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Searching for gravitational waves from binary inspirals with LIGO

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Abstract
We describe the current status of the search for gravitational waves from inspiralling compact binary systems in LIGO data. We review the result from the first scientific run of LIGO (S1). We present the goals of the search of data taken in the second scientific run (S2) and describe the differences between the methods used in S1 and S2.

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1. Introduction

The Laser Interferometer Gravitational Wave Observatory (LIGO) [1] has completed three science data taking runs. The first, referred to as S1, lasted for 17 days between 23 August and 9 September 2002 [2]; the second, S2, lasted for 59 days between 14 February and 14 April 2003; the third, S3, lasted for 70 days between 31 October 2003 and 9 January 2004. During the runs, all three LIGO detectors were operated: two detectors at the LIGO Hanford observatory (LHO) and one at the LIGO Livingston observatory (LLO). The GEO detector in Hannover, Germany operated during S1 and in the latter part of S3 from 30 December 2003 to the end of the run. The detectors are not yet at their design sensitivity; however, the detector sensitivity and amount of usable data have improved between each data taking run. The noise level is low enough that searches for coalescing compact binaries are worthwhile and since the start of S2, these searches are sensitive to extra-galactic sources.

The analysis of the LIGO data for gravitational waves from coalescing neutron star binaries has been completed for S1 [3] and S2 [4], and is in progress for S3. Additional searches for binary black-hole coalescence and binary black-hole MACHOs in the galactic halo are underway using the S2 and S3 data. Here we review the result of the S1 search and describe the scientific goals of the searches of the S2 data. We review the S2 binary neutron star search and highlight the differences between the methods used in S1 and those currently employed.

2. Results from the first LIGO science run

The S1 analysis for inspiralling neutron star binaries searched a total of 236 h of LIGO data from the 17 day run. Data from the GEO detector and the Hanford 2 km (H2) interferometer were not used in this analysis, since the sensitivity of these instruments was significantly less than the Hanford 4 km (H1) and Livingston 4 km (L1) interferometers. The additional data from these instruments would not have provided increased confidence in a detection or significantly decreased the upper limit on the rate. The amount of *double coincident data*, defined as data taken when both L1 and H1 were operating, was only 116 h during S1. The decision was therefore taken to also use *single interferometer data*, data taken when only one of the L1 or H1 interferometers was operating, to produce the upper limit. This meant that there were times in the analysis when a candidate event could not have been confirmed by coincidence, but the amount of data available for the upper limit was increased to 236 h.

The distance to which an interferometric detector is sensitive to gravitational radiation from a coalescing binary depends on the noise spectrum of the interferometer and the component masses of the binary system. To provide a standard measure of the range of a detector we choose the distance to which we can detect a pair of non-spinning *optimally oriented* $1.4M_\odot$ neutron stars at a signal-to-noise ratio $\rho = 8$. An optimally oriented binary is located directly above the z-axis of the detector, with the arms of the detector defining the x- and y-axes, and the angular momentum vector of the binary system is oriented parallel to the z-axis of the detector. In S1 the maximum distance of L1 was 176 kpc and the maximum distance of H1 was 46 kpc. The interferometers were sensitive to inspirals in the Milky Way and the Magellanic Clouds.

No double coincident candidates were found in the S1 data. The loudest inspiral trigger found had a signal-to-noise ratio $\rho = 15.9$ in L1 detector. Further analysis of this event showed that it was due to a photodiode saturation and not a gravitational wave. In addition the next nine loudest events from the interferometers were also examined. We investigated the behaviour of the signal-to-noise and χ^2 near the inspiral trigger. We also examined the time frequency structure of the interferometer data associated with the trigger. None of the triggers examined were consistent with a binary neutron star inspiral signal of astrophysical origin; the triggers were consistent with instrumental misbehaviour. The analysis of these false triggers has suggested better tests of data quality prior to the analysis [5] used in S2 as well as additional signal-based veto methods [6], which will be used in future analyses.

The S1 binary neutron star search set an upper limit of $R_{90\%} < 1.7 \times 10^2$ per year per Milky Way Equivalent Galaxy (MWEG) with no gravitational wave signals detected. Details of this analysis can be found in [3].

3. Analysis goals for the second LIGO science run

Figure 1 shows the typical sensitivity of the LIGO interferometers during S2. Both the average range and the duty cycle of the interferometers have improved since S1. The average distance

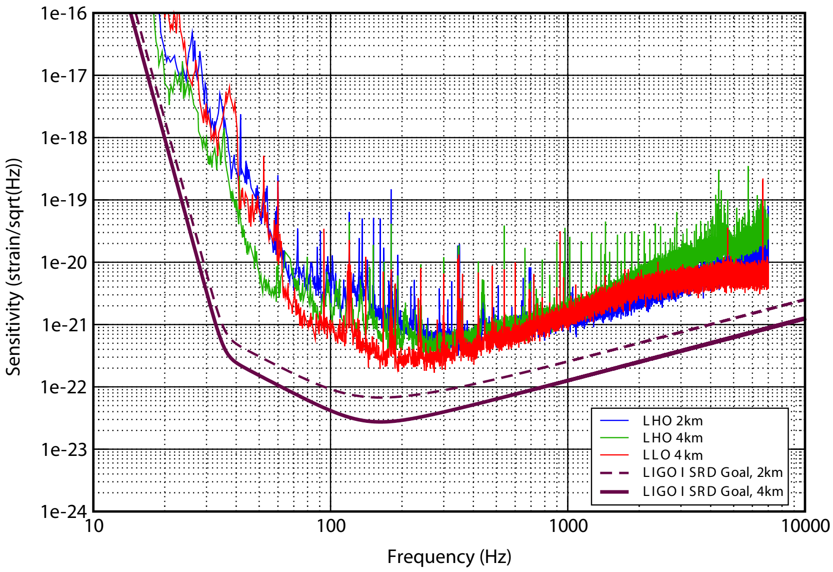

Figure 1. Typical sensitivities of the three LIGO interferometers during the second LIGO science run [7] shown as strain amplitude spectral density, $\tilde{h}/\sqrt{\text{Hz}}$. The smooth solid curve shows the design sensitivity (SRD Goal) of the 4 km interferometers and the smooth dashed curve shows the design sensitivity of the 2 km interferometer.

(This figure is in colour only in the electronic version)

to the optimally oriented binary described in section 2 is 1.81 Mpc for L1, 0.90 Mpc for H1 and 0.60 Mpc for H2. This increase in range means that the detectors are now sensitive to binary inspirals in Andromeda as well as the Milky Way and Magellanic Clouds. There is also some sensitivity to the galaxies M33, M32 and M110. This is a significant improvement over S1. A further increase in sensitivity and population is expected in the S3 data.

The increase in the amount of time when the data were suitable for analysis has allowed us to restrict the S2 analysis to times of double and triple coincident data. We are pursuing three different searches in the S2 data.

3.1. Binary neutron stars

We continue to search for gravitational waves from inspiralling binary neutron stars with component masses in the range 1–3$M_\odot$. The scientific goal of the data analysis in S2 is the detection of a gravitational wave from a coalescing binary neutron star system. In the absence of a detection, the population models available allow us to place upper limits on the rate of inspiralling compact binaries in the universe. The non-spinning binary systems that we search for have well-modelled waveforms using the second-order post-Newtonian approximation [8]. It is expected that spin does not significantly decrease the detection efficiency of these systems. We describe this search in more detail in section 4.

3.2. Non-spinning binary black holes

As mentioned above, the sensitivity of the inspiral search depends on the masses of the objects in the binary system. For the binary system of component masses m_1 and m_2, the signal-to-noise ratio scales with the *chirp mass*, $\mathcal{M} = M\eta^{3/5}$. Here $M = m_1 + m_2$ is the total mass of the binary and $\eta = m_1 m_2/M^2$. The scaling is approximately $\rho \propto \mathcal{M}^{5/6}/d$ where d is the distance to the binary [9]. This means that if an optimally oriented binary described above consisted of a pair of $10M_\odot$ black holes then it would produce signal-to-noise ratio 8 at a distance of 9.32 Mpc, rather than at a distance of 1.81 Mpc for a pair of $1.4M_\odot$ neutron stars. We therefore wish to pursue a search for gravitational waves from inspiralling binary black holes. For systems with a total solar mass above $6M_\odot$ the waveforms used in the binary neutron star search become unreliable. The post-Newtonian expansion begins to break down as the orbital velocity becomes relativistic. Several possible waveforms have been suggested for detection of gravitational waves from binary black holes [10]. Bounnano, Chen and Valisineri (BCV) have proposed a *detection template family* (DTF) of waveforms [11] that can be used to search for several classes of binary black-hole waveforms in a single search. The goal for S2 is to use the non-spinning BCV DTF waveforms to search for the gravitational radiation from binary black holes. The effect of spin can be significant for binary black-hole systems; however, here we restrict ourselves to non-spinning binaries for simplicity. A search for spinning black-hole binaries is in the early stages of development.

3.3. Binary black hole MACHOs

Observations of gravitational microlensing of stars in the Magellanic Clouds suggest that between 8% and 20% of the galactic halo is composed of a population of massive astrophysical compact halo objects (MACHOs) of mass between 0.15 and $0.9M_\odot$ [12]. It has been suggested that if these MACHOs are primordial black holes (PBHMACHOs) then some fraction of the PBHMACHOs may be in binary systems and could be detectable by ground-based interferometers such as LIGO [13]. Although these binaries are a speculative source, modelling of their formation in the early universe suggests a detection rate significantly higher than that of binary neutron stars [14]. The second-order post-Newtonian waveforms used in the binary neutron star search provide excellent template for these PBHMACHO binaries; the low mass of these systems means that LIGO is sensitive to a much earlier stage of inspiral when the orbital velocity is low. We will search for these systems and, in the absence of detection, place an upper limit on the rate using population models obtained from galactic halo densities.

4. S2 binary neutron star search

We have made several modifications to the binary neutron star data analysis pipeline since the S1 analysis. In the S2 analysis we consider only coincident interferometer data; a total of 355 h of data has been used for the analysis. This consists of 231 h of triple coincident data when all three LIGO interferometers were operating, 92 h of data where only L1 and H1 were operating and 31 h when only L1 and H2 were operating. We select a subset (approximately 10%) of the data to be used as a *playground*. This is used to tune the various thresholds in the analysis pipeline. To ensure that the playground is representative of the entire run, we select 600 s of data every 6370 s as playground data [15]. In the absence of a detection, we can set an upper limit on the rate of inspirals in the universe using data not in the playground [16]. Excluding the playground ensures that we do not introduce a statistical bias into the upper limit by tuning on data that are used to produce the limit. We do not exclude the possibility of a detection in the playground data.

In order to avoid the possibility of correlated noise sources affecting the background rate estimation, we chose not to use the data when only the H1 and H2 interferometers were in operation. There data, as well as the discarded single interferometer data, will be used in coincidence with data from the TAMA detector in a search for galactic inspiralling binaries. In this section we describe the methods employed in the S2 binary neutron star search.

4.1. Inspiral trigger generation

We search for inspiral signals in the LIGO data with a matched filtering [17] algorithm implemented in the *findchirp* package [18] of the LIGO/LSC Algorithm library [19]. The LIGO data are recorded at a sampling rate of 16 384 Hz. The highest frequency of gravitational radiation that we are searching for is approximately 2200 Hz and so we resample the data to 4096 Hz for the matched filtering. An eighth-order Butterworth filter was applied to the interferometer data which attenuated the signal by 10% at 100 Hz. This prevented numerical corruption of the power spectral estimate due to large power in the LIGO noise curve at low frequencies. Initial analysis of the data from the L1 interferometer discovered that a large non-stationary noise source at around 60–70 Hz was producing an excessive number of inspiral triggers. A low frequency cutoff was applied in the frequency domain by setting the data to zero at frequencies below 100 Hz. The shape of the noise power spectra was such that this did not produce a significant loss in inspiral range.

Data are analysed in 2048 s *analysis chunks* consisting of fifteen 256 s *analysis segments* which are overlapped by 128 s. A median power spectrum is computed for each of these analysis segments; for each frequency bin, the median value of the 15 power spectra is used to calculate the average power spectrum used in the matched filter. A *template parameter bank* is used to generate second-order post-Newtonian templates in the frequency domain using the stationary phase approximation to the inspiral signal. For a given template and analysis segment we construct the signal-to-noise ratio, ρ, and search for times when this exceeds a threshold, $\rho > \rho^*$. If this happens, we construct a template-based veto, the χ^2 veto [20]. Small values of χ^2 indicate that the signal-to-noise was accumulated in a manner consistent with an inspiral signal. If the value of the χ^2 veto is below a threshold, $\chi^2 < \chi^{2*}$, then an inspiral trigger is recorded at the maximum value of ρ. For a given template multiple triggers can be recorded in a segment. The triggers are clustered so that distinct triggers are separated by at least the length of the template. Each analysis segment is filtered through all the templates. It is possible for multiple templates to trigger at same time. Details of the template banks passed to the trigger generation code are described in the following section.

4.2. Data analysis pipeline

The interferometer operators, in consultation with scientific monitors present at the observatory during data taking, flag times when the interferometers are in stable operation and the data are suitable for analysis. Further studies of the raw data yield a series of *data quality cuts* that are used to exclude anomalous data from the inspiral analysis [5]. We have excluded times when (i) servo controls in the L1 interferometer were set incorrectly, (ii) calibration information is unavailable for the analysis, (iii) there are photodiode saturations, (iv) data have invalid time stamp information and (v) the noise in the H1 interferometer is significantly larger than average. In general, the interferometer is considered to be malfunctioning during these times with the exception of (i) and (ii) which are due to operator error. In the case of (v), we ensure that the increased noise is not due to the presence of an inspiral signal in the data by only excluding times when the noise is excessive for more than 180 s, which is significantly longer that our longest inspiral signal of 3.7 s.

As can be seen from figure 1 and the average sensitivity during S2, the range of the L1 detector is approximately twice that of the H1 detector, which is larger than that of the H2 detectors. At all times during the run L1 is more sensitive than H1 and H1 is more sensitive than H2. We use this and the fact that we demand that a trigger be present in multiple interferometers to construct a *triggered search pipeline*. This allows us to save a significant amount of computational effort during the search, without reducing the detection efficiency. Here we illustrate the method of the triggered search for two interferometers. Further details of the triggered search pipeline for multiple interferometers can be found in [4].

For each analysis chunk a template bank is generated for the L1 detector for binary neutron stars with component masses between 1.0 and $3.0 M_{\odot}$, as described in [21]. The *minimal match* of the bank is chosen to be 0.97. A random inspiral signal lying in the space of the bank would lose no more than 3% of the signal-to-noise ratio due to mismatch between the signal and the nearest template. We filter each L1 analysis chunk through the corresponding bank to generate inspiral triggers. We then select each template from the L1 bank that produced one or more inspiral triggers to construct a *triggered bank*. The triggered bank, which is a subset of the original template bank, is used to filter the data from the less sensitive interferometer (e.g. the H1 detector) to produce a second list of inspiral triggers. We demand coincidence between triggers from the different interferometers, as described below, to produce the list of *coincident triggers*. We apply instrumental vetoes to this list of coincident triggers to exclude triggers that are due to known instrumental or environmental artefacts in the data, as described in [5]. Any surviving triggers are considered to be the list of candidate inspiral triggers from the analysis.

To perform the triggered search pipeline on the full data set, we constructed a directed acyclic graph (DAG) that described the work flow. The DAG is executed using the Condor high throughput computing system [22] on the UWM and Caltech clusters.

4.3. Trigger coincidence

For a trigger to be considered coincident in two interferometers, we demand that it is observed in both interferometers within a temporal coincidence window δt. Monte Carlo analysis with simulated signals suggests that we can measure the time of a trigger to within 1 ms, so we demand $\delta t = 1$ ms if the interferometers are located at the same observatory. If the detectors are not co-located, we allow for the 10 ms light travel time between the LIGO observatories by demanding $\delta t = 11$ ms. We also demand that the waveform of the triggers are consistent by requiring that the two mass parameters, m_1 and m_2, of the binary are identical.

We now consider an amplitude cut on the signals. The Livingston and Hanford detectors are not co-aligned. There is a slight misalignment of the detectors due to the curvature of the earth and so the antenna patterns of the detectors differ. This causes the measured amplitude of a gravitational wave to differ between the sites. In the extreme case, it is possible for a binary to be completely undetectable by the L1 detector, but still detectable by the H1 and H2 detectors. For a given inspiral trigger, we measure the *effective distance* of the binary system. This is the distance at which an optimally oriented binary would produce the observed signal-to-noise ratio. Figure 2 shows the ratio of effective distances between the two LIGO observatories for the population of binary neutron stars considered in the S2 analysis. The significant variation of the effective distance precludes using a naive test for amplitude coincidence. It is possible to obtain information about sky position from time delay between sites to construct a more complicated amplitude cut, but this has not be used in the S2 analysis.

In the case of triggers from the H1 and H2 interferometers that are coincident in time and mass, we apply an amplitude cut that tests that the effective distance of the triggers is coincident given the relative sensitivity of the detectors, while allowing for error in this measurement which is determined by Monte Carlo simulations. When testing for triple coincident triggers

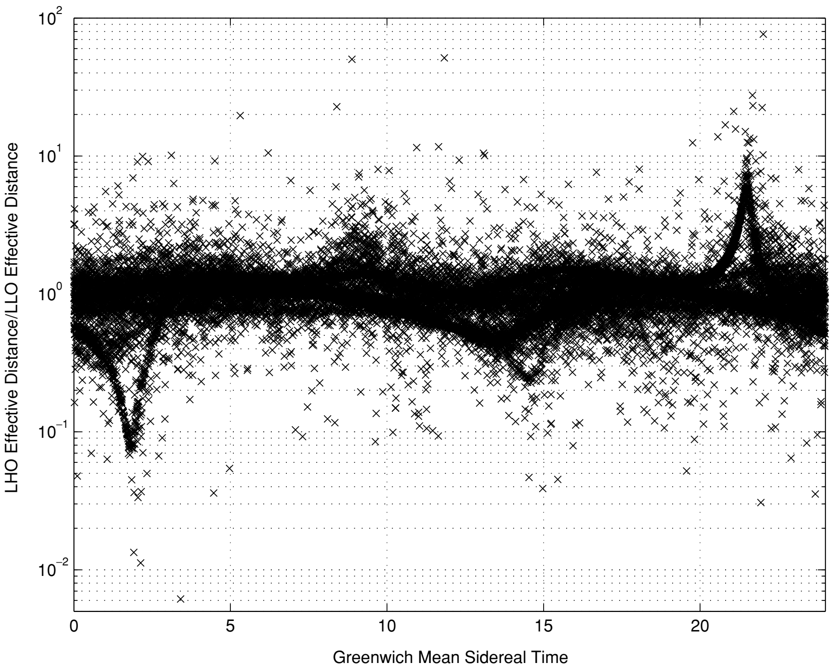

Figure 2. The ratio of the known effective distance of an injected signal in the Hanford Observatory (LHO) to the known effective distance of an injected signal in the Livingston Observatory (LLO) as a function of Greenwich Mean Sidereal Time. The slight misalignment of the interferometers at the two different observatories due to the curvature of the Earth causes the antenna pattern of the detectors to differ. As a result the distance at which a binary system appears is different in each detector, even in the absence of noise. The ratio of effective distances can be significant, so this precludes the use of an amplitude cut when testing for inspiral trigger coincidence between different observatories.

we accept triggers that are coincident in the L1 and H1 detectors that are *not* present in the H2 detector *if* the effective distance of the trigger is further than the maximum distance to which H2 is sensitive at the time of the candidate trigger. This maximum distance is dependent on the both the sensitivity of H2 at the time of the candidate trigger and the signal-to-noise threshold, ρ^*, chosen for H2.

As in the S1 analysis, the list of surviving candidate triggers is followed up by examining the raw gravitational wave data, auxiliary interferometer channels and physical environment monitoring channels to determine if the triggers are truly of astrophysical origin.

4.4. Background estimation

Since we restrict the S2 analysis to coincident data and require that at least two of the interferometers must be located at different observatories, we may measure a background rate for our analysis. After generating triggers for each interferometer, we slide the triggers from one observatory relative to the other observatory and look for coincidences between the shifted and unshifted triggers. The minimum slide length is chosen to be greater than the length of the longest filter (20 s) so any coincident triggers detected must be due to background and not astrophysical events. By examining the distribution of background events in the (ρ_H, ρ_L)

plane we can attempt to determine contours of constant false alarm rate in order to construct a combined effective signal-to-noise ratio for a coincident trigger [4].

4.5. Detection efficiency

In the absence of detection, we will construct an upper limit on event rate. To do this, we must measure the detection efficiency of the analysis pipeline to our population. A Monte Carlo method is used to measure this efficiency. We simulate a population of binary neutron stars [23] and *inject* signals from that population into the data from all three LIGO interferometers. The injection is performed in software by generating an inspiral waveform and adding it to interferometer data immediately after the raw data is read from the disc. We inject the actual waveform that would be detected in a given interferometer accounting for both the masses, orientation, polarization, sky position and distance of the binary, the antenna pattern and calibration of the interferometer into which this signal is injected. The effectiveness of software injections for measuring the response of the instrument to an inspiral signal is validated against *hardware injections* [24] where an inspiral signal is added to the interferometer control servo during operation to produce the same output signal as a real gravitational wave. The data with injections are run through the full analysis pipeline to produce a list of inspiral triggers. The detection efficiency of the pipeline, ϵ, is the ratio of the number of detected signals to the number of injected signals.

5. Conclusion

The S1 binary neutron star search is now complete [3]. No coincident gravitational wave candidates were found and an upper limit of $R_{90\%} < 1.7 \times 10^2$ per year per MWEG was set on the rate of inspiralling binary neutron stars. Results of the S2 binary neutron star search are currently under LSC review and will be available shortly. In addition to this we will soon be in a position to present results from the non-spinning binary black-hole search and the search for binary black-hole MACHOs in the galactic halo.

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