

# Recent results on the search for continuous sources with LIGO and GEO 600

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**Abstract.** An overview of the searches for continuous gravitational wave signals in LIGO and GEO 600 performed on different recent science runs and results are presented. This includes both searching for gravitational waves from known pulsars as well as blind searches over a wide parameter space.

## 1. Introduction

Construction of the LIGO [1, 2] and GEO 600 [3] instruments began in the mid-1990s. When the construction phase of the project was completed, the LIGO instruments were officially inaugurated on November 1999. Since then the commissioning of the instruments has alternated with a sequence of short engineering and science runs at increasing sensitivity. The four science runs to date are: S1: August 23 – September 9, 2002, S2: February 14 – April 14, 2003, S3: October 31, 2003 – January 9, 2004 and S4: February 22 – March 23, 2005. Both LIGO and GEO 600 are to begin a full science run (S5) in November, with the aim of gathering data continuously for 18 months. During the previous science runs although these instruments were still to reach their design sensitivity, their performances were sufficiently good to justify a serious test of our search algorithms on real interferometer data, in particular, to search for continuous gravitational waves from very dense, rapidly-spinning stars, such as neutron or quark stars.

Rapidly rotating neutron stars are the most likely sources of periodic, persistent gravitational waves in the frequency band between 100 and 1000 Hz. These objects may generate gravitational waves through a variety of mechanisms, including non-axisymmetric distortions of the star, velocity perturbations in the star's fluid, and free precession. Regardless of the specific mechanism, the emitted signal is a quasi-periodic continuous wave whose frequency changes slowly during the observation time due to the intrinsic frequency drift induced by the energy loss through gravitational wave emission (and possibly other mechanisms) and the motion of the detector with respect to the source. As the intrinsic amplitude of gravitational waves from this class of sources is several orders of magnitudes smaller than the typical root-mean-square value of the noise, detection can only be achieved by means of long integration times, of the order of weeks-to-months.

Code to search for this kind of sources has been under development within the LIGO Scientific collaboration (LSC) since the mid- to late 1990s. For S1–S4 the LSC continuous-wave search

group has developed several methods to search and set upper limits on signals from radio pulsars as well as to perform an all-sky search for unknown neutron stars [4, 5, 6, 7, 8, 9, 10]. So far none of the searches conducted provided a detection but upper limits were set on the gravitational wave emission and these results are summarized in this paper.

## 2. Search methods and results

In the S1 analysis [4], two techniques were used to set upper limits on gravitational wave emission from pulsar J1939+2134 (the fastest rotating known millisecond pulsar): a Bayesian time-domain method [11, 12] and a classical frequency-domain method. The main result from this S1 analysis was an upper limit on signals from pulsar J1939+2134 of  $h_0 < 1.4 \times 10^{-22}$  with 95% confidence.

For the LIGO S2 run, the time-domain search (which is more suitable for targeted sources) was expanded to include all well-known isolated pulsars with putative gravitational wave frequencies above 40 Hz [5]. Using the S2 data, multi-detector upper limits were set on gravitational wave emission from 28 pulsars including J1939+2134 and the Crab pulsar. The tightest limit on gravitational wave strain came from pulsar J1910–5959D with a 95% upper limit that  $h_0 < 1.7 \times 10^{-24}$ . At that time this was the lowest upper limit, for an astrophysical source, ever set by an interferometric gravitational wave detector. The same method is currently applied to analyze S3–S4 LIGO and GEO data [9]. The main change in this search since S2 has been the addition of pulsars in binary systems. Currently 93 pulsars are being searched of which 60 are binaries and 33 are isolated. The improved sensitivity of the detectors in S3–S4 promise to give interesting results for several sources. For the Crab pulsar, we should be within a factor of a few of the spin-down based upper limit. Moreover, for S5, expectations for the Crab would be that within a year we would beat the spin-down limit.

The frequency-domain statistical technique used in the S1 analysis is currently being used for broad all-sky searches for unknown sources and for a rotating neutron star in a binary system. In fact, this search has been the test-bench for the core science analysis that the *Einstein@home* [10] project is carrying out. *Einstein@home* is a public distributed computing project that the LSC has been operating since February 2005, built using the Berkeley Open Infrastructure for Network Computing (BOINC). Members of the general public can easily install the software on their personal computer. When otherwise idle, their computer downloads data from *Einstein@home*, searches it for pulsar signals, then uploads information about any candidates. Another example of the coherent frequency-domain technique is [8] which uses S2 data in coincidence from two of the LIGO detectors to perform two different searches: (i) for signals from isolated sources over the whole sky and the frequency band 160–728.8 Hz using 10 h of data, and (ii) for a signal from the Low-Mass X-ray Binary Scorpius X-1 over orbital parameters in the frequency bands 464–484 Hz and 604–624 Hz using 6 h of data.

Future continuous wave searches will involve searching longer data stretches (on the order of months to years) for unknown sources over a large parameter space. It is well known that the computational cost of coherent techniques for searches of this type is absolutely prohibitive, thus hierarchical methods have been proposed [13, 14, 15, 16], where coherent and incoherent search stages are alternated in order to identify efficiently statistically significant candidates. An essential step towards the actual implementation of a “hierarchical pipeline” for production analysis is the thorough investigation and characterization of its building blocks – the coherent and incoherent stages – over a large parameter space and on actual data sets; in fact the optimal sensitivity can be ultimately achieved through careful tuning of a variety of search parameters that are difficult to determine on pure theoretical grounds, including the choice of thresholds at each stage, the different tilings of the parameter space, the quality cuts in the data and the choice of coincidence windows.

In [7] we report results obtained by applying for the first time an incoherent analysis to the data collected during the S2 run. The search method is based on the Hough transform, which is

a computationally efficient and robust pattern recognition technique. We apply this technique to perform an all-sky search for isolated spinning neutron stars using the two months of data. The main results of this paper are all-sky upper limits on the strength of gravitational waves emitted by unknown isolated neutron stars on a set of narrow frequency bands in the range 200–400 Hz. Our best 95% frequentist upper limit that we obtain in this frequency range is  $h_0 < 4.43 \times 10^{-23}$ . Based on the statistics of neutron star population with optimistic assumptions, this upper limit is about 1 order of magnitude larger than the amplitude of the strongest expected signal, but with 1 yr of data at design sensitivity for initial LIGO, we should gain about 1 order of magnitude in sensitivity, thus enabling us to detect signals smaller than what is predicted by the statistical argument mentioned above.

Other incoherent techniques, such as “stack-slide” [14] or “power-flux” as well as the Hough transform [17], are used by the LSC continuous-wave search group to analyze S4 data. All of them use, in some way, the power from the Fourier transforms of short stretches of data, which are added in a way that compensates for the Earth’s motion and the pulsar’s spin-down during the observation period. These analyses will provide us with the first thorough understanding and characterization of such approaches and allow us to place upper-limits on regions of the parameter space that have never been explored before.

Future searches, using sophisticated hierarchical analysis techniques, together with the computing power of *Einstein@home* will allow the deepest pulsar searches, and thus initial LIGO at full sensitivity will have some chance of observing a continuous gravitational wave signal.

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