow-band
Pulsar Wind Nebula (pwn)	11	not known	not well known	All-sky semi-directed
Supernova remnant (snr)	17	not known	not well known	All-sky semi-directed
Potential pwn or snr (spp)	96	not known	not well known	All-sky semi-directed

Unassociated: 2132 in Fermi-LAT ($\sim 39\%$)

INTEGRAL catalog presents the following interesting sources: 10 SNR, 19 Pulsar-like sources and 216 unidentified ones (23%) which sky distribution is shown in Fig. 1 below:

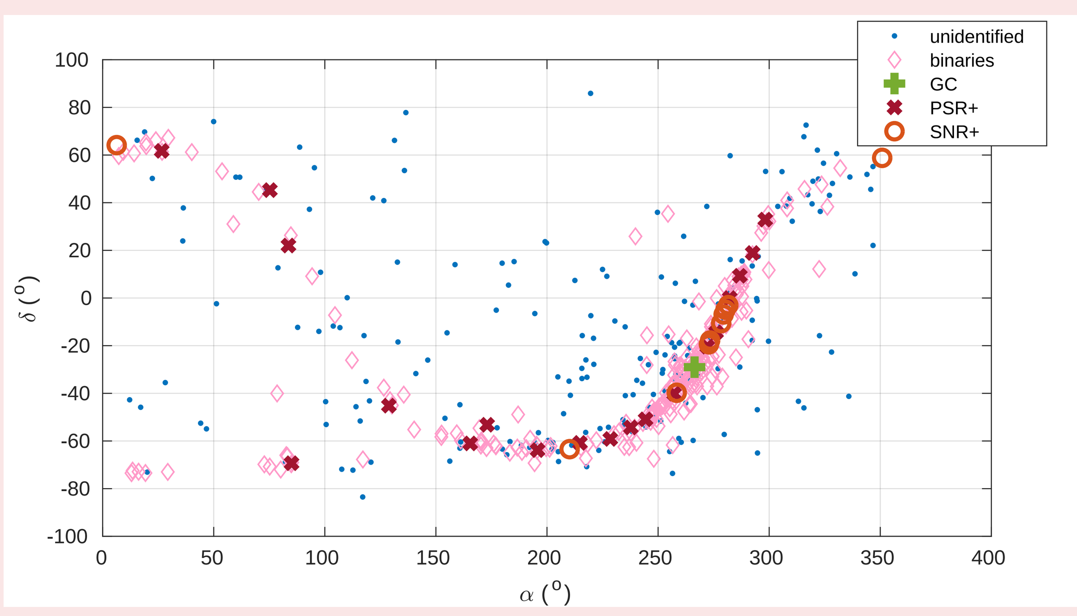
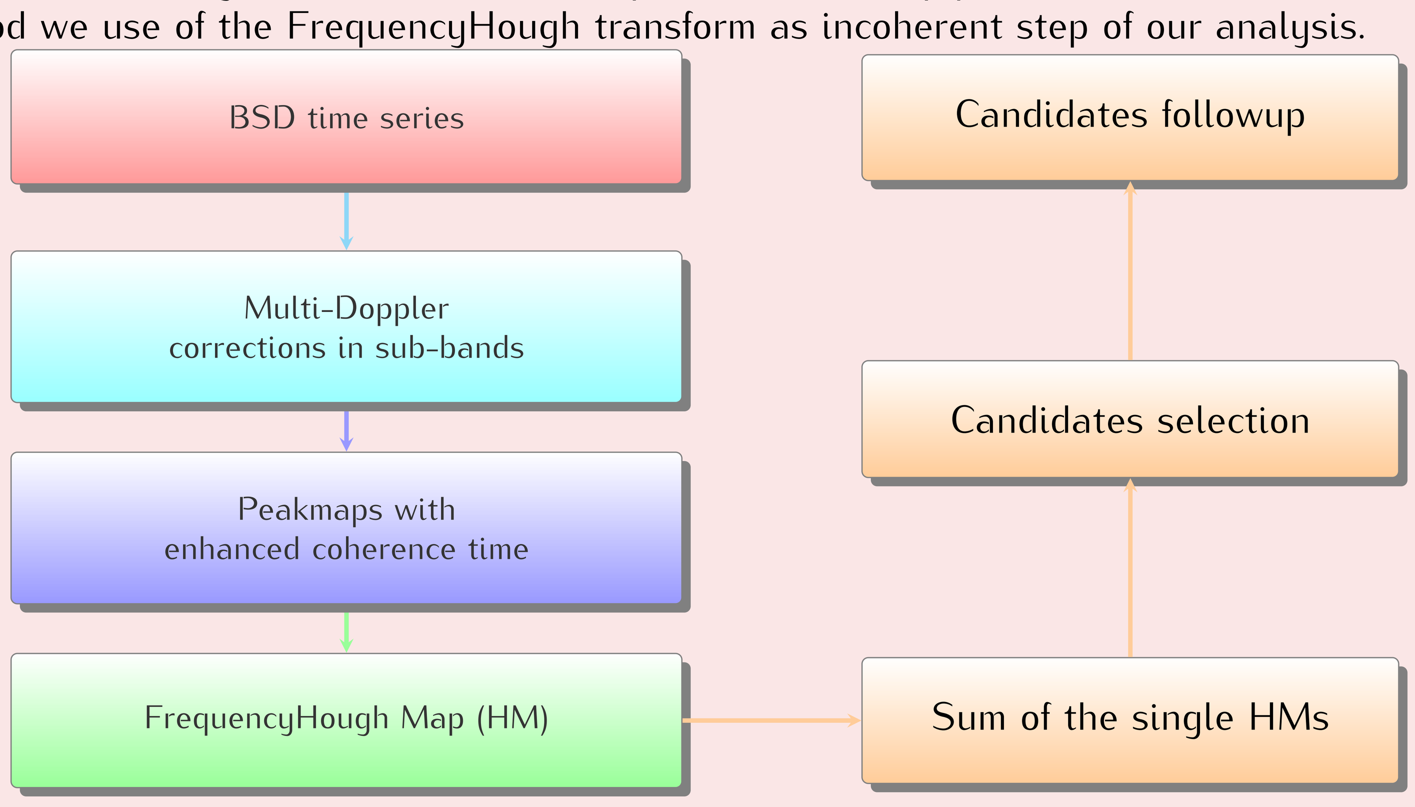


Fig. 1: Sky distribution of CW potential sources taken from the IBIS-INTEGRAL catalog

Band-Sampled-Data directed search pipeline

We have developed a new directed search pipeline based on the Band-Sampled-Data (BSD) framework [2] and the FrequencyHough transform [5], for the search of CWs from isolated NSs. The following scheme shows the steps of the search pipeline. In this semi-coherent method we use of the FrequencyHough transform as incoherent step of our analysis.



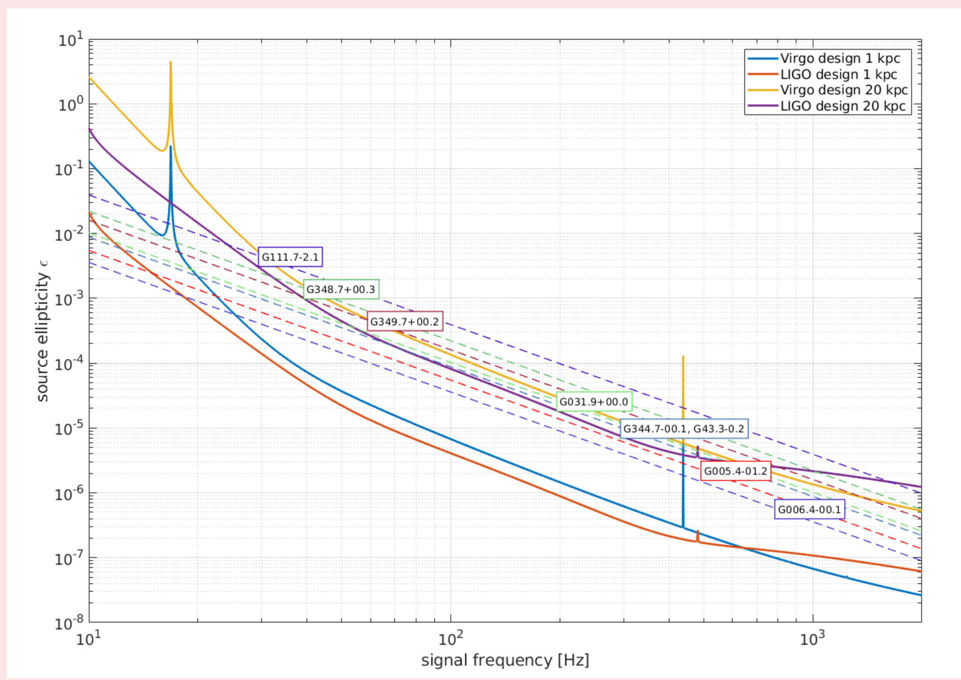
- BSD: dataset containg the time series opportunely down-sampled
- Multi-Doppler Corrections: correction for the Doppler (Eq. (1)). It's done using the sky position of the directed search and it's applied for each 1 Hz.
- Peakmap: collection of time-frequency peaks, selected on the equalized power spectrum
- FrequencyHough: maps the time frequency peaks of the peakmap into the source intrinsic rotational parameters $(t, f) \rightarrow (f_0, \dot{f}_0)$

Theoretical indirect upper limits on the ellipticity

Given the noise level of the data $S_n(f)$, it is possible to compute the theoretical search sensitivity (at 95% C.L.) as the minimum detectable GW-strain amplitude as in [5]:

$$h_{0_{min}}^{95\%} \approx \frac{\sqrt{S_n(f)}}{\alpha^{95\%}} \tag{4}$$

where $\alpha^{95\%}$ is a parameter strictly connected to the coherence time we used in the first stage of the analysis and to the thresholds we use for peaks and candidate selection. Given $h_{0_{min}}^{95\%}$, we can compute the corresponding minimum value for the star ellipticity $\epsilon^{95\%}$ (inverting Eq. (1)), parameterizing this function by the distance (see Figure 2). Since in directed searches the frequency evolution of a source is unknown, it is possible to compute an indirect upper limit h_{age} and ϵ_{age} based on the age and the distance of the source. We report in Figure 2 the theoretical ellipticity indirect upper limits for 8 SNR present in the Fermi-LAT catalog, which are potentially detectable by the BSD-directed search pipeline.



Given the age of a CW source, it is possible to compute the theoretical indrect upper limit for the star ellipticity

$$\epsilon_{age} \leq \sqrt{\frac{5c^5}{128\pi^4 G I_{zz} \tau f^4}}$$

Fig. 2: (dashed-lines): SNR ellipticity indirect upper limits ϵ_{age}. (solid-lines): values of ϵ converted from the theoretical sensitivity estimates of the search (Eq. (4)), taking $S_n(f)$ equal to the advanced detectors design sensitivity [7]. We show the curve of $\epsilon^{95\%}$ for the case of LIGO and Virgo detectors with $d = 1$ kpc and 20 kpc

Conclusion

For this work we select some CW potentially emitting sources, taken from two astronomical catalogs: Fermi and INTEGRAL. We focused on few SNR which indirect upper limits are beaten by the search sensitivity, hence those represent a promising set of sources for the BSD-directed search pipeline. The total computational power needed for this search is ~ 300 CPU hours.

References [1] P. Lasky, Pubs. Astron. Soc. Australia 32 34 (2015), [2] Piccinni O. J. et al. CQG 36 015008 (2019), [3] https://fermi.gsfc.nasa.gov/ssc/data/access/lat/fl8y/, [4] A. J. Bird et al. Astro. J. Supp. S., 223 1 (2016), [5] Astone P. et al. PRD 90, 042002 (2014), [6] Wette, K. CQG, 25, 235011 (2008), [7] Abbott P.B. et al., Liv. Rev. in Rel., 21 3 (2018)