Data Analysis of Gravitational Wave Signals from Millisecond Pulsars

Fernanda G. Oliveira, Rubens M. Marinho Jr and Jaziel G. Coelho

Instituto Tecnológico de Aeronáutica, Praça Marechal Eduardo Gomes 50, São José dos Campos, SP 12228-900, Brazil

Nadia S. Magalhaes

Universidade Federal de São Paulo, DCET, Rua São Nicolau 210, Diadema, SP 09913-030, Brazil

Received Day Month Year
Revised Day Month Year

The present work is devoted to the detection of monochromatic gravitational wave signals emitted by pulsars using ALLEGRO’s data detector. We will present the region (in frequency) of millisecond pulsars of the globular cluster 47 Tucanae (NGC 104) in the band of detector. With this result it was possible to analyse the data in the frequency ranges of the pulsars J1748-2446L and J1342+2822c, searching for annual Doppler variations using power spectrum estimates for the year 1999. We tested this method injecting a simulated signal in real data and we were able to detect it.

Keywords: Data analysis; Gravitational Waves; Pulsar

PACS numbers: 11.25.Hf, 123.1K

1. Introduction

The focus of this work was to analyse ALLEGRO’s data for the year 1999 taking into account the effect due to the orbital motion of the Earth for specific frequencies, 891.0 Hz and 923.4 Hz, that correspond to the pulsars located in 47 Tucanae (NGC 104) named 1748-2446L and J1342+2822c, respectively. This analysis was based on estimates of power spectrum of the data using averaged modified periodograms which reinforce the presence of peaks due to monochromatic signals.

2. The Characteristic Amplitude of a Pulsar’s Gravitational Waves

Pulsars with non-axisymmetric rotation are expected to emit monochromatic gravitational wave signals (MGW). The amplitude of gravitational waves (GW) emitted by a rotating neutron star (NS) can be expressed in terms of the NS rotation period $P$, the distance to the Earth $r$, the moment of inertia $I$ and the ellipticity $\epsilon$ resulting from the distortion process as:

$$h_c = 4.21 \times 10^{-4} \left(\frac{\text{ms}}{P}\right)^2 \left(\frac{\text{kpc}}{r}\right) \left(\frac{I}{10^{38}\text{kgm}^2}\right)^2 \left(\frac{\epsilon}{10^{-6}}\right).$$

(1)
Its value depends on the physical mechanism that makes the star non-axisymmetric and is highly uncertain. The values of $h_c$ resulting from Eq. (1) are shown in the Figure for millisecond pulsars in 47 Tucanae.

3. Determination of the Observation Time

In the present analysis we are interested only in the annual Doppler shift that a monochromatic, continuous gravitational wave signal should experience, so we need to choose an observation time, $\Delta t$, such that the diurnal Doppler shift, $\Delta \nu_d$, remains in the same frequency bin $\Delta f = 1/\Delta t$. The minimum size of this bin, $\Delta f_{\text{min}}$, corresponds to the maximum diurnal Doppler shift, $\Delta \nu_{d_{\text{max}}} = \Delta f_{\text{min}} = 1/\Delta t_{\text{max}}$. The maximum diurnal Doppler shift happens when the Earth and the star are in the line of the nodes:

$$\Delta \nu_{d_{\text{max}}} = \nu_s \frac{2w r}{c},$$

where $w$ and $r$ are the angular velocity of rotation and the radius of the Earth, respectively. The annual Doppler shift in a full year of observation is,

$$\Delta \nu_a = \nu_s \frac{2R \Omega}{c},$$

where $R$ is the average radius of the Earth’s orbit around the Sun and $\Omega$ is its angular velocity in this orbital motion. The values of the Doppler shift obtained for the pulsars radiating with frequency $\nu_s$ are given in Table 1.

| Pulsar           | $\nu_s$ (Hz) | $\Delta \nu_{d_{\text{max}}}$ (mHz) | $\Delta \nu_a$ (Hz)  | $\Delta t_{\text{max}}$ (s) |
|------------------|--------------|-------------------------------------|---------------------|-----------------------------|
| PSR J1748-2446L  | 891.0        | 2.8                                 | 0.1770              | 362                         |
| PSR J1342+2822c  | 923.4        | 2.9                                 | 0.1835              | 350                         |

In order to eliminate the daily Doppler shift we used $\Delta t = 300$ s for the observation time in our data analysis.

4. The Strain-Noise Sensitivity of ALLEGRO

In Figure we present the region of MGW signals from pulsars in the strain-noise spectrum of ALLEGRO. This figure shows the gravitational strain $h_{EC}$ for the known pulsars in the band of ALLEGRO from the ATNF catalog. This quantity was derived assuming that all observed spin-down is due to energy loss caused by emission of gravitational radiation (and no other braking mechanisms). The strain for the pulsars is compared to the noise sensitivity curve (in units of $h/\sqrt{Hz}$) for the ALLEGRO detector.
Fig. 1. The figure shows the gravitational strain $h_{EC}$ (EC stands for Energy Conservation or spin-down limit) for the known pulsars in 47 Tucanae (NGC 104). The strain $h_{EC}$ is compared to the strain-noise spectrum of the detector ALLEGRO (in units of $h/\sqrt{\text{Hz}}$).

Fig. 2. Upper plot: Variation of the power spectrum for PSR J1748-2446L. Lower plot: Variation of the power spectrum for the simulated signal added to the data.

5. The Data Analysis

The goal of the analysis was to search for an annual Doppler shift in ALLEGRO’s data. For this we established an observation time $\Delta t = 300$ s so that the frequency of a possible observed signal would not change from one bin to another during the day. We have taken the power spectral density for 266 days of the year 1999. We fixed our attention on the bins that contained the frequencies 891.0 Hz and 923.4
Hz that would correspond to GW radiated respectively by the pulsars J1748-2446L and J1342+2822c, looking for an excess energy in these bins during those 266 days. We have chosen these two pulsars because their radiated frequencies were near the frequencies where the detector is the most sensitive[1]. We simulated a GW signal with dimensionless amplitude $h = 2.6 \times 10^{-17}$ and added it to ALLEGRO’s data. The results of this analysis are shown in Figures 2 and 3.

6. Conclusions

In this analysis we are not able to identify any Doppler modulation in real data, as seen from the upper plots in Figures 2 and 3. However, it was possible to test our data analysis procedure for detection of monochromatic gravitational wave signals since we were able to notice the simulated signal buried in the noise (lower plots in Figures 2 and 3). The calculation of the detection probability using the Neyman-Pearson criterion will be the subject of a forthcoming paper.

References

1. E. Mauceli., P. M. McHugh., W.O. Hamilton., W.W. Johnson and A. Morse. Phys. Rev. D 54, 1264 (1996).
2. F. G. Oliveira et al., Inter. Journ. of Mod. Phys. D 19, 1293 (2010).
3. E. Gourgoulhon and S. Bonazzola, Gravitational Waves from isolated neutron stars. [ArXiv:astro-ph/9605150v1], (1996).
4. F. G. Oliveira et al., Nuclear Physics. B, Proceedings Supplement 199, 353 (2010).
5. G. Santostasi, Upper and lower limits on the Crab pulsars astrophysical parameters set from gravitational wave observations by LIGO: braking index and energy considerations. ArXiv:gr-qc/0807.2485v1, (2008).
6. P. D. Welch, IEEE Trans. and Audio Electroacoust., AU-15, 70 (1970).