Searches for continuous gravitational waves with LIGO and GEO600

M. Landry for the LIGO Scientific Collaboration

LIGO Hanford Observatory, Richland, WA 99352

Abstract.
Current searches for astrophysically generated gravitational waves include the ground-based interferometers GEO600 and LIGO. The sensitive band of the detectors is at audio frequencies, from a few tens of Hz to several kHz. We report on efforts to search the data from these detectors for gravitational waves from spinning compact objects such as neutron or quark stars.

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INTRODUCTION

Gravitational waves are distortions in the space-time metric predicted by Einstein's General Theory of Relativity. Current searches for astrophysically generated gravitational waves include the ground-based interferometers GEO600 and LIGO. The detectors sensitive band includes audio frequencies from a few tens of Hz to several kHz. Compact objects such as neutron or quark stars are anticipated to radiate gravitational waves, albeit weakly, at these frequencies. Given the weakness of a signal, long stretches of data (months to years) must be analyzed in order to draw it out from the noise floor of a detector. Emission mechanisms include nonaxisymmetric distortions in the solid part of the star (signal at twice the rotation frequency f_r), free precession (signal at f_r), and fluid r-modes (signal roughly at $4f_r/3$).

Here we briefly overview the efforts of the LIGO Scientific Collaboration to analyze data from the LIGO and GEO600 detectors for evidence of continuous gravitational waves. We note the detectors, the expected signal behaviour, and the data analysis methods. Observational results of the searches are available at (`http://ligo.org/`) and references herein.

Detectors

The Laser Interferometer Gravitational Wave Observatory (LIGO) [1] is composed of two sites, LIGO Livingston (Louisiana, LA) and LIGO Hanford (Richland, WA). A single four-km power-recycled Michelson with Fabry-Perot arm-cavities (denoted L1) occupies the Livingston vacuum envelope, while 2 similar detectors (four-km and two-km machines, denoted H1 and H2) occupy the Hanford vacuum. The GEO600 machine [2] is a 600m folded Michelson interferometer located in Hannover, Germany. The analyses of data from these gravitational wave observatories are under the auspices of the LIGO Scientific Collaboration (LSC).

Figure 1 shows the progression of strain sensitivities of the LIGO interferometers. Curves are strain-equivalent noise output of the gravitational wave channel of the most sensitive interferometer during each science run, S1 (2002), through to the present S5 run. The black curve is the design noise curve (science requirement), in which sensitivity is limited at low frequencies by seismic noise, middle frequencies by thermal noise of test masses and suspension systems, and at high frequencies by the shot noise of the laser. Evident in the strain curves are stationary and quasi-stationary discrete line noise sources such as 60Hz and harmonics from power lines, ∼345Hz and harmonics from test mass recoil due to suspension wire violin modes, injected calibration lines, and internal resonances of suspended optics such as beam splitters and test masses.

Sources

Spinning compact objects such as neutron or quark stars should be a source of continuous gravitational waves (CW) in the audio band. Quasi-sinusoidal gravitational waves detected from pulsars would be Doppler modulated by relative motions of the detector and star, and amplitude modulated by the sweeping of the detector beam pattern (variations in detector sensitivity as a function of position) across the sky. These modulations provide an effective filter to match against data when searching for a signal, but dramatically increases the number of templates one must search.

The quasi-sinusoidal gravitational wave incident on an interferometric detector will produce a strain response of

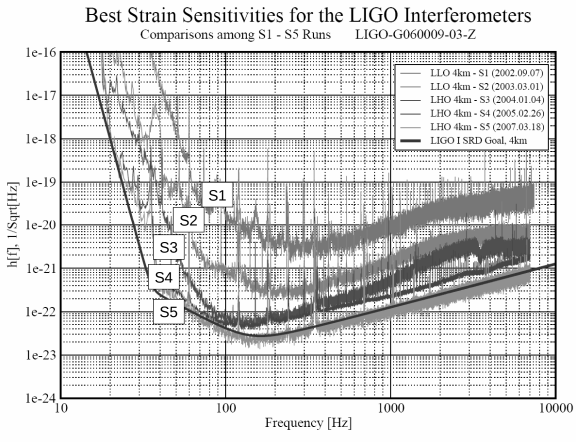

FIGURE 1. The progression of strain sensitivities of LIGO interferometers during science runs S1 through S5, compared to the design (science requirement, or SRD) goal.

the form

$$\begin{aligned} h(t) = \quad & A_+ F_+(\psi,t)\cos[\Phi(t)+\Phi_0] \quad + \\ & A_\times F_\times(\psi,t)\sin[\Phi(t)+\Phi_0] \quad , \end{aligned}$$

where $h(t)$ is the strain, A_+ and $A_\times$ are the amplitudes of the plus and cross polarizations of the gravitational wave, F_+ and $F_\times$ are the respective response functions (or antenna patterns) of the detector, ψ is the polarization angle, and Φ is the gravitational wave phase, with Φ_0 the initial phase [3].

DATA ANALYSIS METHODS

Targeted searches

Known pulsars are targeted in searches for gravitational waves at twice the spin frequency of the star. Radio timing data are employed to construct templates that predict the phase evolution of an expected gravitational wave signal. Searches performed on LIGO/GEO data from the LSC third and fourth science runs on 78 radio pulsars [4] found no gravitational wave sources, hence upper limits were set. For this analysis, radio timing was provided by the Jodrell Bank Pulsar Group (M. Kramer and A.G. Lyne).

Searches for continuous waves over a wider parameter space than a single template are underway on specific, interesting objects of known sky position such as the Crab pulsar and the supernova remnant Cas A. Furthermore, data from LIGO's second science run was used to search the LXMB Sco-X1 [5], and plans to search other LMXBs are under development. These searches are fully coherent (see the $\mathscr{F}$-statistic method, below), and the parameter space includes both f and $\dot{f}$. A targeted area search of the galactic center will be launched soon.

All-sky searches

All-sky, blind searches for gravitational waves from unknown pulsars are computationally limited. The computational cost increases rapidly with observation time T since the number of templates a search must cover scales at T^5 for a search over sky position, frequency, and the frequency's first time derivative, while the search sensitivity scales as only $T^{1/2}$. The addition of orbital parameters in the case of binary searches, or higher derivatives for younger sources add powers of T. The computational challenge requires distributed computing and optimal search methods. The best sensitivity can be achieved by a hierarchical search, in which data is passed by layers of both coherent and semi-coherent search algorithms.

Coherent methods

Wide parameter space, fully coherent analyses of LIGO and GEO data [5] are made by matched filtering in the frequency domain. The optimal detection statistic (maximum likelihood) is the so-called $\mathscr{F}$-statistic, as described in ref [3].

All-sky coherent searches are made over large parameter spaces including frequency (typically the most sensitive band of the instrument, from 50-1500Hz), spindown, and all sky positions. Due to computational constraints, the stretches of data analyzed coherently are limited to approximately tens of hours, (e.g. 30h for the coherent searches of the fourth science run, from several interferometers), although many such segments are analyzed and compared.

Semi-coherent methods

The LSC has three semi-coherent search algorithms (Powerflux, Stackslide and Hough transform) that take short Fourier transforms (SFTs) of data as input, account for Doppler shifts and spindown, and then form sums over power (or weighted 1's and 0's in the case of Hough). [6]. The sums are weighted according to the antenna patterns F_+ and $F_\times$ and the noise.

While intrinsically not as sensitive as fully-coherent methods, these semi-coherent algorithms are faster computationally, typically allowing the full dataset from a given science run to be analyzed, resulting in comparable sensitivity to coherent analyses. The Powerflux routine has been used as a fast first-review of data from the fifth science run S5.

Hierarchical methods and Einstein@Home

Built atop the Berkeley Open Infrastructure for Network Computing, or BOINC, Einstein@home (`http://einstein.phys.uwm.edu/`) provides roughly 70 TFlops of distributed computing resources for LSC CW searches. Over 55,000 users actively contribute CPU time to the project, while more than three times that number have contributed to searches. The current CW search running under Einstein@home is a hierarchical one employing interleaved passes of the coherent $\mathscr{F}$-statistic algorithm and the semicoherent Hough transform algorithm. Einstein@home searches to date have been all-sky ones, broad-band in frequency, for emission from unknown neutron stars. Future distributed searches may target smaller, interesting parameter spaces.

RECENT RESULTS

Recent results for searches of continuous gravitational waves with LIGO and GEO600 appear in Refs. [4, 5, 6], and at `http://einstein.phys.uwm.edu/`. No gravitational waves have been observed, and upper limits on putative sources are set. These analyses make use of data from LSC science runs two (S2) through four (S4). Sensitivities of these measurements are in part limited by the length of the early runs (weeks to months).

In addition, LIGO's 5th Science run recently completed, successfully achieving the goal of running at initial design sensitivity and collecting one year of triple-coincident data between the three LIGO interferometers. Several publications with analysis results for continuous gravitational-waves using data from this run are in preparation.

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