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Gravitational wave detectors: New eyes for physics and astronomy

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Abstract. Several interferometric gravitational wave detectors around the world are now starting to achieve better sensitivity to gravitational waves than ever before. We describe the prospects these detectors offer for physics and astronomy and review the rapid progress and the present status of the detectors' sensitivities. We also report the progress made by the LIGO Scientific Collaboration in analysing the data produced by the LIGO and GEO detectors during the Collaboration's Science Runs.

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1. Gravitational waves and gravitational wave detectors

The quest for gravitational waves is now becoming more exciting than ever before due to the progress achieved in the new interferometric techniques for their detection, making the direct observation of gravitational waves a plausible prospect in the near future.

Gravitational waves, as predicted by Einstein's theory of general relativity, would be produced by almost any system with time-varying mass quadrupole. The disturbances in the fabric of space-time would travel away from the source at the speed of light, and produce changes in the distance between freely falling masses, proportional to the distance between the masses. The strain in distances produced by a binary system of compact stars (neutron stars, black holes) in the last seconds before coalescence is $\sim 10^{-21}$ for systems 200 Mpc away [1], making the measurement of such small strains a difficult experimental enterprise.

Different search strategies for the detection are now taking place, all complementing each other in several ways. A network of resonant bar gravitational detectors has been looking for $\sim$1 ms bursts of gravitational waves (exciting their resonance frequencies near 1 kHz), exchanging data within the International Gravitational Event Collaboration (IGEC). The IGEC has recently published the results of joint operation during the years 1997–2000 [2]. The results are consistent with no observation of gravitational bursts, and set an upper limit on the rate of gravitational waves of <100 per year with Fourier component 2×10^{-21} Hz^{-1}, and <2 per year with Fourier component 10^{-20} Hz^{-1}.

There are several broadband interferometric gravitational wave detectors in operation and under construction in the world: the LIGO project in the US [3] has built two detectors, one 2 km long and another 4 km long, in the LIGO Hanford Observatory, and a third detector 4 km long in the LIGO Livingston Observatory. The Virgo project [4], a French–Italian enterprise, is building a 3 km detector in Cascina, Italy. The British–German GEO600 project [5] is running a 600 m long detector near Hannover, Germany. The Japanese TAMA300 team [6] has been running a 300 m long detector in Mitaka, near Tokyo, for several years now.

All of these detectors are getting close to their expected sensitivity, and some of them have already taken data and analysed it for setting upper limits on the strengths of gravitational waves in the frequency bands between 100 Hz and a few kHz. When reaching design sensitivity limited by fundamental noise sources (seismic noise, Brownian motion and shot noise), the frequency band will extend to frequencies as low as 10–40 Hz, and peak sensitivities in spectral density $3 \times 10^{-23}/\sqrt{\mathrm{H}z}$ (near 100 Hz).

The future holds even better prospects: there are plans to install 'advanced' LIGO detectors in the LIGO Observatories, taking advantage of technologies developed at many universities in the LIGO Science Collaboration, some of them tried by the GEO600 detector. These advanced detectors would have a sensitivity ten times better than the present detectors, and offer plausible prospects for many sources [7]. For binary neutron star systems, the advanced LIGO detectors would be able to detect the last few minutes before coalescence of systems at 300 Mpc or closer, with a predicted rate of $\sim$1 per day [8]; it is likely that these detectors will also allow the detection of black hole binary systems with ten solar masses or smaller. Systems with large black holes (like the ones at the centers of galaxies) would emit stronger signals, but sweeping a lower frequency range: this is where a space detector, with a long baseline, holds the best promise. The LISA project [9] is a joint NASA–ESA enterprise that could take off as early as 2011; it is in the advanced designing stages of an interferometric detector with three satellites in a heliocentric orbit, in the same orbit as the Earth (but 20° behind the Earth). The sources of gravitational waves for this detector would be plentiful [7], from such exciting sources as supermassive black holes, and smaller objects 'falling' into a black hole. Galactic binary white dwarf systems would be detected in such numbers that their signals may not be resolved, forming instead a stochastic background, similar to more traditional 'noise' sources like shot noise and Brownian motion.

In this article, we will describe the latest results from the LIGO Scientific Collaboration, which has begun taking data with the three LIGO detectors and the GEO600 detector. Although the detectors are not working yet at their goal sensitivity, they have better sensitivity than previous detectors and work in some frequency bands never explored before. Even though the likelihood of a detection from known or understood sources is very low, the data available make the search for gravitational waves a very worthwhile enterprise: we need to test our data analysis methods on real data; we can use the data to set upper limits on the different plausible kinds of gravitational waves; and, most importantly, we begin to open 'new eyes' for physics and astronomy.

2. Science Runs and progress in sensitivity

The LIGO Scientific Collaboration gathered data for 17 days in September 2002 during its first Science Run (S1). Since then, the Collaboration has taken data in two other two-month long Science Runs: S2 in February–April 2003 and S3 in October 2003–January 2004. The S1 run used the GEO600 detector and the three LIGO detectors [10]. During S2, the GEO detector did not run, and the TAMA detector took data in coincidence. During the most recent Science Run, the GEO detector and TAMA were running part of the time. The GEO and LIGO data is analysed by the LIGO Scientific Collaboration; and the TAMA data is analysed by the TAMA project team, but there are plans underway to combine results, showing that the era of an international network of detectors is becoming a reality.

During S1, the GEO detector used a power-recycled Michelson configuration, and used a folded arm configuration to achieve an effective arm length of 1200 m. Since then, the GEO detector has made significant progress towards its final configuration, using an output mirror for signal-recycling, and achieved significantly improved sensitivity for S3. The LIGO detectors have been operating with their final optical configuration, a power-recycled Michelson with Fabry–Perot cavities in their arms for all the Science Runs. The LIGO detectors have different sensitivities in each of the Science Runs, as shown in figure 1 for S1. However, their sensitivities improved very significantly from one science run to the next, as shown in figure 2.

The duty cycle of the detectors, or fraction of time the detectors are operational, is also different for different instruments: GEO, having an alignment control system fully implemented, achieves an impressive 98%; the LIGO Hanford detectors had duty cycles varying between 58% and 73% in all three Science Runs; the LIGO Livingston has a considerably lower duty cycle, varying between 22% and 47%, mostly due to local human activity nearby. A new seismic isolation upgrade is being installed in 2004 in the LIGO Livingston Observatory to improve the duty cycle, and to make seismic disturbances at both LIGO Observatories comparable.

One way to post a single figure of merit to qualify a noise spectrum in a gravitational wave detector is the maximum distance at which the signal emitted by a binary neutron star system, with average orientation in the sky and of its orbit, is found with a high signal-to-noise ratio when analysing the data with matched templates [11]. Using this figure of merit, the LIGO detectors have improved from a maximum reach of 5 kpc with H2 in the last engineering run before S1, to 100 kpc with L1 (covering the galaxy) in S1, to 1 Mpc also with L1 (reaching Andromeda) in S2, to 6 Mpc with H1 (reaching several other galaxies) in S3.

3. Results from the first Science Run

The LIGO Scientific Collaboration has formed four 'search' groups, that develop and test algorithms to search for different kinds of gravitational waves: signals coming from inspiral sources (compact binary systems before coalescence); signals forming a stochastic background (from cosmological origin, early universe or from unresolved sources); signals originated as a continuous monochromatic wave by rotating stars; and short duration signals, or bursts, from sources such as supernovae explosions and collisions of compact stars. All groups have obtained results with the

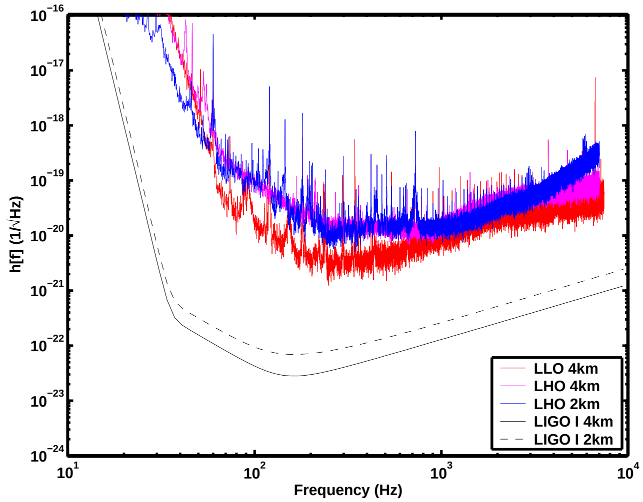

Figure 1. Typical power spectral densities of the noise measured in the three LIGO detectors during the S1 run.

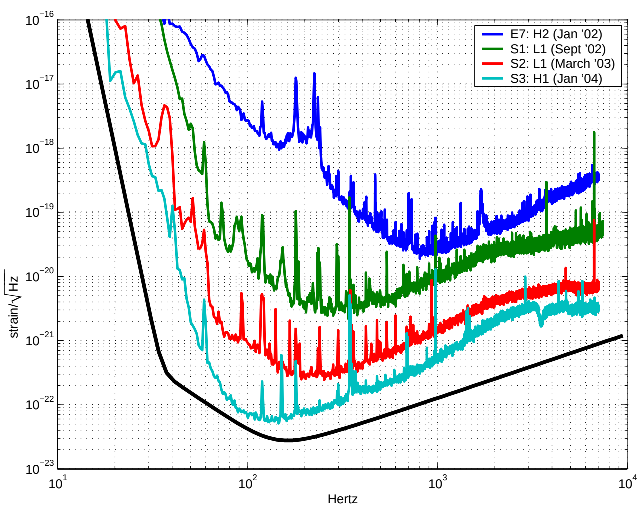

Figure 2. Examples of noise power spectra in the different Science Runs of the LIGO Scientific Collaboration.

data taken in the first Science Run, which have been published elsewhere [12–15], and we summarize in the following paragraphs.

3.1 *Inspiral signals from compact binary systems*

Compact binary systems with black holes, neutron stars, or white dwarfs will evolve with increasingly smaller orbits and smaller energies, until the systems get close enough to coalesce. The orbital evolution until some time before the final coalescence can be approximated using 'post-Newtonian' expansions of Einstein's equations, which are particularly accurate for binary neutron star systems. The binary system emits gravitational radiation predominantly at twice its orbital frequency, and this emission circularizes and shrinks the orbit, thus increasing the amplitude and frequency of the gravitational waves emitted. The wave-form has a 'chirp' character, with the coalescence happening for neutron stars at an orbital radius of 15 km, corresponding to gravitational waves of 1 kHz, so the signal will sweep through the detectors' band in the last seconds before coalescence.

With the data from the 17 day-long first Science Run for the two most sensitive detectors (the Livingston and Hanford 4 km interferometers), we have searched for wave-forms matching a second post-Newtonian approximation of gravitational waves emitted by binary neutron star systems. In principle, we could have seen signals from such systems in the Milky Way and even in the Magellanic Clouds, as proven with simulated injected signals in the data, although the predicted probability for such an event was very low: the predicted rate is about 1 event/2500 yr. Not surprisingly, no trigger with consistent masses and signal-to-noise ratio was found at both detectors within a 11 ms time window. Nonetheless, we used the results for the search using data at both detectors (even if not operating in coincidence) to set an observational upper limit [12] $\mathcal{R} < 1.7 \times 10^2$ events per year per Milky Way equivalent galaxy, with 90% confidence, on the coalescence rate of binary systems in which each component has a mass of 1–3 solar masses.

We defined candidate events in each detector as the data that matched a wave-form template with a threshold in signal-to-noise of 8, and a quality-of-fit threshold based on a non-centrally distributed, time-frequency, χ^2 parameter, corresponding to a χ^2/DOF threshold of 3.5 for a signal with SNR = 8 (however, the threshold is a function of the SNR of the candidate). Only candidates in each detector with high enough SNR and low enough χ^2 were kept, and then tested for coincidence.

The average distance at which an inspiral system with two 1.4 solar masses neutron stars in the optimal direction and orientation with respect to each detector would produce a signal-to-noise ratio of 8 was ~180 kpc for the Livingston detector, and ~50 kpc for the Hanford detector. There were hundreds of candidates with signal-to-noise ratio larger than 8 in the Livingston detector at times when the Hanford detector was also taking data, but no candidate corresponded to a possible source close enough to expect a signal-to-noise ratio larger than 8 in the Hanford detector. Thus, we had a background of event candidates that could not be confirmed by coincidence, either because the other detector was not operating, or because the source, if true, would have produced too weak a signal in the second detector. We used this background to set the observational galactic upper limit. The actual limit was determined by the loudest candidate, a trigger in L1 with SNR = 15.9 (when H1 was not operating). Upon further inspection, this candidate was determined to have been caused by a saturation in the photodiode used to detect the gravitational wave signal.

3.2 *Stochastic background*

A stochastic background of gravitational waves could be produced by cosmological sources from the early universe, or from many unresolved astrophysical sources.

There upper limits on stochastic background set by Big Bang nucleosynthesis are well below the initial LIGO detectors' sensitivities, but the data analysis for such sources is interesting in its own right as a direct observational upper limit. The spectrum of a stochastic background is usually described by a dimensionless quantity $\Omega_{\rm gw}(f)$, representing the energy density per unit logarithmic frequency due to gravitational waves, as a fraction of the critical energy needed to close the universe: $\Omega_{\rm gw}(f) = (f/\rho_{\rm c})\mathrm{d}\rho_{\rm gw}/\mathrm{d}f$. A flat, frequency-independent, isotropic, unpolarized, stationary and Gaussian spectrum $\Omega_{\rm gw}$ would produce a stationary, Gaussian strain-spectrum $S_{\rm gw}(f) \propto f^3$ in units of strain^2/Hz.

A stochastic background of gravitational waves could be detected with cross-correlation techniques using two or more detectors, assuming that the noise in the detectors is uncorrelated. A cross-correlation analysis was done for all three pairs of LIGO detectors, using data from the first Science Run. The expected signal overlap between a pair of distant detectors is a function of frequency: the signals between the Livingston detector and any of the Hanford detectors are not correlated at frequencies above a few hundred Hertz. The analysis for the LLO–LHO pairs was done in the band 40–314 Hz, and in the band 40–300 Hz for the LHO pair, excluding some frequency bins with known or possible correlations (such as harmonics of the power lines at 60 Hz).

The absence of instrumental correlations was proven to be a bad assumption for the two detectors in the Hanford Observatory: a strong, *negative* correlation was observed in their signals later traced to acoustical disturbances. The measured correlation between the LHO detectors and the Livingston detector were both consistent with zero correlation, and an upper limit was set assuming a Gaussian statistics with fixed rms deviation (with the rms deviation measured from the data). The best upper limit was obtained from the L1–H2 pair [13]: $\Omega_0 h_{100}^2 \leq 23 \pm 5$, with 90% confidence and with h_{100} being the Hubble constant in units of 100 km/s/Mpc. This limit is four orders of magnitude better than the previous direct limits set by interferometric detectors!

3.3 *Continuous wave sources*

Rotating compact stars emit gravitational waves at twice their rotation frequency if they have any quadrupolar moment, such as non-spherical distribution due to crust 'cracks' or 'mountains' on neutron stars. The known millisecond pulsars can be such sources and they make the search for gravitational waves they may be emitting particularly interesting because their position in the sky and their rotation frequencies are known. We used the data from all four detectors in the first Science Run to search for the fastest known pulsar, PSR J193+2134, with a rotation frequency of 642 Hz. An upper limit on the amplitude of gravitational waves emitted by this pulsar can be set from its spin-down rate, and the limit, $h_0 < 2 \times 10^{-26}$, is well below the limit the initial LIGO detectors will be able to set with one year of observation. However, the limit set by the data taken with the first Science Run is a direct limit, and the experience gained in this search can now be used to look for all known pulsars. Two independent methods were used, a frequency domain and a time domain method, used for 401 h of GEO data, 13 h of L1 data, 209 h of H1 data and 214 h of H2 data. The best result is obtained from the L1 detector, which had the best sensitivity. A frequentist upper limit [14] of $h_0 \leq (2.7 \pm 0.3) \times 10^{-22}$ with 95% confidence was obtained from the frequency domain analysis, derived from the statistic distribution of the h_0 parameter estimated from 60 s short Fourier transforms. A Bayesian upper limit [14] of $h_0 \leq (1.4 \pm 0.1) \times 10^{-22}$ with 95% confidence was obtained, also for L1, heterodyning the data at the known pulsar frequency, taking into account the motion of the detector on the Earth with respect to the source.

An upper limit on the gravitational wave amplitude emitted by the pulsar can also be interpreted as an upper limit on the neutron star's equatorial ellipticity. For an estimated distance of 3.6 kpc, the Bayesian limit $h_0 \leq \times 10^{-22}$ corresponds to an upper limit in ellipticity of 2.9×10^{-4} $(10^{45}$ g cm$^2/I_{zz})$. Both these limits are much higher than the limits set by the spin-down rate, but they are significantly better than the previous limits from direct observations on the same system. Similar limits for the ellipticity from a search of unknown pulsars may place interesting constraints on the interior magnetic fields or the existence of solid cores in neutron stars.

3.4 *Gravitational wave bursts*

Many sources of gravitational waves will produce 'bursts' of gravitational wave radiation that are not easily modeled, like the coalescence of compact binary systems (with neutron stars and black holes) or supernovae explosions. The search for these gravitational waves in a broadband detector like the interferometric detectors of the LIGO Scientific Collaboration need methods that are model-independent, qualitatively different from the ones used for inspiral sources or continuous waves (both well-modeled), and for stochastic background (assuming a background present at all times in the search). Several methods are being developed for these searches, and two methods were tried from the beginning to the end looking for coincident events in all three LIGO detectors during the first Science Run.

The search for gravitational bursts may be the oldest one in the field, since bar detectors have been looking for such events in their data for decades now with ever increasing sensitivity. However, the interferometric detectors truly open a new window for the observation of these events in frequency bands never explored before.

The search focused on bursts between 4 ms and 100 ms in the frequency band between 150 and 3000 Hz, and set a bound for the rate of such events detected in all three detectors of 1.6 events/day at 90% confidence level [15]. To interpret these results in terms of gravitational wave amplitudes, a source model is needed; in the absence of physical models, the data are interpreted in terms of the detection efficiency of simple wave-forms with Gaussian shapes, and since waves modulated with a Gaussian envelope, parametrized by their root-sum-square strain $h_{\rm rss}$. The sensitivity of the detectors in these units was between 10^{-19} and 10^{-17}strain/$\sqrt{\rm Hz}$ depending on the parameters of the wave-form.

Two different algorithms were used to identify gravitational wave candidates in each detector. One method set a threshold on the output of a differentiator linear filter applied to the uncalibrated, but prefiltered, data in the time domain, measuring in effect the 'slope' in the data. The parameters of this method were tuned to make it most sensitive to sine waves of ∼1 kHz. A second method was done in the time–frequency domain, looking for clusters in the time–frequency plane that are not consistent with noise. This method used an adaptive threshold, derived from its estimation of the expectations from measured noise in six minute intervals. From the set of triggers generated by each method for the three detectors, a temporal coincidence window and, for the time–frequency method, a frequency consistency cut was applied to select the gravitational wave candidates. The slope-measuring method had a 40 ms ringdown time associated with some impulsive events, so a 50 ms window was required to find the triple-coincident candidates. The time–frequency analysis has a time resolution of 125 ms, and based on simulated signals, a time window of no more than 500 ms was required. The frequency window determining consistency among triple-coincident candidates identified by the time–frequency method was 80 Hz. A clustering method was also used on the resulting triggers. A background rate for each method was estimated using time shifts between Livingston and Hanford data (to keep possible correlations between the Hanford detectors included in the background), to compare with the actual number of events that resulted from the search. However, the background estimate for the slope-measuring method was deemed unreliable, since the measured background changed on short time-scales due to the non-stationarity of the noise. The time–frequency method, using an adaptive threshold, had a more reliable background estimation that could be meaningfully compared with the actual measured rate.

Searching over a total of 35.5 h of data, five triple-coincident candidate events were found with the slope-measuring method, and six with the time–frequency method, although none of the events detected by one method were detected by the other. The background estimate for the time–frequency method was 10.1 ± 0.6 events.

The efficiencies of both methods to detect ad hoc Gaussian and sine-Gaussian wave-forms were measured, and together with the background estimate for the time–frequency method, we can draw an exclusion region in the $h_{\rm rss}$-rate plane as an upper limit. For 554 Hz, sine-Gaussians with a $Q = 9$ decay parameter, the upper limit on the rate is 2 events/day with $h_{\rm rss} > 10^{-17}$ strain/$\sqrt{\rm Hz}$.

4. Conclusions

Several papers have now been published on the results from the frist Science Run of the LIGO Scientific Collaboration using data from four interferometric detectors. There is already better data taken by the Collaboration in the second and third Science Runs, and all detectors are rapidly progressing in sensitivity. It is likely then that within a year the LIGO detectors will be working at their design sensitivity.

The VIRGO detector is also making progress and it has now successfully sent light through both the 3 km-long arms. There are plans for data exchange between the LIGO Scientific Collaboration and the TAMA detector as well as with VIRGO, when it begins taking data.

Gravitational wave bar detectors published results from a 3-year joint search, and also keep improving in sensitivity and data quality.

Although predicted rates from known astrophysical systems for all these detectors remain low, the window opened by new and better instruments keeps getting larger and clearer: we can now look for waves in different frequency bands, as also in the same frequency bands, with increasing sensitivity. Even in the absence of detection, the observational upper limits may begin constraining theories of gravitational wave sources in the near future.

More importantly, what has been proven is that the field of gravitational wave physics can work very fruitfully, taking advantage of better technology and of the opportunity of international collaboration. The projections for the future are very bright with advanced interferometric detectors and even space detectors: the starting time of these projects may likely be in the next decade and both of them have high predicted event rates for known sources.

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