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LAPP-EXP 2003-18
October 2003

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at the 5th Edoardo Amaldi Conference on Gravitational Waves

Tirrenia (Pisa), Italy, July 6-11, 2003

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Abstract. Most of the known pulsars with frequencies lying in the best sensitivity range of the Virgo/LIGO/TAMA interferometers belong to binary systems. Accordingly their frequencies are Doppler shifted in an unknown way. We investigate a new method to search and extract the parameters of such pulsars. A first preliminary test of this method, performed on the Virgo data recorded during the E4 engineering run, is presented.

1 Introduction

Pulsars are potential sources of gravitational waves with amplitudes and frequencies lying in the sensitivity band of the interferometric detectors that will be soon operating with their full planned sensitivity: Virgo[1], LIGO[2], TAMA[3] and GEO[4]. Rotating stars which belong to a binary system are possible emitters which will, for the large majority of them, escape detection with the "classical methods"[5], because of the Doppler shift effect due to their movement around their companion.

We present here a new method aimed at the detection of these binary pulsars. In section 2 we recall the motivations for such a study, in section 3 we briefly describe the new method investigated in this work and in section 4 we present the first test of this "Sine-Hough" technique[6] on the data of the Virgo engineering run E4.

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2 Motivations

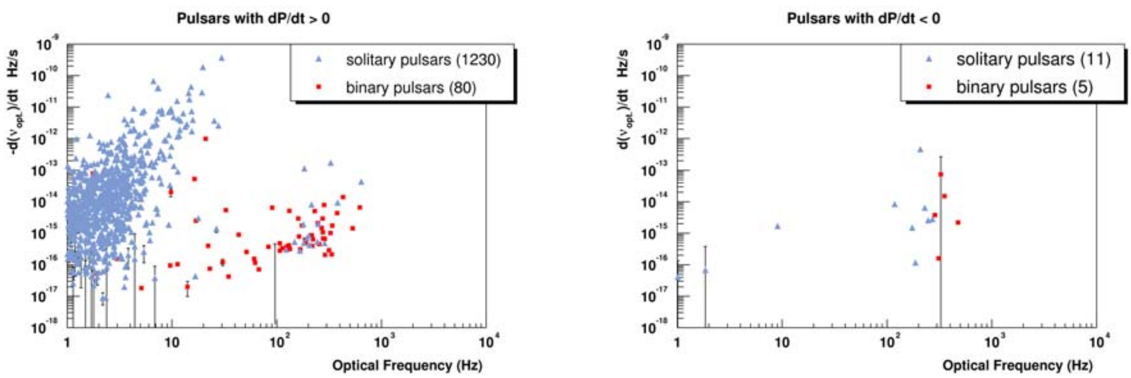
2.1 Interferometers sensitivity and pulsars frequencies

Using the data from the ATNF catalog[7], we show on figure 1 the rate of frequency change versus the frequency for the 1326 pulsars compiled in the database. We note that the bulk of these objects lies below 10Hz, far out of the good sensitivity region of the terrestrial interferometric detectors and that, in the frequency range above 10 Hz, we are dominated by pulsars belonging to binary systems.

2.2 Properties of the milliseconds pulsars

From figure 1, we also note that the fast spinning pulsars seem to belong to a different class of objects, their rate of change of frequency is notably lower than the rate of most of the low frequency ones. This observation is not new, it has been discussed by many authors and the general consensus about it is that there is an accretion phenomena which gives rotational energy to these spinning stars[8]. If this hypothesis turns out to be true, the corresponding gravitational wave energy can reach a very high value.

Obviously such possible high gravitational waves signals from pulsars located in binary systems makes them an important target in the general quest for gravitational waves. This task is complicated by the Doppler shift of their frequency which is, in almost all cases, dominated by the relative motion around the companion star (and not by the Earth motion as in the case of solitary pulsars).



Decelerating pulsars Accelerating pulsars

Figure 1: Frequency properties of the 1326 pulsars from the ATNF Catalog

Since, as we note from the above-mentioned catalog, only a few binary systems present non negligible eccentricities we will restrict ourselves, in this study, to the cases of circular orbits where the Doppler shift is sine-modulated according to the period of the orbit.

3 The Sine-Hough Method

3.1 Time-Frequency diagram

The maximum time during which a Fourier transform can be performed in order to keep the signal in a single frequency bin is a function of the Doppler shift of the signal, in the case of binary systems it is given by[9]:

$$T_{FFT}^{\max} = (1-e)\frac{P_b}{2\pi}\sqrt{\frac{c}{a_1 \sin i}\frac{1}{\nu_g}}$$

where e is the eccentricity, P_b the binary period, $a_1 \sin i$ the projected semi-major axis of the system, c the speed of light and ν_g the frequency of the emitted gravitational wave. For example, for the pulsar J0034-0534, (P_b=1.59days, $a_1 \sin i$ = 1.44 light.sec, $\nu_g = \nu_{\text{opt}}$ = 532.7Hz) this corresponds to $T_{FFT}^{\max}$=800s whereas, taking only the Earth motion into account and the "classical" formula[5], we find $T_{FFT}^{\max}$=4800s .

In order to build the time-frequency diagram we:

a) Fourier transform a time slice of data of length T weighted by a Hanning window. Along all this work, we took T=800 s (a value which satisfies the $T_{FFT}^{\max}$ criterium for 73% of the known binary pulsars and is optimum for 9% of them).

b) Select all bins in the amplitude spectrum exceeding a given threshold, computed from nearby frequency bins, and plot a point in the time-frequency diagram with abscissa its frequency and ordinate the time corresponding to the Fourier transform

We illustrate this method on figure 2 where the resulting plot with a very large signal given to the simulated pulsar J0034-0534 is shown.

This simulation, including the Virgo noise and the pulsar properties, was performed in the time domain using the simulation package SIESTA[10]; it includes all Doppler effects (Earth , Earth-Sun and binary system rotation).

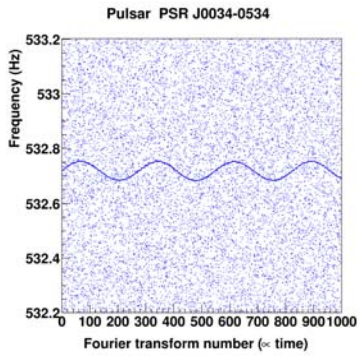


Figure 2: Building the time-frequency diagram

If we restrict ourselves to the cases where the eccentricity is small (88% of the binary systems have $e<0.01$) and taking only a relatively small time slice for each search (a week), the problem is reduced to the identification of a sinusoidal shape in the presence of background.

3.2 Principle of the method

The sine shape we are searching for can be written as a function of time: $y(t) = y_0 + a\sin(2\pi\nu t + \varphi)$, where y_0 (the pulsar frequency), a (the amplitude of the Doppler shift due to the binary rotation), ν (the binary system rotation frequency) and the phase φ are to be determined.

Our approach to this problem is the following:

a) Fix the value of y_0 and, in the time-frequency diagram, select a frequency band around y_0, wide enough to include the sine shape (a parameter to be optimized).

b) Take 3 points (with different time coordinate) located inside the band and, from them, compute the 3 remaining unknowns a, ν, φ. This non-linear solution is solved numerically with some care in order to reject non-physical and useless solutions[11].

c) From the obtained values, increment the corresponding cells in a 3-dimension histogram of axis: a, ν, φ.

d) Loop over all combinations of points, taken 3 by 3, inside the selected band

e) Search the maximum cluster inside the volume a, ν, φ.

f) Scan all possible values of y_0 and plot, as a function of y_0, the content of this maximum cluster.

On Figure 3 we show a simple application of this Sine-Hough method performed on a very simple Monte Carlo simulation: 400 randomly distributed points to which 15, points taken randomly along a sine function, are added. These input data are sketched on figure 3-a, on figure 3-b the output of the Sine-Hough algorithm applied to this data set is shown. This example is just displayed here to illustrate the pattern recognition power of the algorithm.

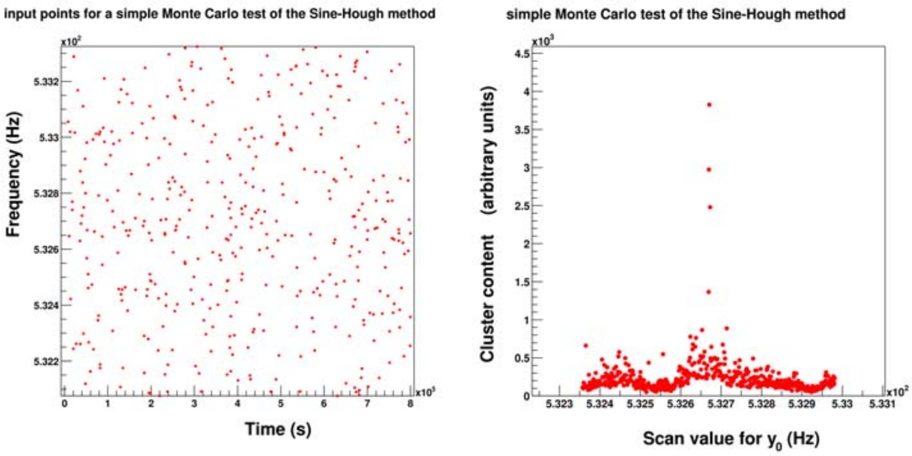
4 A first application to real data

The aim, here is to test the robustness and the ability of the Sine-Hough algorithm to find a signal in a "realistic" data environment.

4.1 The data used

The Virgo CITF[12] has been tested and data were recorded during five engineering runs. During the last one (July 12th to July 15th, 2002) a total of 40 hours of data, splitted in four stable running periods, have been selected. Using the Virgo standard *h* reconstruction including some line elimination[13].

In order to perform the test under "realistic" conditions we have simulated, in the time domain, the 66 well measured pulsars in binary systems with their parameters (position in the sky, frequency…) as found in the ATNF catalog[7], except that we have optimistically[b] added 1 Hz to each pulsar frequency. This simulation, also performed using SIESTA[10] generates the *h* signal at optical frequency and at double-frequency (then shifted by 2 Hz). This so-produced signal (132 candidates) is added to the CITF data after adjusting their generated amplitude "by hand".



(a) (b)

Figure 3 Simple Monte Carlo test of the Sine-Hough method a) input points, b) scan with the Sine-Hough algorithm

We used a 4kHz sampling rate, a 800s Fourier transform with Hanning window shifted by 400s between two lines of the time frequency diagram.
In figure 4 the E4 data sensitivity, together with the mean *h* values (at detector level) as injected in the simulation, are shown.

4.2 Data analysis

The aim being to test the robustness and the ability of the Sine-Hough algorithm to find a signal in a "realistic" data environment and the sensitivity of the CITF being low, we have not performed a full blind binary pulsar search but rather concentrated on an analysis using 800s-long Fourier transforms. We present at this conference this 800s results (a time length which is optimum only for a fraction of the existing pulsars) and will discuss only the case of two pulsars in binary system. A more detailed discussion of this work is available in [11].

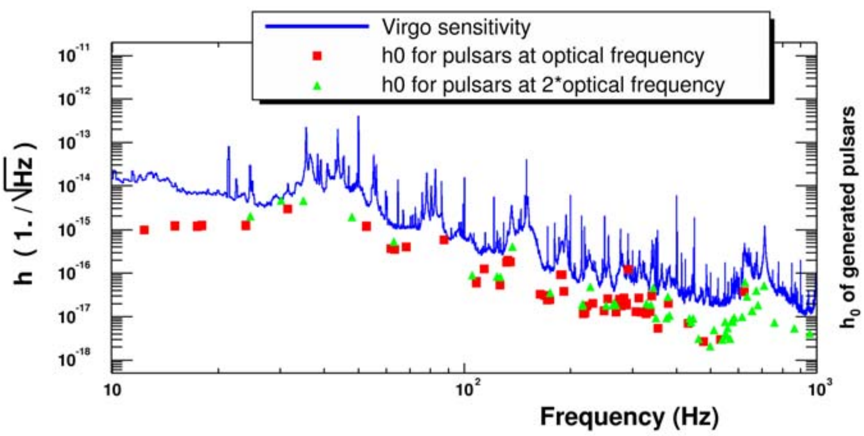


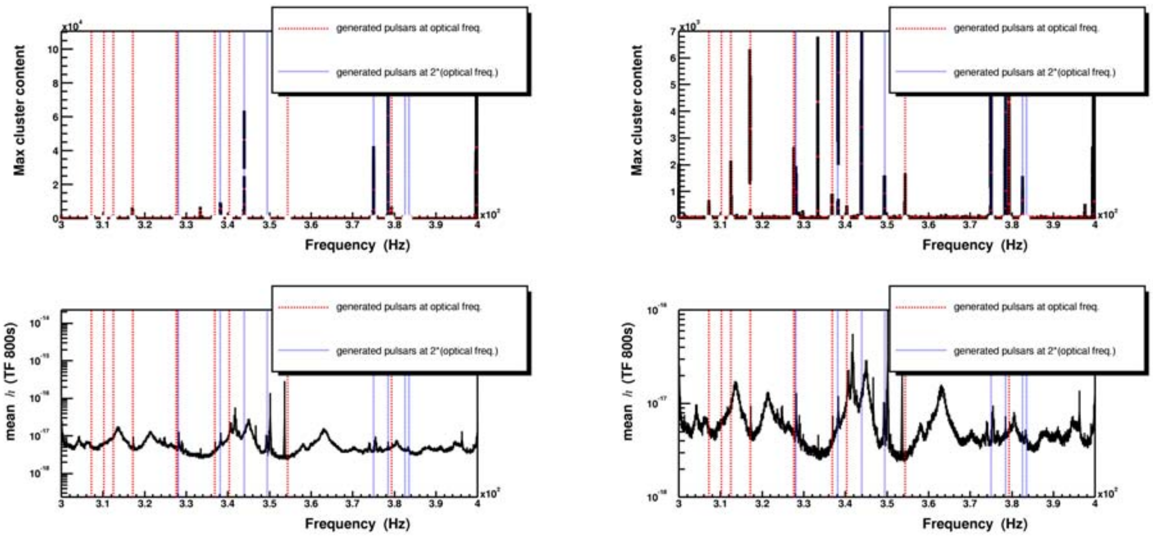
Figure 4 *h* frequency spectra and h_0 amplitude of generated pulsars as added to the E4 data

[b] This simulation will then be usable directly when Virgo will reach its full sensitivity

In Figure 5 (upper plot) the Sine-Hough algorithm response in the range 300-400 Hz is shown, the vertical lines are the frequency values of the added pulsars (dashed are the pulsars at optical frequency and dotted at the double of the optical frequency). In the bottom plot the mean *h* spectrum over all the 800s Fourier transforms is shown. Part (b) is the same as part (a) with an enlarged vertical scale. The response for the other frequency bands is qualitatively not very different, the algorithm performs quite well, it finds almost all injected binary pulsars even in this preliminary approach where several parameters are not tuned to optimum values.

Moreover, it works well even in very noisy regions where it is limited only by the computing time (this forced us to discard several small regions, a total of 0.3% of the spectrum).

All this search is performed on the previously defined time-frequency diagrams where we have set the cut limit using a "running" threshold calculated from the 100 nearby bins of the FFT modules, the cut being placed at a value of 3.76 rms above their mean. This value of 3.76 was taken as a compromise in order to remain within a reasonable computing time, obviously it has to be refined. An other drastic condition used was the rejection of accumulation in only one frequency bin: if, in the time-frequency diagram, one bin row accumulates more than 40 points, the corresponding frequency line is eliminated, thus rejecting all non binary pulsars candidates and all stationary frequency noise lines.



(a) (b)

Figure 5 a) Sine-Hough algorithm scan result between 300 and 400 Hz (top), bottom shows the mean value of *h* (800s FFt). b) same as a) with a vertical zoom

4.3 Results for pulsars J0024-7204H and J0024-7204S

In the following we concentrate on two pulsars: J0024-7204H and J0024-7204S, chosen as examples to make sure that this Sine-Hough algorithm is able to find such exotic objects (they are located in the same globular cluster and are spinning with an increasing frequency) and to extract their parameters.

The Sine-Hough algorithm results, concerning these two pulsars, at both their optical frequency and their double frequency are shown in Table 1 where the quoted h_0 value corresponds to the mean generated amplitude for the pulsar over one day at detector level. On figure 6, the corresponding response in a frequency band of 4 Hz around the generated pulsars frequencies is shown.

We observe that, even if the search parameters remain to be fine-tuned:

a) in each case the pulsar is found even when in the *h* spectrum it is not apparent to the naked eye

b) when a spurious peak is present in the h spectrum, the algorithm only seldom gives a positive response, a welcome fact well illustrated in figure 6 for the pulsar J0024-7204H at $2\nu_{opt.}$ and pulsar J0024-7204S at $\nu_{opt.}$

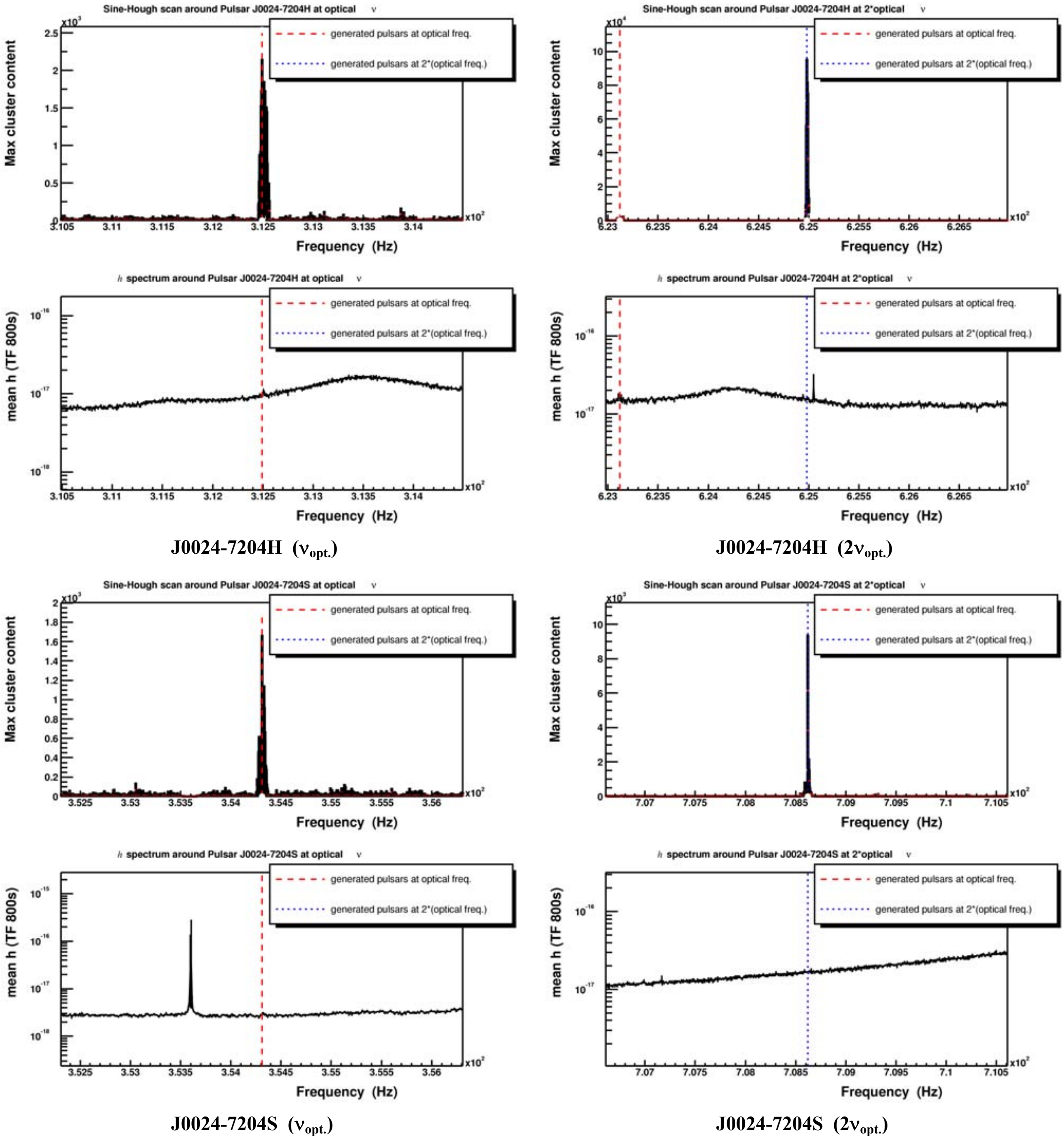


Figure 6 top: Sine-Hough algorithm response, bottom: mean h spectrum (800s Fourier transform)

	J0024-7204H		J0024-7204S	
	νopt.	2νopt.	νopt.	2νopt.
generated h_0	1.61 10-16	3.74 10-16	3.2 10-17	3.11 10-16
catalog frequency (Hz)	311.493	622.698	353.306	706.612
generated frequency (Hz)	312.49	624.98	354.31	708.61
reconstructed* frequency (Hz)	312.49	624.98	354.31	708.61
catalog freq. of bin. syst. (Hz)	4.909 10-6	4.909 10-6	9.63710-6	9.637 10-6
generated freq. of bin. syst. (Hz)	4.909 10-6	4.909 10-6	9.637 10-6	9.637 10-6
reconstructed* freq. of bin. syst. (Hz)	4.78 10-6	4.75 10-6	9.71 10-6	8.25 10-6
catalog Δnu max (Hz), calculated	0.02	0.04	0.016	0.032
generated Δnu max (Hz), calculated	0.02	0.04	0.016	0.032
reconstructed* Δnu max (Hz)	0.022	0.046	0.016	0.042

Table 1 Numerical conditions and results from the Sine-Hough algorithm, (*) values at peak

5 Conclusion

In the sensitivity range of the gravitational waves interferometric detectors, the pulsar population is dominated by pulsars in binary systems, hence a strong case for developing algorithms which are well suited to detect them. The Sine-Hough method we present here is very promising since, even if the search parameters are not fully tuned, it allows to find in a "real environment" the large majority of the simulated pulsars hidden in the data. We have not yet optimised the parameters in order to find the limit in sensitivity it allows to reach but the preliminary results we present here are a strong motivation to work deeper in this direction.

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