

# Report on an all-sky LIGO search for periodic gravitational waves in the S4 data

**Alicia M Sintes for the LIGO Scientific Collaboration**

Departament de Física, Universitat de les Illes Balears, Cra. Valldemossa Km. 7.5, E-07122  
Palma de Mallorca, Spain  
Max-Planck-Institut für Gravitationsphysik, Albert-Einstein-Institut, Am Mühlenberg 1,  
D-14476 Golm, Germany

E-mail: [sintes@aei.mpg.de](mailto:sintes@aei.mpg.de)

**Abstract.** We report on an all-sky search with the LIGO detectors for periodic gravitational waves in the frequency range 50-1000 Hz and having a negative frequency time derivative with magnitude between zero and  $10^{-8}$  Hz/s. Data from the fourth LIGO science run have been used in this search. Three different semi-coherent methods of summing strain power were applied. Observing no evidence for periodic gravitational radiation, we report upper limits on strain amplitude and interpret these limits to constrain radiation from rotating neutron stars.

## 1. Introduction

The LIGO detector network consists of a 4-km interferometer in Livingston Louisiana (called L1) and two interferometers in Hanford Washington, one 4-km and another 2-km (H1 and H2, respectively) [1, 2]. The data analyzed in this paper were produced during LIGO's 29.5-day fourth science run (S4) [3, 4]. This run started at noon Central Standard Time (CST) on February 22 and ended at midnight CST on March 23, 2005. During the run, all three LIGO detectors had displacement spectral amplitudes near  $2.5 \times 10^{-19}$  m Hz<sup>-1/2</sup> in their most sensitive frequency band near 150 Hz. In units of gravitational-wave strain amplitude, the sensitivity of H2 is roughly a factor of two worse than that of H1 and L1 over much of the search band.

In this paper we summarize the results from our search for periodic gravitational waves in the S4 data. The search was carried out in the frequency range 50-1000 Hz, having a negative frequency time derivative with magnitude between zero and  $1 \times 10^{-8}$  Hz/s and over the entire sky. Isolated neutron stars in our galaxy were the prime target. For further details on the analysis and discussions we refer the reader to [5].

## 2. Overview of the search methods

Three different analysis methods were considered for the search of periodic gravitational wave signals. These have many features in common, but also have important differences that are summarized in Table 1. All three methods are based on searching for cumulative excess power from a hypothetical periodic signal by examining successive spectral estimates based on Short Fourier Transforms (SFTs) of 30-minute intervals of the calibrated detector strain data. The simplest method used, known as "StackSlide" [6, 7, 8, 9], averages normalized power (i.e., power divided by an estimate of the spectral density of the noise) from each SFT. In the "Hough"

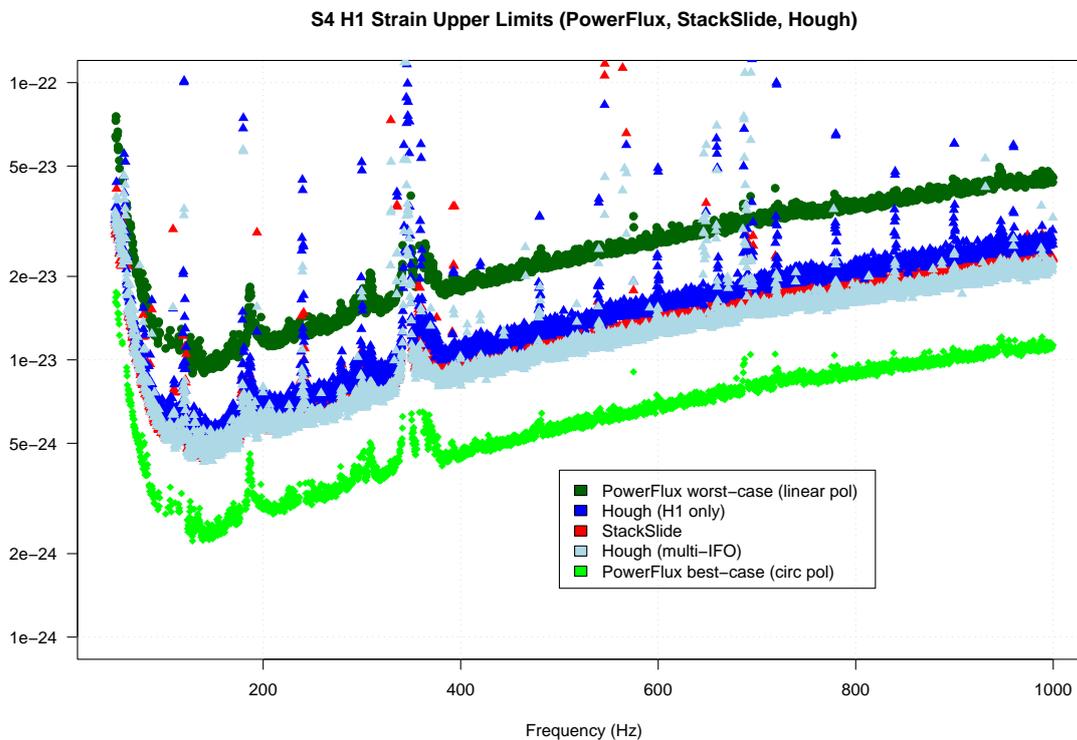
**Table 1.** Summary of similarities and differences among the three analysis methods used.

	StackSlide	Hough	PowerFlux
Windowing	Tukey	Tukey	Hann
Noise estimation	Median-based floor tracking	Median-based floor tracking	Time/frequency decomposition
Line handling	Cleaning	Cleaning	Skyband exclusion
Antenna pattern weighting	No	Yes	Yes
Noise weighting	No	Yes	Yes
Spindown step size	$2 \times 10^{-10}$ Hz/s	$2 \times 10^{-10}$ Hz/s	Frequency dependent
Limit at every skypoint	No	No	Yes
Upper limit type	Population-based	Population-based	Strict frequentist

method [10, 11, 12, 13, 14, 15, 16], the sum is of weighted binary zeroes or ones, with weighting based on antenna pattern and detector noise, where an SFT contributes only if the power exceeds a normalized power threshold. This scheme also allows for a multi-interferometer search. The third method, known as ‘‘PowerFlux’’ [17, 18], is a variant of the StackSlide method in which the power is weighted before summing. In both the Hough and PowerFlux methods, the weights are chosen according to the noise and detector antenna pattern to maximize the signal-to-noise ratio.

Each method corrects explicitly for sky-position dependent Doppler modulations of the apparent source frequency due to the Earth’s rotation and its orbital motion with respect to the Solar System Barycenter (SSB), and the frequency’s time derivative, intrinsic to the source. This requires a search in a four-dimensional parameter space; a template in the space refers to a set of values:  $\lambda = \{\hat{f}_0, \dot{f}, \alpha, \delta\}$ . The third method, PowerFlux, also searches explicitly over polarization angle, so that  $\lambda = \{\hat{f}_0, \dot{f}, \alpha, \delta, \psi\}$ . All three methods search for initial frequency  $\hat{f}_0$  in the range 50–1000 Hz with a uniform grid spacing equal to the size of an SFT frequency bin. The range of  $\hat{f}_0$  is determined by the noise curves of the interferometers, likely detectable source frequencies, and limitations due to the increasing computational cost at high frequencies. The range of  $\dot{f}$  values searched is  $[-1 \times 10^{-8}, 0]$  Hz s<sup>-1</sup> for the StackSlide and PowerFlux methods and  $[-2.2 \times 10^{-9}, 0]$  Hz s<sup>-1</sup> for the Hough method. The ranges of  $\dot{f}$  are narrow enough to complete the search in a reasonable amount of time, yet wide enough to include likely signals. The number of sky points that must be searched grows quadratically with the frequency  $\hat{f}_0$ , ranging in this search from about five thousand at 50 Hz to about two million at 1000 Hz. All three methods use nearly isotropic grids which cover the entire sky.

Other differences among the methods concern the data windowing and filtering used in computing Fourier transforms and data handling. StackSlide and Hough apply high pass filters to the data above 40Hz, in addition to the filter used to produce the calibrated data stream, and use Tukey windowing. PowerFlux applies no additional filtering and uses Hann windowing with 50% overlap between adjacent SFT’s. StackSlide and Hough use median-based noise floor tracking. In contrast, Powerflux uses a time-frequency decomposition. The StackSlide and Hough searches used 1004 SFTs from H1 and 899 from L1, the two interferometers with the best broadband sensitivity. For PowerFlux, the corresponding numbers of overlapped SFTs were 1925 and 1628. The Hough search also used 1063 H2 SFTs. Sharp instrumental lines, which can mimic a continuous gravitational-wave signal for parameter space points that correspond to small Doppler modulation, are also handled differently. StackSlide and Hough carry out removal of known instrumental lines of varying widths in individual SFTs. The measured powers in those



**Figure 1.** H1 upper limits on  $h_0$  from the three methods. The StackSlide and Hough limits are population-based, while those from PowerFlux are strict and apply, respectively, to the most favorable and least favorable pulsar inclinations. Also shown are the multi-interferometer limits from the Hough search.

bins are replaced with random noise generated from the noise observed in neighboring bins. PowerFlux flags single-bin lines during data preparation so that when searching for a particular source an individual SFT bin power is ignored when it coincides with the source's apparent frequency. The PowerFlux search also divides the sky into regions according to susceptibility to stationary instrumental line artifacts and excludes the less favorable ones when setting upper limits.

### 3. Summary of results

All three methods described above have been applied in an all-sky search over a frequency range 50-1000 Hz. All the loud candidates produced were checked for coincidences between H1 and L1 and the only surviving candidates were associated with the hardware injected pulsars and instrumental lines. Also different types of qualitative follow-up tests were performed on each of the coincident outliers. As described in [5], no evidence for a periodic gravitational wave signal was observed in any of the searches and upper limits on sources were determined.

For the StackSlide and Hough methods, 95% confidence-level frequentist upper limits were placed on putative rotating neutron stars, assuming a uniform-sky and isotropic-orientation parent sample. Depending on the source location and inclination, these limits may overcover or undercover the true 95% confidence-level band. For the PowerFlux method, strict frequentist upper limits were placed on linearly and circularly polarized periodic gravitational wave sources,

assuming *worst-case* sky location, avoiding undercoverage. The limits on linear polarization are also re-interpreted as limits on rotating neutron stars, assuming worst-case sky location and worst-case star inclination.

Figure 1 shows superimposed the final upper limits on  $h_0$  from the StackSlide, Hough, and PowerFlux methods when applied to the S4 single-interferometer H1 data, together with the multi-interferometer H1+H2+L1 Hough search. The reader should notice that the Hough search sensitivity improves with the summing of powers from two or more interferometers. Over the LIGO frequency band of sensitivity, these S4 all-sky upper limits are approximately an order of magnitude better than those published previously from the second science run (S2) [20, 12]. The best population-based upper limit with 95% confidence on the gravitational-wave strain amplitude, found for simulated sources distributed isotropically across the sky and with isotropically distributed spin-axes, is  $4.28 \times 10^{-24}$  (near 140 Hz) for the multi-interferometer Hough search.

In this search we have reached an important milestone on the road to astrophysically interesting all-sky results: Our best upper limits on  $h_0$  are comparable to the value of a few times  $10^{-24}$  at which one might optimistically expect to see the strongest signal from a previously unknown neutron star according to a generic argument originally made by Blandford (unpublished) and extended in our previous search for such objects in S2 data [20]. Moreover, the multi-interferometer Hough transform search could have detected an object at the distance of the nearest known neutron star RX J1856.5–3754, which is about 110–170 pc from Earth.

Comparing the three methods we found that Hough is computationally faster and more robust against large transient power artifacts, but is slightly less sensitive than StackSlide for stationary data [12, 8]. The PowerFlux method is found in most frequency ranges to have better detection efficiency than the StackSlide and Hough methods, the exceptions occurring in bands with large non-stationary artifacts, for which the Hough method proves more robust. However, the StackSlide and Hough methods can be made more sensitive by starting with the maximum likelihood statistic (known as the  $\mathcal{F}$ -statistic [19, 11, 20]) rather than SFT power as the input data, though this improvement comes at an increased computational cost. The trade-offs among the methods means that each could play a role in our future searches. The lower computational cost of the Hough search would be an advantage in this case. Multi-interferometer searches also increase the sensitivity, while reducing outliers (false-alarms), without having to increase greatly the size of the parameter space used, as illustrated by the Hough search in this paper. A fifth science run (S5), which started in November 2005 and finished at the end of September 2007, has generated data at initial LIGO's design sensitivity. Our plans are to search this data using the best methods possible, based on what is learned from this and previous analyses, and given the computational bounds.

### Acknowledgments

The authors gratefully acknowledge the support of the United States National Science Foundation for the construction and operation of the LIGO Laboratory and the Science and Technology Facilities Council of the United Kingdom, the Max-Planck-Society, and the State of Niedersachsen/Germany for support of the construction and operation of the GEO600 detector. The authors also gratefully acknowledge the support of the research by these agencies and by the Australian Research Council, the Council of Scientific and Industrial Research of India, the Istituto Nazionale di Fisica Nucleare of Italy, the Spanish Ministerio de Educacion y Ciencia, the Conselleria d'Economia Hisenda i Innovacio of the Govern de les Illes Balears, the Scottish Funding Council, the Scottish Universities Physics Alliance, The National Aeronautics and Space Administration, the Carnegie Trust, the Leverhulme Trust, the David and Lucile Packard Foundation, the Research Corporation, and the Alfred P. Sloan Foundation.

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