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Search Method for Gravitational Wave Fingerprints of Soft Gamma Repeater QPOs

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Abstract: Soft Gamma Repeaters are young neutron stars with very strong magnetic fields that emit X-ray and gamma-ray bursts at irregular intervals, and occasionally produce hyperflares. Quasi Periodic Oscillations (QPOs) have been observed in the X-ray tails of the December 2004 hyperflare from SGR 1806-20 [1,2] and the August 1998 hyperflare from SGR 1900+14 [3,4]. These QPOs can plausibly be accompanied by gravitational wave emission up to the energy scale of the electromagnetic emission [5,6]. The search algorithm proposed here relies on coincident data streams from multiple interferometric gravitational wave detectors. It can incorporate the temporal and directional information available from the detected SGR flares.

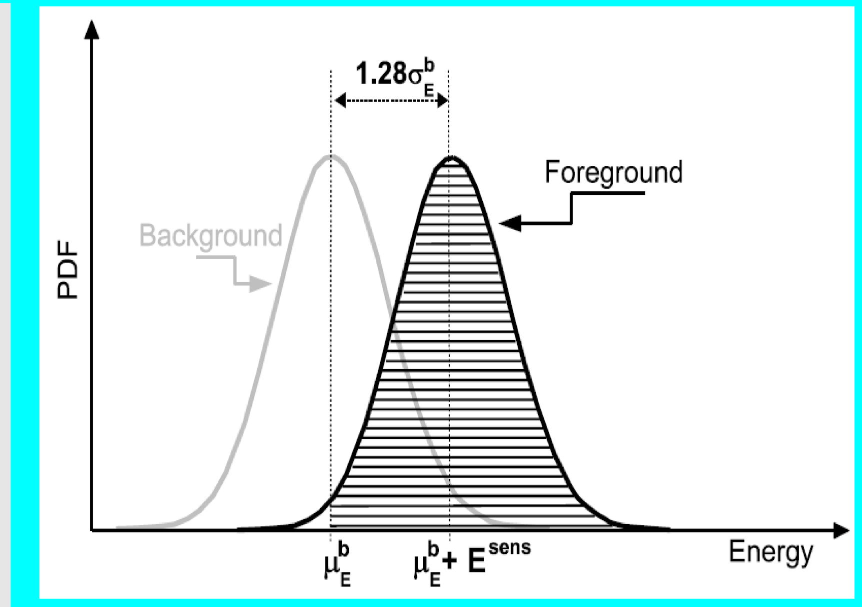

Figure 4: Median of the energy distribution of the off-source data segments (background) and that of the injection added off-source data segments (foreground) is separated by the search sensitivity "E^{sens}" which is the energy of the smallest injection for which 90% of the foreground lies above the background median.

3. Search algorithm:

The analysis pipeline identically processes three sets of data (Figure 5): the on-source data segment (data collected during the target event), the off-source data segments (data collected prior to the targeted event time when the physical conditions of the detectors were identical to that during the target event), and the off-source data segments with injections.

First, the excess-power (Eqn. v) of the background data stream is measured in 250ms long blocks which are then summed over Δt seconds to determine the energy of each off-source data segment. Energy distribution of these segments provides the underlying noise distribution of the detector (Figure 4). Injections are then added to each data segment so that the measured energy of 90% of the injection-added segments lie above the median energy of the background segments. The search sensitivity (E^{sens}) is defined as the energy of the smallest injection that fulfills this criterion.

Next, the energy of the on-source data segment is measured and compared to the background energy distribution. We use statistical analysis to determine if a detection has been made, and else, to set an upper limit on the possible Gravitational Wave emission from the source.

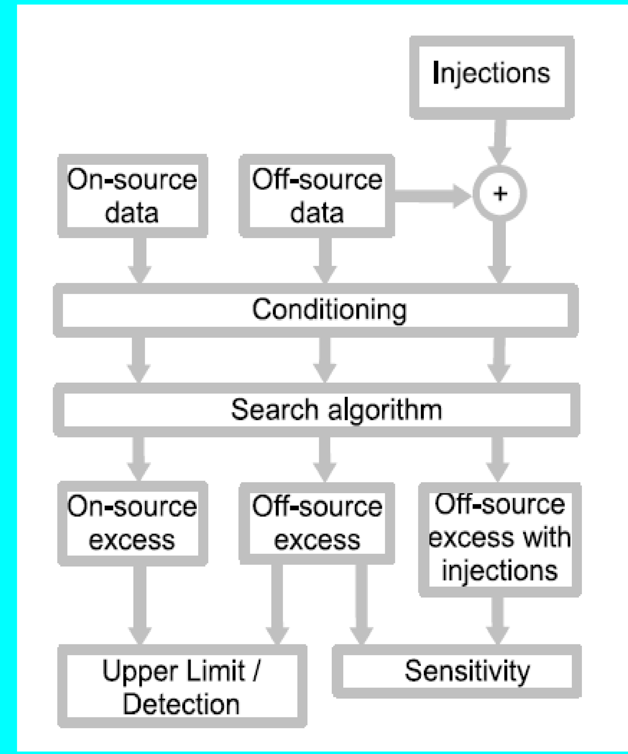

Figure 5: Analysis pipeline flowchart. The on-source data, off-source data, and off-source data with injections are identically processed.

8. Conclusions:

We have shown that the search algorithm previously used for the analysis of a single data stream from LIGO detectors can be extended for analyzing multiple data streams to search for co-incident gravitational wave signatures of Quasi Periodic Oscillations in the tails of X-ray flares emitted by Soft Gamma Repeaters. Analytically derived search sensitivity and the numerical sensitivity provided by the analysis pipeline with simulated detector noise have been found to be in reasonable agreement.

The extended analysis pipeline presented here can successfully exploit the presence of multiple Gravitational Wave detectors for the flare emissions from SGR 1806-20 and SGR 1900+14 during LIGO's fifth science run. It will allow us to analyze LIGO data collected during those events by incorporating the temporal and directional information available from the detected SGR flares.

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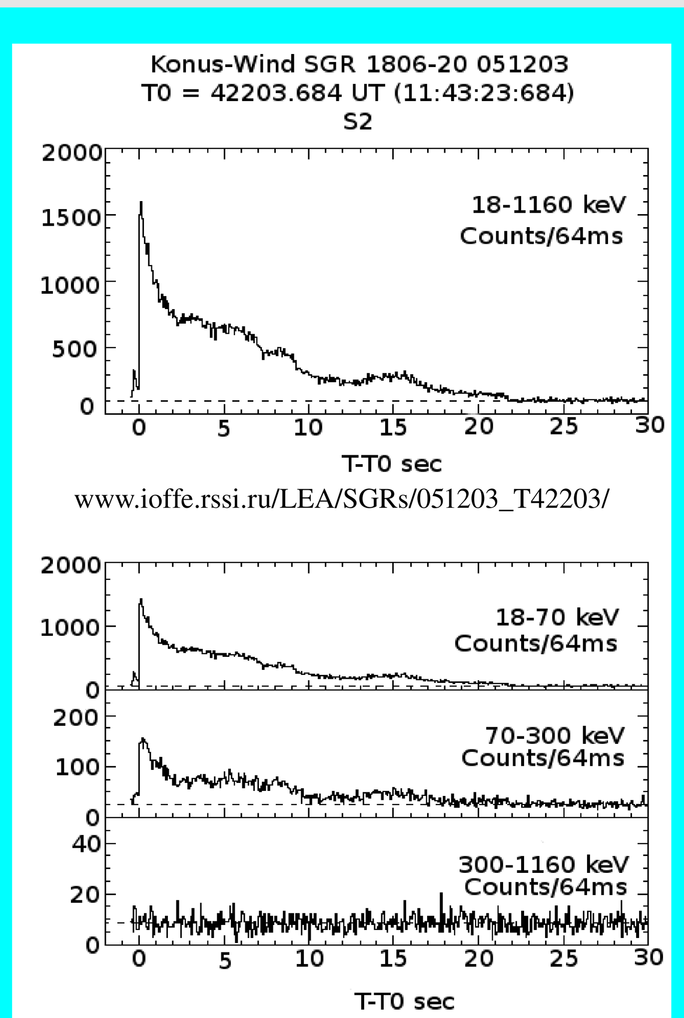

Figure 1: Light curve of the SGR 1806-20 hyperflare event on 27 December 2004.

1. Introduction:

Over 250 incidents of Soft Gamma Repeater (SGR) activity [7] have been recorded from two known SGRs in our galaxy, SGR 1806-20 and SGR 1900+14, by various X-ray and Gamma ray detectors on satellites during the recently concluded fifth science run (S5) of the LIGO gravitational wave detectors, data collection period when the interferometers reached design sensitivity. A majority of them occurred while both the 4km LIGO interferometers were collecting science quality data (Table 1). These events include those during a period of intense activity of the SGR 1900+14 on March 29, 2006 (Figures 2, 3).

Quasi Periodic Oscillations (QPOs) in the X-ray tail of such flares can be accompanied by gravitational wave emission [5,6]. A previous study has analyzed the data collected by the 4km LIGO detector at Hanford, WA [8,9], during the December 2004 SGR 1806-20 hyperflare (Figure 1). We present an extension of that search algorithm for the case of multiple interferometric gravitational wave detectors. We analytically derive the search sensitivity, and compare it to the numerical sensitivity provided by the analysis pipeline.

2. Fundamental Motivations for the Search:

Current understanding of the physical process behind the production of SGR flares is based on the magnetar model, in which the object is a neutron star with high magnetic field, and the flares are produced by catastrophic rearrangements of the star's crust and magnetic field: a starquake. The QPOs observed in the tails of the X-ray light-curves can possibly be associated with seismic modes of the star excited by the catastrophic event [10,11,12]. Potential gravitational wave emission associated with the observance of QPOs can last for tens of seconds and would be limited to a narrow bandwidth around the observed QPO frequencies [5,6]. Our search algorithm can utilize this knowledge to analyze LIGO data to search for gravitational wave signatures of SGR QPOs.

SGR 1806-20: 204 Events		**SGR 1900+14:** 58 Events	
~106	Triple Coincident	~43	Triple Coincident
~9	H1L1 Coincident	1	H1L1 Coincident
~48	H1H2 Coincident	~10	H1H2 Coincident
~5	H2L1 Coincident	0	H2L1 Coincident
~2	H1 only data	~2	H1 only data
~7	H2 only data	1	H2 only data
~7	L1 only data	0	L1 only data
~20	No Data	1	No Data

Table 1: SGR event statistics [7] during S5. H1 and H2 are the 4km and 2km LIGO interferometers in Hanford, WA. L1 is the 4km LIGO interferometer in Livingston, Louisiana. "No Data" indicates that a SGR event took place while none of the LIGO detectors were collecting science quality data.

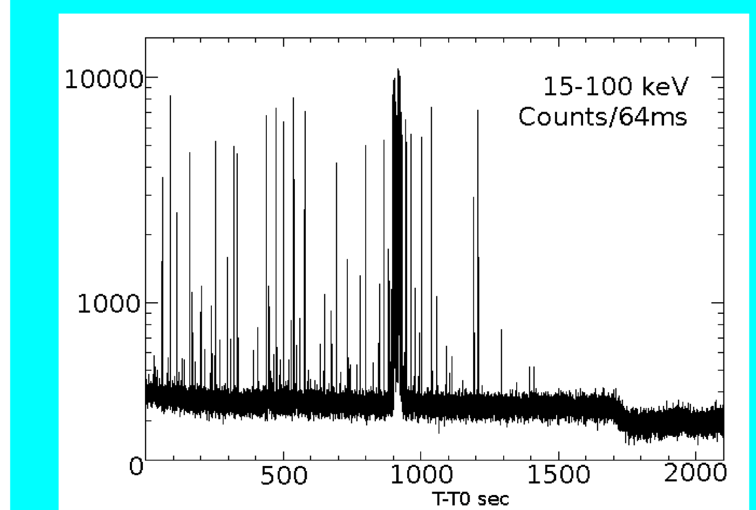

Figure 2: Light curve of the SGR 1900+14 period of intense activity on 29 March 2006. Horizontal zero of the plot is 2006-03-29 02:38:10 UT.

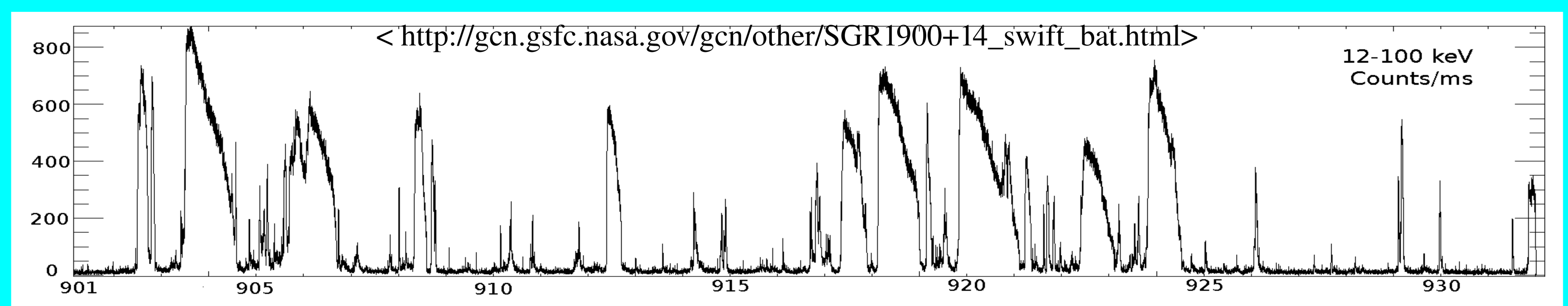

Figure 3: Detail of the SGR 1900+14 burst "storm" on a millisecond integration scale.

4. Coherent Search:

For the single detector case, the signal energy (E) and the search sensitivity (E^{sens}) are expressed by -

$$E = \frac{1}{F_s}\sum_{i=1}^{N} y_i^2 \quad \text{...(i)} \qquad E^{sens} = 1.28\sqrt{\frac{3}{2}}\,\tilde{n}^2(\Delta t\cdot\Delta f)^{\frac{1}{2}} \quad \text{... (ii)}$$

where F_s is the sampling frequency, y_i the measurements, $\tilde{n}$ the detector's noise floor, Δt and Δf the duration and bandwidth of energy measurement. For two detectors, the cross-correlated energy E is the inner product of the two data streams, and E^{sens} is predicted from equation (iv) -

$$E = \frac{1}{F_s}\sum_{i=1}^{N} x_i\cdot y_i \quad \text{...(iii)} \qquad E^{sens} \le 1.28\sqrt{\frac{3}{2}}\,\tilde{n}_1\cdot\tilde{n}_2(\Delta t\cdot\Delta f)^{\frac{1}{2}} \quad \text{... (iv)}$$

The search is conducted in the excess-power domain. The excess-power in the targeted QPO band is measured by subtracting average energy of the adjacent frequency bands from the energy of the targeted band:

$$\Delta E = E - E_{avg};\ E_{avg} = \frac{1}{2}(E_{down} + E_{up}) \quad \text{... (v)}$$

The strain sensitivity of the search in units of $1/\sqrt{Hz}$ is the square root of the sensitivity in energy units, that is, $h_{rss-det}^{sens} = \sqrt{E^{sens}}$ ... (vi).

5. Tests with Simulated Detector Noise:

We have measured search sensitivity of the extended analysis pipeline using simulated detector noise, at the strain noise floors of $4\times10^{-23}(1/\sqrt{Hz})$ and $3.5\times10^{-23}(1/\sqrt{Hz})$ for the two detectors, which are roughly representative of the published noise floors of the two 4km LIGO detectors around 92.5Hz during S5. For the geographic coordinates of the LIGO detectors, the sky location of SGR 1900+14 during the March 29, 2006 events, 92.5Hz frequency, 10Hz bandwidth (Δf), and 50s duration (Δt), the analytically expected strain sensitivities and the strain sensitivities achieved with the analysis pipeline are -

$Unit: (1/\sqrt{Hz})$	Expected	Achieved
Detector 1	2.3×10^{-22}	2.3×10^{-22}
Detector 2	2.0×10^{-22}	1.9×10^{-22}
Cross-Correlation	2.2×10^{-22}	1.8×10^{-22}

These numbers validate the relation, $E_{12}^{sens} \le \sqrt{E_1^{sens}\cdot E_2^{sens}}$ ...(vii), which is derived from relations (ii) and (iv).

6. Use of Antenna Factors:

Gravitational waves are emitted and propagated into plus and cross polarizations. The amplitude response of the detector at a given time for a given direction for the two polarizations, called antenna factors (F_+ and F_x), are smaller than 1. Originally, the pipeline would determine E^{sens} assuming ideal detector orientation (F^{eff}=1). The effective sensitivity is then gotten from the following relations -

$$F^{eff} = \sqrt{\frac{(F_+^2 + F_x^2)}{2}} \quad \text{... (viii)} \qquad h_{rss-det}^{sens} = \frac{\sqrt{E^{sens}}}{F^{eff}} \quad \text{... (ix)}$$

We scale the injections as $h_{inj} = (h_+\cdot F_+ + h_x\cdot F_x)$ ...(x) where h_+ and h_x are injection energy measurements for plus and cross polarizations, and h_{inj} the actual injection added. Also, equations (vi), (vii), (ix) yield $F_{12}^{eff} \ge \sqrt{F_1^{eff}\cdot F_2^{eff}}$ ...(xi).

The example case in Section 5 thus become -

$Unit: (1/\sqrt{Hz})$	Expected	Achieved
Detector 1	5.7×10^{-22}	5.4×10^{-22}
Detector 2	3.7×10^{-22}	3.6×10^{-22}
Cross-Correlation	4.6×10^{-22}	4.1×10^{-22}

7. Inverse Power Method:

Analysis of the background data stretch of two detectors allows us to determine the noise statistics for each detector and for the cross-correlated search. Analysis of the on-source data stretch provides the signal with noise measurement. Using the inverse power method [12] we can retrieve the energy content of the two polarization modes of the gravitational wave candidate:

$$A_{ijx} = F_{ix}F_{jx};\ A_{ij+} = F_{i+}F_{j+};\ A_{ijx+} = F_{ixj+}F_{jxi+};\ C_{ij} = \sum_{t=t_1}^{t=t_2} x_i\cdot y_j$$

$$H_{xx} = \sum_{t=t_1}^{t=t_2} h_x\cdot h_x;\ H_{++} = \sum_{t=t_1}^{t=t_2} h_+\cdot h_+;\ H_{x+} = \sum_{t=t_1}^{t=t_2} h_x\cdot h_+;$$

$$\begin{bmatrix} H_{xx} \\ H_{++} \\ H_{x+} \end{bmatrix} = \begin{bmatrix} A_{11x} & A_{11+} & A_{11x+} \\ A_{22x} & A_{22+} & A_{22x+} \\ A_{12x} & A_{12+} & A_{12x+} \end{bmatrix}^{-1} \left[\begin{bmatrix} C_{11} \\ C_{22} \\ C_{12} \end{bmatrix} - \begin{bmatrix} N_{11\Sigma} \\ N_{22\Sigma} \\ N_{12\Sigma} \end{bmatrix} \right]$$

$\Rightarrow \boldsymbol{H} = \boldsymbol{A}^{-1}\cdot(\boldsymbol{C} - \boldsymbol{N})$ ...(xii) where **N** is the noise statistics, **C** the on-source measurements, **A** the effective antenna factor matrix, and **H** the emitted energy measurements for plus and cross polarizations and their combination.

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