Status of the LIGO detectors

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Abstract

All three LIGO gravitational wave detectors have reached their design
sensitivities. A sky-averaged detection range (SNR > 8) of more than 15 Mpc
for gravitational waves emitted from inspiral binary neutron stars with masses
of 1.4 $M_{\odot}$ has been achieved with the two 4 km instruments. The fifth LIGO
science run started in November 2005 and ended in September 2007. A full
year of triple coincidence data has been acquired. The duty cycle of a single
instrument was between 66% and 79%. Results from previous science runs are
presented.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

The LIGO gravitational wave detectors are Michelson interferometers which deploy arm
cavities and power-recycling [1, 2]. The light bounces an average of about 100 times in the
arm cavities enhancing the gravitational-wave signal by effectively increasing the arm length
of the Michelson [3]. Under normal running the anti-symmetric port of the beamsplitter
is operated on a dark fringe. This will return most of the light back towards the laser. A
partially transmitting mirror is installed in this path to form the power-recycling cavity [4]. If
its transmission is matched to the light losses in the main interferometer, all the light is lost
inside the interferometer and no power is returned to the laser. The power-recycling increases
the light power on the beamsplitter by about a factor of 40–70. The laser light is generated
by a solid-state Nd:YAG laser operating at 1064 nm and delivering 10 W of output power in
the fundamental mode [5]. Before the light is launched into the instrument it is stabilized in
frequency and amplitude and passed through a triangular ring cavity which serves as a spatial
mode cleaner. To isolate the optics (test masses) from disturbances introduced by motion of
the ground due to seismic and man-made activities and to allow for free movement of the test
masses in the gravitational wave frequency band, LIGO implements seismic isolation systems
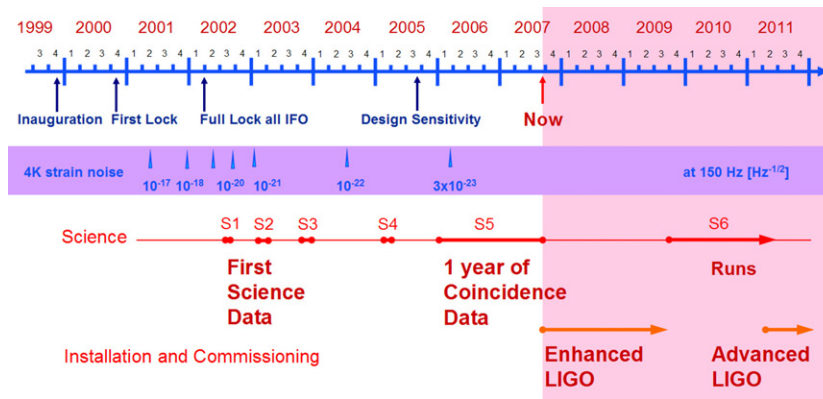
Figure 1. Time line of the LIGO project. Design sensitivity has been reached by the third quarter of 2005. The fifth science run has been finished on 30 September 2007 and work on Enhanced LIGO has started. Another long science run is planned before the start of installation and commissioning of Advanced LIGO in 2011.

[6] from which the mirrors are suspended by wires [7]. They form a coupled pendulum system with low eigenmode frequencies and high isolation at the frequencies above ∼1 Hz. Numerous servo loops are required to hold the cavities on resonance [8], to operate on a dark fringe, to stabilize the laser frequency and to automatically align the mirrors relative to the beam direction [9]. Most of these compensation networks are implemented using digital controls [10]. A data acquisition system is used to record the gravitational-wave signal, as well as a number of auxiliary channels to monitor the physical environment and the performance of the instrument.
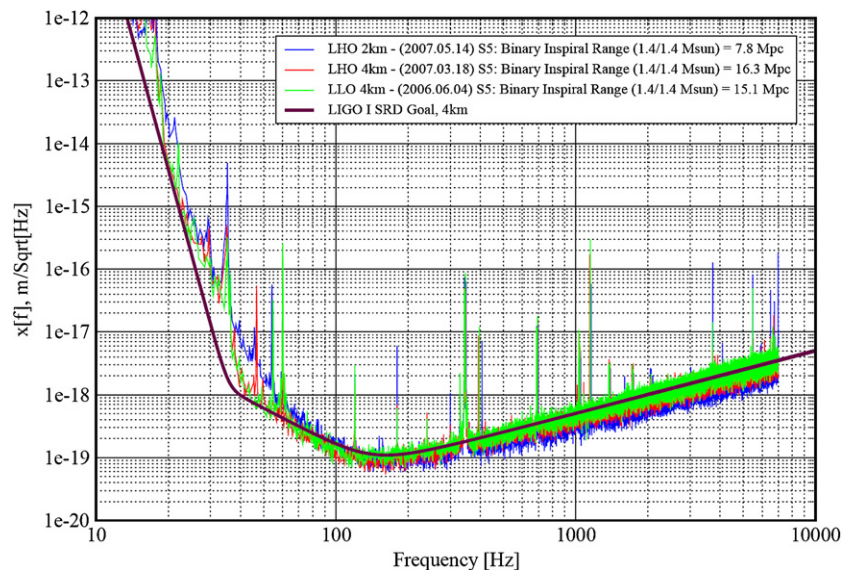
2. Context and overview

The LIGO project consists of three instruments located at two sites. At the LIGO Livingston Observatory a single 4 km instrument (L1) is operated, whereas at the LIGO Hanford Observatory both a 4 km instrument (H1) and a 2 km instrument (H2) are operated.

Figure 1 shows the time line of the LIGO project. It shows important milestones such as the inauguration, the first lock, the first time all interferometers were fully locked and the date the design sensitivity was reached. It shows a history of the LIGO science runs and indicates the improvements in sensitivity achieved over the same time. The fifth science run has just been finished and the current main effort is an enhancement project which will lead to a final science run with initial LIGO. Advanced LIGO is scheduled to start installation and commissioning in 2011.

3. Current sensitivity and noise budget

The current displacement sensitivities of the three LIGO instruments are shown in figure 2. The design sensitivity has been reached for all the three detectors. The strain sensitivity can be deduced by dividing by 4000 m and 2000 m for the 4 km and 2 km instruments, respectively.

The noise budget of the 4 km instrument at Hanford is shown in figure 3. The measured noise curve is denoted by DARM whereas the design sensitivity is denoted by SRD. The total contribution from all known noise sources is denoted by the dashed green line. At frequencies above about 200 Hz the instrument is limited by shot noise (Shot). Other noise sources such

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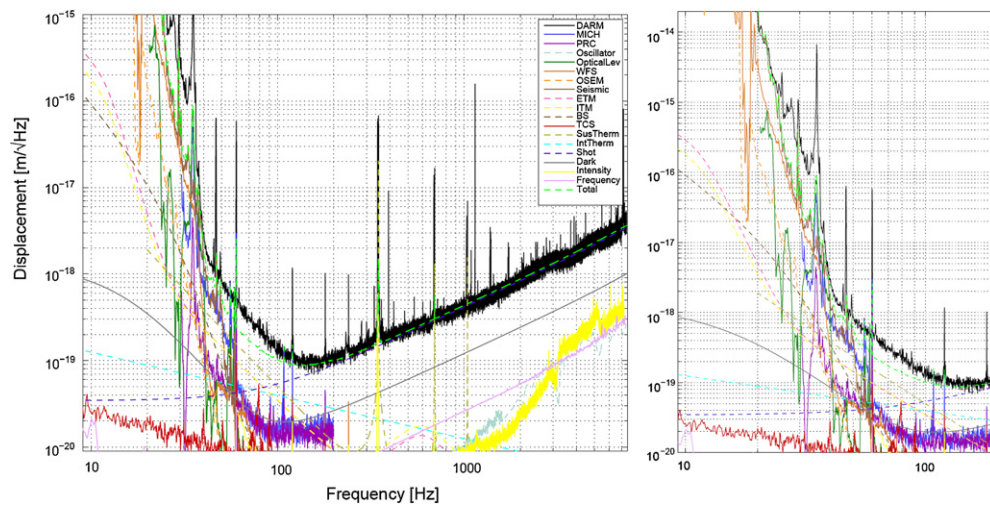
Figure 2. Current displacement sensitivity of the 2 km interferometer at Hanford (blue), the 4 km interferometer at Hanford (red) and the 4 km interferometer at Livingston (green). The dark smooth curve depicts the design sensitivity. All three instruments have clearly reached this goal for all frequencies above about 40 Hz. The legend also lists the astrophysical sky-averaged range to a 1.4/1.4 solar mass neutron star inspiral event assuming a signal-to-noise ratio of 8. Both 4 km instruments are at 15 Mpc or just above. The 2 km instrument is about half as sensitive (due to being half as long).

as dark noise (Dark) from the photodetectors and readout electronics, laser intensity noise (Intensity) and laser frequency noise (Frequency) are all well below the shot noise. At low frequencies numerous noise sources contribute to the measured noise spectrum: (i) the cross-couplings from auxiliary servo loops such as the Michelson length (MICH) and the power recycling cavity length (PRC), (ii) the local oscillator (Oscillator), (iii) the angular control loops with the optical levers (OpticalLev), the wavefront sensors (WFS) and the local sensing (OSEM), (iv) the remaining seismic excitation (Seismic), (v) the actuator noise from the end test masses (ETM), the input test masses (ITM) and the beamsplitter (BS), (vi) the laser fluctuations of the thermal compensation system (TCS), and (vii) the thermal noise from the suspension wires (SusTherm) and the test masses (IntTherm). There is a small region between 50 Hz and 100 Hz where the noise is not completely accounted for. Possible candidates are noise from the actuator magnets (Barkhausen effect), seismic up-conversion due to a nonlinear actuator response and scattered stray beams which form parasitic interferometer paths. The noise between 20 Hz and 50 Hz is mainly due to man-made activities and is highly non-stationary. It varies minute by minute and is hard to estimate at any given point in time.

4. The fifth LIGO science run

The fifth LIGO science run started on 4 November 2005 and ended on 30 September 2007. Just over 365 days of triple coincidence data have been acquired. A little more than 400 days of two site coincident data have been archived. The duty factor for the 4 km interferometer at

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Figure 3. The noise budget for the 4 km instrument at Hanford. Zoomed version to the right. See the text for explanation.
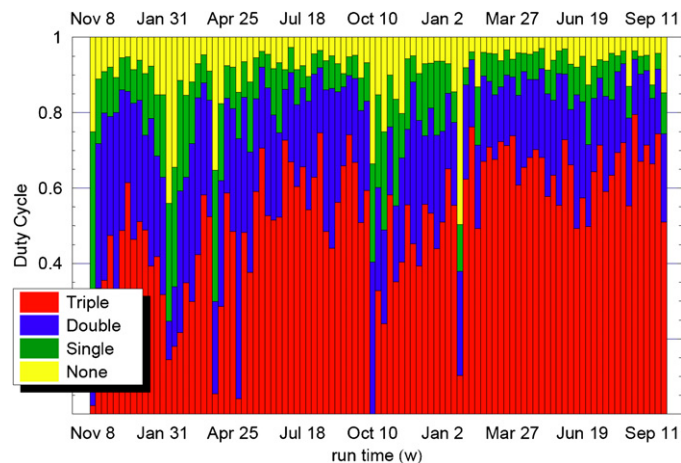
Figure 4. Weekly duty factor of the LIGO instruments during the fifth science run. The red bars indicate the triple coincidence time, the top of the blue and green bars indicate the times where at least two or at least one instrument were operating, respectively. The yellow bars indicate the time where no instrument was up. Some of the weeks with very low duty factor were due to in-run commissioning activities.

Hanford was around 78%, it was about 79% for the 2 km interferometer at Hanford and was about 66% for the Livingston interferometer. The triple coincidence duty factor was 53%, whereas the two-site coincidence duty factor was 60%. Figure 4 shows a weekly trend of the duty factor during the fifth science run.

Figure 5 shows a histogram of the scientific reach to detect binary neutron star coalescence events. The range is computed every minute for two 1.4 solar mass neutron stars spiraling into each other. The range is sky averaged for a signal-to-noise ratio of 8. Different range peaks
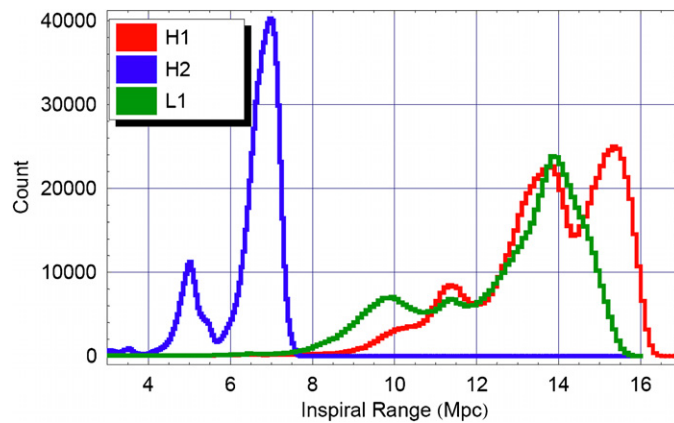
Figure 5. Histogram of the astrophysical reach. The curves show the sky-averaged range to a 1.4/1.4 solar mass binary neutron star inspiral with a signal-to-noise ratio of 8. Different peaks for the same interferometer are typically due to changes in the instrument as part of the in-run commissioning improvements.

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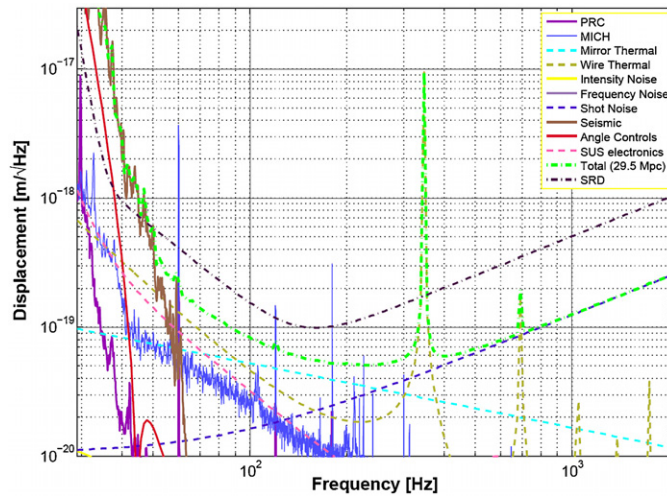
5. Enhanced LIGO plans

Enhanced LIGO [11] is a project to upgrade the two 4 km interferometers with an in-vacuum output mode cleaner, in-vacuum photodetectors at the anti-symmetric port, a dc readout scheme, a new advanced LIGO seismic isolation system for the detection bench, a 30 W laser from Laser Zentrum Hannover, a more powerful thermal compensation system and input optics which can handle higher power. These improvements are envisioned to yield an improvement of the inspiral range by a factor of two. Figure 6 shows the proposed noise spectrum. The combination of increased power and dc readout scheme yields up to a factor of four improvements in shot noise sensitivity. The dc readout scheme has the additional advantage of being insensitive to local oscillator noise, but requires a quiet laser.

6. Results

The data from the fifth LIGO science run are still being analyzed. However, results from previous science runs have been analyzed and published [12–37]. So far no detection has been made and all results are quoted as upper limits. The most recent results are for the fourth LIGO science run with some results including the third LIGO science run as well. For binary inspiral events at the 90% confidence level the rate limits are 1.2/y/L10 for neutron star binaries in the mass range of 1 to 3 solar masses, 0.5/y/L10 for black hole binaries in the mass range of 3 to 80 solar masses and 4.9/y/L10 for primordial black hole binaries in the range from 0.35 to 1 solar masses. The unit L10 stands for a mass equivalent of 10^{10} solar blue luminosity. The Milky Way has an estimated 1.6 L10.

Strain limits on the gravitational radiation from 78 known pulsars have been established as low as 3.2×10^{-25} and as low as 1×10^{-6} on the eccentricity (95% confidence level). The energy limit on a stochastic gravitational background as a fraction of the closure density is

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Figure 6. Projected noise budget for Enhanced LIGO. The green curve is the planned sensitivity improvement. The legend is similar to figure 3.

$\Omega_{GW} \leqslant 6.5 \times 10^{-5}$ at a 90% confidence level. This limit is for a frequency independent gravitational wave spectrum between 51 Hz and 150 Hz. The sensitivity to burst events is in the range of $h_{rss} \sim 10^{-21}$ Hz$^{-1/2}$ to 10^{-20} Hz$^{-1/2}$, where h_{rss} denotes the root-square-sum strain amplitude of the event. The rate limit at the 90% confidence level is at 0.15 per day which corresponds to about 8×10^{-8} solar mass of released energy in gravitational waves at a distance of 10 kpc with a waveform that is centered at 150 Hz and has a quality factor of 9. For the SGR1806-20 hyperflare on 27 December 2004, the limit in strain is $h_{rss} \leqslant 4.5 \times 10^{-22}$ Hz$^{-1/2}$. No more than 4.3×10^{-8} solar mass of gravitational energy was released by this event.

7. Conclusions

All LIGO interferometers have reached design sensitivity. For sources such as binary neutron star and black hole coalescence we can see well into the Virgo cluster. The fifth LIGO science run has been completed with 1 year of triple coincidence data. Preparations for Enhanced LIGO are well underway. Another long science run is planned with a factor of two better sensitivity—before Advanced LIGO installation and commissioning starts in 2011.

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