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An enhanced sensitivity procedure for continuous gravitational-wave detection

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Summary. — Isolated rotating neutron stars, asymmetric with respect to their rotational axes, are expected to emit nearly monochromatic gravitational wave signals. The signal arriving at the detector is frequency modulated by the Earth's motion and by the intrinsic source spin-down. Searches for such signals from stars with parameters only loosely known, or unknown, are computationally challenging because of the large volume of parameter space to be explored. One way to increase the final sensitivity of the search, limiting the high computational cost of it, is presented in this work. We have developed a new framework for future continuous-wave searches, consisting of a fast production of band-limited time series, already downsampled and cleaned. This new setup will be applied to the next all-sky searches for electromagnetically-silent neutron stars and will be used for future searches for signals from *Fermi* LAT "unassociated" sources, many of which are expected to be neutron stars with completely unknown rotational parameters and a slightly uncertain position.

1. – Introduction

After the detection of the first gravitational wave event (GW150914) the era of the gravitational wave astronomy has begun [1]. All the GW signals detected in the first Advanced LIGO observing run have been emitted by black holes in a binary system [2]. Among the yet unobserved GW signals, there are the continuous gravitational waves, emitted by astrophysical sources such as isolated rotating neutron stars or spinning neutron stars in binary systems. In our Galaxy an order of 10^8–10^9 neutron stars (NS) are expected to exist, while only ~ 2500 have been electromagnetically observed. A large number of electromagnetically silent neutron stars are expected to emit in the LIGO and Virgo detector sensitivity band, making the detection of CW signal plausible. A CW detection would improve our knowledge about neutron stars astrophysics. Indeed, besides giving a better overview on the NS population in our Galaxy, from the gravitational waveform of a detected GW signal it is possible to infer the ellipticity of the star, which gives an information on the degree of asymmetry of the source and indirect clue of its internal structure. This paper is organized as follows: in sect. **2**, the most important features of a continuous wave signal are reviewed, in sect. **3**. I will explain why a new dataset is needed in order to partially decrease the computational cost of the search. In sect. **4** the most important feature of the new framework are illustrated. In sect. **5** a particular demodulation technique is described. Finally, sect. **6** is left as conclusion.

2. – The signal

A CW signal emitted by a rapidly rotating neutron star, is a long-lived, quasi-monochromatic signal with a frequency proportional to the rotational frequency of the star. The gravitational wave strain at the detector site can be written as

$$h(t) = H_0 \left(H_+ A^+(t) + H_\times A^\times(t) \right) \mathrm{e}^{j\Phi(t)}, \tag{1}$$

where $\Phi(t) = \omega(t)t + \Phi_0$ is the time-dependent signal phase, sum of the intrinsic signal phase plus an initial phase. The complex amplitudes H_+ and $H_\times$ are functions of the parameters ψ and η, which define the polarisation state of the wave. The time-dependent functions $A^+(t)$, $A^\times(t)$ are the detector response to a passing GW and depend on the source position, the detector location and its orientation on the Earth. The emitted signal frequency f_0 at a given time t_0, is related to the star rotational frequency by $f_0 = \frac{\omega_0}{2\pi} = 2f_{rot}(t_0)$. The CW signal frequency measured by the detector, is modulated by the Doppler effect, due to the detector motion, and slowly decreases due to the intrinsic spin-down of the source. In particular, this spin-down effect, due to the rotational energy loss of the star and the consequent emission of electromagnetic or gravitational radiation, is easily described by a Taylor series expansion

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

where $[\dot{f}_0, \ddot{f}_0, \ldots]$ are the so called spin-down parameters. Furthermore, the signal frequency is Doppler modulated as

$$f(t) = f_0(t) \left(1 + \frac{\vec{v} \cdot \widehat{n}}{c} \right), \tag{3}$$

where $\vec{v} = \vec{v}_{orb} + \vec{v}_{rot}$ is the detector velocity in the Solar System Barycenter (SSB), sum of the Earth's orbital and rotational velocities, while $\widehat{n}$ is the versor pointing at the source sky position. Finally, the power of the signal in eq. (1) is spread among the five angular frequencies ω_0, $\omega_0 \pm \Omega_\oplus$ and $\omega_0 \pm 2\Omega_\oplus$, where $\Omega_\oplus$ is the Earth sidereal angular frequency, this typical pattern is also known as 5-vector [3] and is caused by the Earth sidereal motion.

3. – Motivation

The search for CW in the data of LIGO and Virgo detectors is a difficult computational challenge because the signal is buried in the noise. The CW signal amplitude is expected to be very weak, thus long integration time of the data is needed (order of months or years), in order to increase the signal-to-noise ratio and claim a detection.

On the other side, the longer the integration time, the larger the number of points in the parameter space that need to be explored, especially if the signal parameters are completely unknown. While a complete coherent search is possible when the source parameters are well known as in the case of targeted [4] and narrow-band searches [5], this is not possible when the sky position of the source or its rotational parameters (frequency and its derivatives) are completely unknown, as in the case of blind all-sky [6] or directed searches [7]. In order to face this computational problem, many hierarchical methods, based on the incoherent combination of the data previously analysed coherently, have been developed. For further details on the different search methods developed for the search of continuous gravitational waves in LIGO and Virgo data see [8].

A typical CW search, starts with the construction of a short Fast-Fourier-Transform database (SFDB) from the detector calibrated data [6]. The Fast-Fourier-Transform (FFT) time duration T_{FFT} (*i.e.* the data chunk used), called coherence time, is chosen using the condition of keeping a signal in a single frequency bin. This means that if a signal is present in the data, its frequency, which is modulated by the Doppler and spin-down effects, still remains within a frequency bin. For this reason the maximum FFT duration is constrained by the maximum frequency of the FFT as $\sim \frac{1.1\times10^5}{\sqrt{f_{max}}}$ as discussed in [6]. Although this setup can be a good choice for searches like blind all-sky, this is not always the optimal solution for all CW searches (targeted, narrow-band and direct) and searches for other CW-like signals such as those emitted by neutron stars in binary systems, NSs r-modes or NSs glitches, making the choice of a static FFT database, with FFT durations fixed at the beginning of the search a not so pliable starting point. A way to deal with this crucial starting point and have a more flexible way of picking the coherence time adaptable to all kind of CW searches will be discussed in the next section.

4. – The Band Sampled Data collection

In order to optimize the coherence time of a given CW search, the calibrated detector data organization has been rebuilt. The data is stored in the time domain rather than in the frequency one, in this way the coherence time is no longer fixed but can be chosen accordingly to the type of source we are looking for (binary, transients) or the search we want to perform (all-sky rather than targeted). Detector data is split in several band-limited time series, opportunely sampled, called "Band Sampled Data" (BSD) files [9]. A BSD files contains complex detector data in time domain, spanning one month of data, divided in frequency bands of 10 Hz ([20–30] Hz, [30–40] Hz, ...), and sampled at 10 Hz. The complex data time series is stored in such a way that it has no negative component in the Fourier domain (*i.e.*, no negative frequencies in the power spectrum), this is usually known as the analytic signal. After the creation, science mode(1) data are selected and a first clean procedure for the removal of the big time domain glitches is applied. In particular we delete those glitches whose value is larger than $\theta_{thr} = 10 \times m$, where m is an estimation of the median of the distribution of the non-zero data ($y_{t_{\tilde{0}}}$)

$$m = \sqrt{\text{median}(\text{Re}(y_{t_{\tilde{0}}}))^2 + \text{median}(\text{Im}(y_{t_{\tilde{0}}}))^2} \tag{4}$$

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(1) Good data is flagged as science mode data, excluding those periods where the detector is out of lock or is affected by some external disturbances.

Since the data is divided in 10 Hz bands a suggested FFT length can be recomputed for each band covered by a BSD file, allowing a first gain in the choice of the coherence time especially at lower frequencies. A BSD file contains several auxiliary information, among which there are the so called "peakmaps" which are the time-frequency map of the most significant peaks selected in the equalized spectrum. The peakmaps stored in the BSD are further cleaned by removing known noise lines and the more persistent ones (persistency filter).

5. – Heterodyne corrections

Since the data is stored in the time domain, the signal can be demodulated using a phase shift factor. In this way the angular frequency time-dependent phase of the GW signal in eq. (1) can be corrected for the Doppler and spin-down effects.

5·1. *The Doppler effect.* – The Doppler phase correction can be written as

$$\phi_{dc}(t) = \frac{2\pi}{c} \cdot p(t) \cdot f_0(t), \tag{5}$$

where $p(t)$ is the position of the detector in the SSB, projected along the sky direction of the source position. This information is present in the auxiliary data stored in the BSD file. $f_0(t)$ is the evolution of the source frequency in time as in eq. (2).

5·2. *Spin-down effect.* – Being $sd(t) = \dot{f}_0 \cdot (t - t_0) + \dots$ the sum of the spin-down factors, we can compute the following phase shift to correct the spin-down of the signal:

$$\phi_{sd}(t) = 2\pi \int_{t_0}^{t} sd(t')\mathrm{d}t'. \tag{6}$$

The final phase shift correction will be the sum of the two phases

$$\Phi_{corr} = \phi_{dc}(t) + \phi_{sd}(t). \tag{7}$$

To correct the data we need to multiply it by the exponential factor $\exp[-\mathrm{j}\Phi_{\mathrm{corr}}]$

$$y(t) = [h(t) + n(t)] \exp[-\mathrm{j}\Phi_{\mathrm{corr}}], \tag{8}$$

where $h(t)$ is the strain amplitude of a GW signal in the detector as in eq. (1) while $n(t)$ is the detector noise.

In this way an hypothetical signal becomes monochromatic, unless some residual modulations effects which have not been taken into account (*e.g.*, second-order spin-down or other effects). After the correction there is still an amplitude modulation as cited in sect. **2**, which depicts the signal in the spectrum with the typical 5-vector shape as shown in fig. 1.

6. – Conclusion

The detection of continuous gravitational wave signals in the LIGO and Virgo detector data will permit an increase of our knowledge about neutron star astrophysics. This is a difficult computational challenge since long integration times are needed, in order to

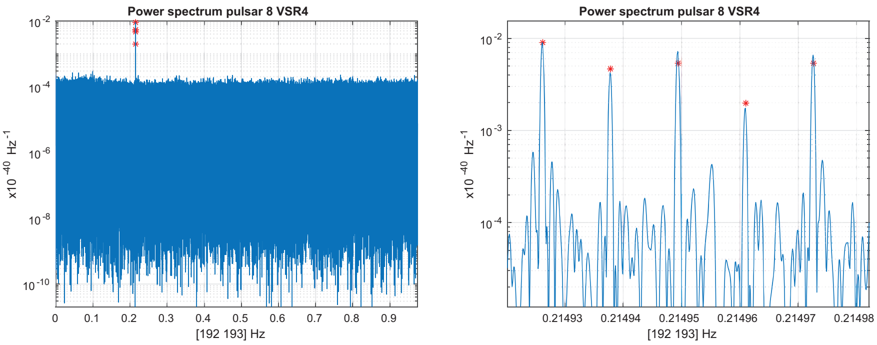
Power spectrum pulsar 8 VSR4

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Fig. 1. – Power spectrum of the hardware injected signal Pulsar 8 in VSR4 data (zoomed in the right plot), corrected using the hetherodyne phase shift factor Φ_{corr}. The typical 5-vector shape is recognizable in figure; * are the theoretical 5-vector frequency values.

increase the signal-to-noise ratio to the detectability level, given the weak amplitude of those signals. On the other side, the longer the integration time, the more the computational cost of the search increases. In order to find a good balance between sensitivity and computational cost, different ways of facing this problem have been developed. In this work we presented a way to allow the use of longer coherence time without worsen the computational cost of the search. The database described has been developed for a better data handling which is transversal for all type of CW searches. This new data set will replace the old concept of SFDB, and has been adapted to the FrequencyHough pipeline for the case of directed searches and for the followup of interesting candidates. Future developments include the generalization to the case of blind all-sky searches and it will be used for a directed search pointing to the Galactic Center and for the *Fermi* LAT "unassociated" sources (see [10]).

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