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2008 Class. Quantum Grav. 25 114028

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All-sky incoherent search for periodic signals with Explorer 2005 data

P Astone¹, D Babusci², M Bassan^{3,4}, P Carelli^{4,5}, G Cavallari⁶,
A Chincarini⁷, E Coccia^{3,4}, S D'Antonio⁴, M Di Paolo Emilio^{5,8},
V Fafone^{3,4}, S Foffa⁹, G Gemme⁷, G Giordano², M Maggiore⁹, A Marini²,
Y Minenkov⁸, I Modena^{3,4}, G Modestino², A Moleti^{3,4}, G P Murtas²,
G V Pallottino^{1,10}, R Parodi⁷, G Piano Mortari^{5,8}, G Pizzella^{2,3},
L Quintieri², A Rocchi^{3,4}, F Ronga², F Saint Just^{1,10}, R Sturani⁹,
R Terenzi^{3,11}, G Torrioli^{1,12}, R Vaccarone⁷, G Vandoni⁶ and M Visco^{4,11}

¹ INFN, Sezione di Roma, Roma, Italy

² INFN, Laboratori Nazionali di Frascati, Frascati, Italy

³ Dip. Fisica, Università di Roma 'Tor Vergata', Roma, Italy

⁴ INFN, Sezione di Roma Tor Vergata, Roma, Italy

⁵ Università di dell'Aquila, Italy

⁶ CERN, Geneva, Switzerland

⁷ INFN, Sezione di Genova, Genova, Italy

⁸ INFN, Laboratori Nazionali del Gran Sasso, Assergi, L'Aquila, Italy

⁹ Dep. de Phys. Théorique, Université de Genève, Genève, Switzerland

¹⁰ Dip. Fisica, Università di Roma 'La Sapienza', Roma, Italy

¹¹ INAF, Istituto Fisica Spazio Interplanetario, Roma, Italy

¹² CNR, Istituto di Fotonica e Nanotecnologie, Roma, Italy

Received 26 September 2007, in final form 27 October 2007

Published 15 May 2008

Online at stacks.iop.org/CQG/25/114028

Abstract

The data collected during 2005 by the resonant bar Explorer are divided into segments and incoherently summed in order to perform an all-sky search for periodic gravitational wave signals. The parameter space of the search spanned about 40 Hz in frequency, over 23 927 positions in the sky. Neither source orbital corrections nor spindown parameters have been included, with the result that the search was sensitive to isolated neutron stars with a frequency drift less than $6 \times 10^{-11} \text{ Hz s}^{-1}$. No gravitational wave candidates have been found by means of the present analysis, which led to a best upper limit of 3.1×10^{-23} for the dimensionless strain amplitude.

PACS numbers: 95.55Ym, 04.80.Nn, 95.75.Pq, 97.60.Gb

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The search for periodic gravitational wave signals is a stimulating challenge for data analysts because of the considerable amount of computing time required.

For blind searches, i.e. without any *a priori* knowledge about the source, a fully coherent analysis cannot handle more than a few days of data because of the steep dependence of the size of the parameter space on the frequency resolution.

In [1], three data sets, each two days long, from the Explorer 1991 run have been coherently studied by means of the \mathcal{F} statistics method [2] which led to an upper limit of 1×10^{-22} on h in the narrow band 921.00–921.76 Hz.

A similar technique, applied in [3] to the most sensitive 10 h of the LIGO S2 run, led to an upper limit of 6.6×10^{-23} for isolated neutron stars in the band between 160 Hz and 728.8 Hz.

With the widening of the frequency band, due to the advent of interferometers as well as to improvements in the readout of resonant detectors, several incoherent and semi-coherent methods have been conceived and employed.

In [4], the Hough transform technique has been applied to the LIGO S2 data to perform a blind search for isolated neutron stars on a set of narrow frequency bands in the range 200–400 Hz, and a best upper limit of 4.43×10^{-23} has been set.

In the present work, the simple technique of adding power spectra has been applied to the most sensitive 40 Hz band of the 2005 run of the Explorer bar [5], resulting in a further improvement on the best upper limit on h , which is set to 3.1×10^{-23} at 920.14 Hz.

According to the results reported at this Amaldi7 conference, the analysis of the LIGO S4 run [6] is leading to a sensible improvement in this direction (about 4.28×10^{-24} around 140 Hz with multi-interferometer Hough search). Quite remarkably, the limit set in the present work is still competitive with the one coming from the S4 data in the same frequency band (where LIGO has indeed $1 \div 3 \times 10^{-23}$, depending on the analysis method employed).

2. The data set

At the end of April 2005, after a short commissioning break, the resonant antenna Explorer was again *on air* and operated with the usual, remarkable duty cycle (86% from April to December 2005) and a good stability.

The data stream taken by the bar until the end of 2005 (after which the sensitivity curve has been modified) has been divided into 25 161 segments, each about 14 min long. The most sensitive band of the Fourier transform of these segments, namely $N_f = 32718$ frequency bins in the range 885–925 Hz, has been selected for the analysis.

A noise cut has been applied to the total power contained in each spectrum, with the purpose of discarding the noisy ones thus creating an homogeneous set of spectra. This allowed us to apply for the subsequent analysis the simple power addition method, without weighting each spectrum with the corresponding noise level.

This selection led to the creation of a data set $\{S_i\}$ made of the $N_1 = 11749$ cleanest spectra (corresponding to an effective data time of 114 days), and of a second set containing just the best $N_2 = 3875$ (used to deal with the critical zones of the spectrum, corresponding to the resonant modes of the bar, around 888 Hz and 920 Hz).

The average sensitivity of the second data set is shown in figure 2 (the first set is similar except around the resonant modes); a few noisy lines may be noted, including small 1 Hz harmonics on the left part.

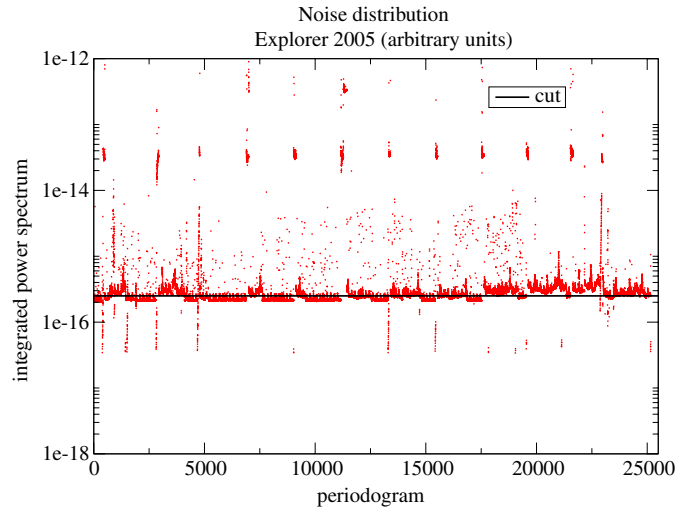


Figure 1. The noise level of Explorer during the 2005 run. The solid horizontal line is the cut applied to select the best spectra.

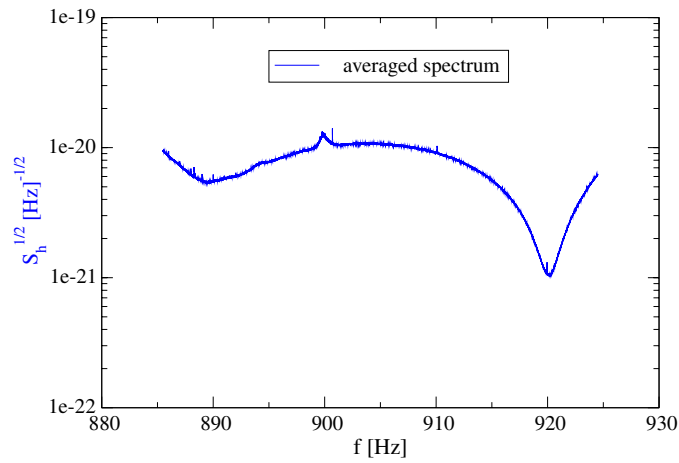


Figure 2. The square root of the average spectrum represents the typical Explorer sensitivity curve during the 2005 run.

3. The analysis method

For a given direction \hat{r}_j in the sky, the selected spectra have been deformed according to the Doppler shift formula

$$f_j^{\text{true}} \simeq f_{\text{exp}} \left(1 - \frac{\vec{v}_{\text{rel}} \cdot \hat{r}_j}{c} \right) \quad (1)$$

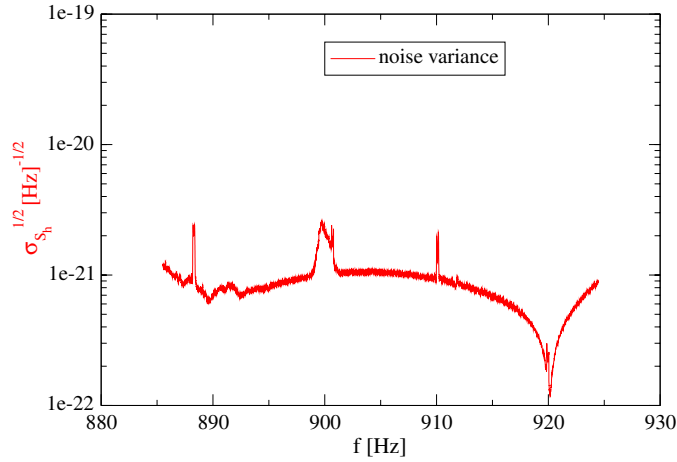


Figure 3. Noise variance of the set of deformed and summed spectra. This has been obtained from the large set made of N_1 spectra, except nearby the resonance modes, where the cleanest set have been used. To help comparison with figure 2, the square root of σ is actually shown.

and then summed and renormalized dividing by N_1 or by N_2 ,

$$\mathcal{S}_j(f^{\text{true}}) = \frac{1}{N_{1,2}} \sum_{i=1}^{N_{1,2}} \mathcal{S}_i(f_j^{\text{true}}).$$

The speed of the detector relative to the Solar System Baricenter has been computed, thanks to the JPL ephemerides [7]. As the speed of the source have not been taken into account, the search is sensitive to isolated neutron stars, and not to those which are part of binary systems.

Spindown has also been neglected: given the frequency resolution of 1.2×10^{-3} Hz, this means being sensitive to an average frequency drift up to 6×10^{-11} Hz s⁻¹ during the observation period.

The procedure has been repeated for any point of an optimized sky grid made of $N_{\text{sky}} = 23927$ possible directions, thus leading to the creation of a set $\{\mathcal{S}_j\}$ containing N_{sky} ‘deformed and summed’ spectra.

The grid has been obtained as a series of circles parallel to the ecliptic plane (along which the Doppler shift is maximum due to the orbital motion of the Earth); the grid step in moving along the circles, and in passing from one circle to another, has been calculated by requiring that the error in the frequency estimation (obtainable through variation of equation (1) with respect to \hat{r}_j) should be less then one half of the frequency resolution.

The variance of the noise is obtained calculating, for each value of the frequency, the variance of the distribution of the N_{sky} deformed spectra. The result, whose square root is shown in figure 3, agrees with the general expectation, based on the central-limit theorem, that

$$\sigma \simeq \frac{S_h}{\sqrt{N_{1,2}}}. \quad (2)$$

As expected, the plot shows an anomalous behaviour of the noise variance in correspondence of the disturbances of the initial data set. These anomalous zones have not been taken into account for the candidate search, but have been included in the upper-limit determination.

The detection threshold is fixed by the requirement that the false alarm rate should be less than 1%. According to Poisson statistics one has to impose

$$P(0, \lambda) = e^{-\lambda} > 0.99,$$

where the expected number of threshold crossings in the absence of signal is

$$\lambda = p \cdot N_f \cdot N_{\text{sky}},$$

with p being the probability of false detection in a single frequency bin and for a single direction in the sky, and $N_f \cdot N_{\text{sky}}$ the trial factor.

One thus finds the condition $p < 1.3 \times 10^{-11}$ which, assuming that the N_{sky} values of the shifted spectra at a given frequency bin are Gaussian distributed, translates to a 7σ threshold.

In other words, a detection is claimed if, for some value of the frequency f , a given deformed spectrum \mathcal{S}_j satisfies the condition

$$\mathcal{S}_j(f) - \bar{\mathcal{S}}(f) > 7\sigma(f), \quad (3)$$

with $\bar{\mathcal{S}}$ being the average of the deformed spectra $\{\mathcal{S}_j\}$ as j spans over the N_{sky} sky grid points.

Since $h \propto \sqrt{\mathcal{S}}$, to translate the detection threshold in h units one has to multiply the values shown in figure 3 by the factor

$$\sqrt{\frac{7}{T}} \cdot \sqrt{\frac{15}{4}},$$

where T is the length of each data segment and the factor $4/15$ (the average angular sensitivity of the bar over the solid angle) is introduced to compensate the fact that amplitude modulation has not been taken into account when summing the deformed spectra.

4. Results

4.1. Candidate search

The threshold is shown by the upper curve in figure 4, while the lower line is the maximum value of h found, at any given frequency bin, among the set of the N_{sky} spectra according to the following formula:

$$h_{\text{max}}(f) = \max_j \left[\sqrt{\frac{15}{4} \frac{\mathcal{S}_j(f) - \bar{\mathcal{S}}(f)}{T}} \right].$$

The anomalous regions of the spectrum have been cut out, since it is not reasonable to assume that they follow a Gaussian distribution. To illustrate the point, the 1 Hz disturbances have been kept in figure 4, to show that they would have produced fake candidates, if they had been included in the analysis.

With these specifications, the maxima are never above the threshold, and thus no candidates have been found.

4.2. Software injections and upper limit

To find an upper limit on h , a variation of the loudest event method [8] has been applied. This method allows us to determine an upper limit starting from the loudest event present in a data stream, irrespectively of the fact that such an event may be due to noise or to a real signal. The idea is basically that if a strong real signal would have been present during the data taking, it would have produced an event louder than the loudest event actually recorded. This idea can

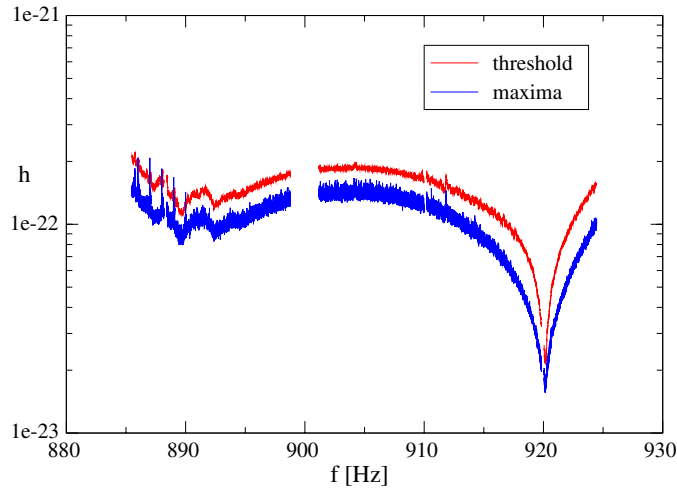


Figure 4. Detection threshold (red, upper curve) and maximal triggers (blue, lower). The 1 Hz disturbances on the left have been left only for illustrative purpose and cannot be considered as genuine threshold crossings.

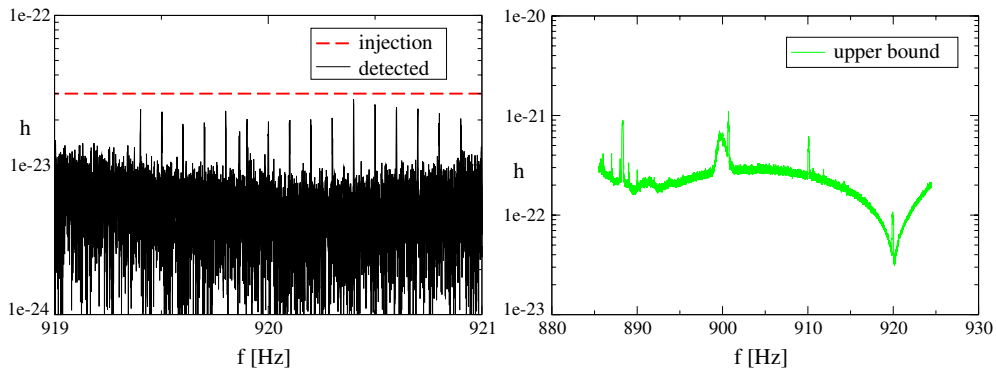


Figure 5. On the left, the outcome of 16 injections, with initial amplitude given by the dashed red line. On the right, the upper-limit curve.

be made quantitative by studying the detection efficiency of the experiment, for example by performing software injections at various SNRs.

In our case, we have a loudest event for any frequency bin, and all these events form precisely the curve of maxima depicted in figure 4. As a preliminary step, we had to determine our detection efficiency by injecting fake periodic signals in the Explorer data stream and finding out how they did look like after the analysis chain: the left plot of figure 5 shows for instance the result of 16 injections of signals with $h = 3 \times 10^{-23}$, equally spaced in frequency by 0.1 Hz starting from 919.4 Hz, and coming from randomly chosen directions in the sky. Then, the upper limit at 95% c.l. has been determined for each frequency bin as the lowest injected amplitude which had produced a signal larger than the actual maximum at least in 95% of the cases.

The right plot on figure 5 shows the result, i.e. the curve of h upper limit at 95% confidence level: the minimum is 3.1×10^{-23} at 920.14 Hz.

5. Conclusion

In the present work, the 2005 run of the Explorer bar have been analysed; the best upper limit for periodical gravitational waves emission by isolated, spindown-free neutron stars is $h > 3.1 \times 10^{-23}$.

This upper limit has already been improved by the LIGO S4 analysis, and further improvements are to be expected in the near future (for instance by the new analysis for the Nautilus bar data [9], which includes also a wider spindown range, or most likely by means of distributed computing projects like Einstein@Home [10]).

However, this result definitely shows that the data produced by the resonant bars community are still scientifically very valuable even in the epoch of large interferometers.

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