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Status of LIGO

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Abstract. LIGO successfully acquired more than one year of three-way coincident observation data using three detectors during its fifth science run from November 2005 to the end of September 2007. All detectors reached sensitivity better than the design. For the two 4 km detectors, the all-sky averaged detection range exceeded 15 Mpc with signal to noise ratio of 8 for inspiral binary neutron stars of 1.4 solar mass each. Latest sensitivity of the detectors, results from the past science runs, and future prospects of LIGO are presented.

1. Introduction

Laser Interferometer Gravitational-wave Observatory (LIGO) is a project aiming at the detection of gravitational wave (GW) from astronomical sources using large laser interferometers[1][2]. LIGO has total of three detectors at two sites. In LIGO Hanford Observatory, an instrument with 4 km arm length (H1) and a 2 km instrument (H2) are operating. LIGO Livingston Observatory is approximately 3000 km apart from Hanford Observatory and has a 4 km instrument (L1). The physical separation of two sites allows us to exclude false events caused by local disturbances such as seismic motion, and upon successful detection of GW would allow us to limit the direction of the source.

All LIGO detectors are Michelson interferometers with some enhancements and suspended optics (Fig. 1). In place of two simple reflectors at the end of orthogonal paths in a Michelson interferometer, each LIGO detector has two "arms" comprising Fabry-Perot resonator of either 4 km or 2 km length. On entering into the resonator, light is in effect bounced back and force approximately 100 times before coming out of the resonator, enhancing the apparent length of travel the light experiences and thus enhancing the phase change exerted on the light by GW. Position of the mirrors are controlled in such a way that two beams coming back from orthogonal paths interfere constructively on the beam splitter in the direction going back to the laser. Any differential phase change in the two arms caused by GW makes a small amount of light leaks into the other direction, and this is detected by a photo detector.

LIGO also uses a technique called power recycling[3], which reuses the light going back to the direction of the laser by placing another mirror and coherently reflects the beam with the light from the laser. This increases the effective input power impinging the beam splitter, and thus improves the sensitivity of the interferometer limited by the shot noise of the photon.

In the past, LIGO successfully performed 5 science data runs as shown in Tab. 1. The fifth run (S5) was the first long observational run with all instruments typically running at or better than the design. S5 started in November 2005 with the mission of acquiring one year's worth of triple coincident observational data. At the end of September 2007, after completing the mission with more than one year's data, LIGO ended S5. It's worth mentioning that historically LIGO

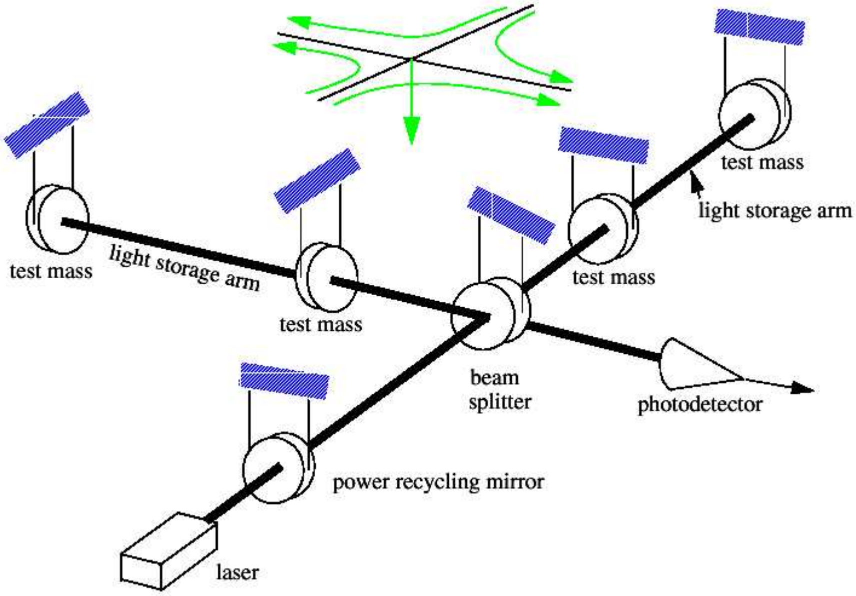

Figure 1. Basic configuration of LIGO instruments.

has always collaborated with other projects during science runs. In S5, due to participation of GEO and VIRGO, sometimes total of 5 large interferometers were running at the same time.

Table 1. LIGO runs in the past. "Collaboration" column lists the name of projects that took part in the coincident observation with LIGO.

Run	Started	Period	Collaboration
S1	8/2002	17 days	GEO, TAMA
S2	2/2003	59 days	TAMA
S3	11/2003	70 days	Allegro, GEO, TAMA
S4	2/2005	30 days	Allegro, AURIGA, GEO
S5	11/2005	23 months	GEO, VIRGO

2. Performance of LIGO Instruments in S5

Figure 2 shows the sensitivity of the LIGO instruments during S5 in terms of linear spectral density of the strain noise. The design strain sensitivity (10^{-21} RMS integrated over a 100 Hz bandwidth centered at the minimum noise region [4], in other words $10^{-22}/\sqrt{\mathrm{Hz}}$ over 100 Hz at around the most sensitive frequency) is represented by a horizontal arrow. Clearly the sensitivity of all of LIGO instruments became better than the design, even though 2km instrument is about a factor of two less sensitive than the others due to smaller length.

The number shown as "Binary Inspiral Range" is the theoretical all-sky averaged detection range for inspiral binary neutron stars, each with 1.4 solar mass, with signal to noise ratio of 8 or more. This means that a part of Virgo cluster is well within our view for sources like coalescence of compact binary system like neutron star and/or black hole binary.

LIGO performed various studies to identify the coupling of various noise into the GW channel of the instruments. Figure 3 is what is called a "noise budget" resulting from such studies.

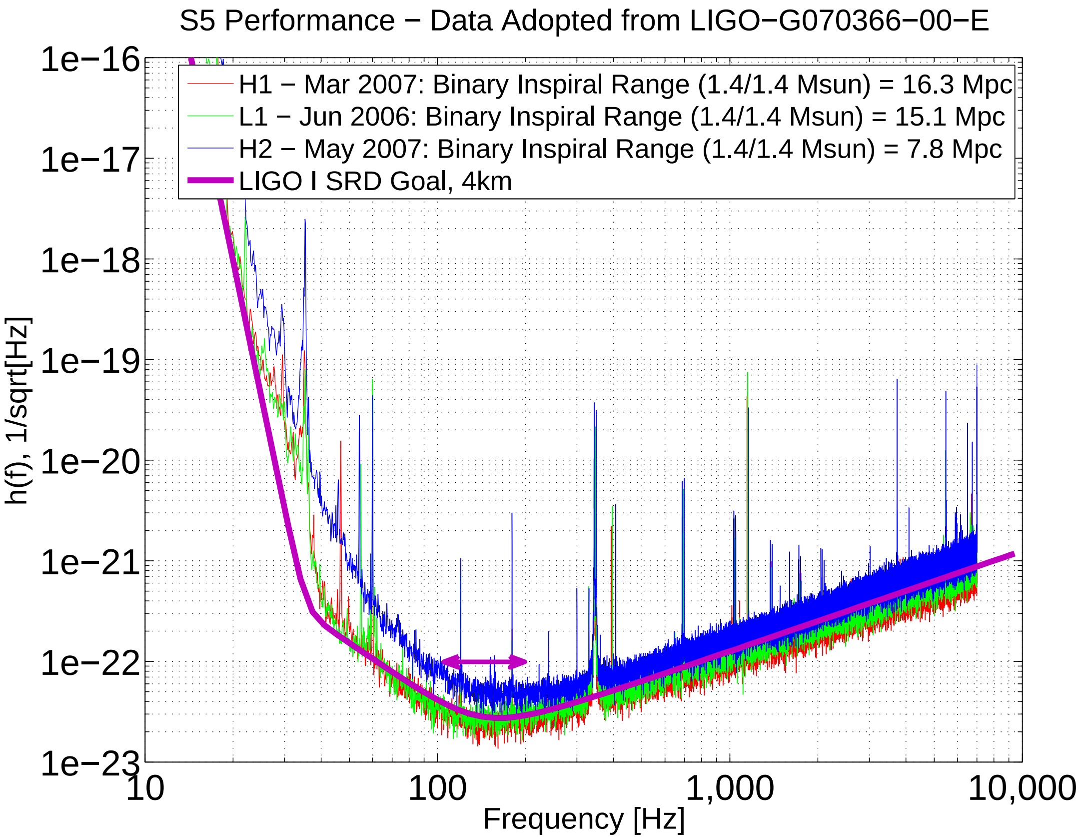

Figure 2. Performance of the Hanford 4km instrument (red), Livingston 4km instrument (green) and Hanford 2km instrument (blue) in S5, plotted as linear spectral density of the strain noise. Arrow represents the design sensitivity, and "LIGO I SRD" is from the initial design parameters for 4km instruments to realize the design sensitivity.

Though this plot is for H1 detector, other detectors show quite similar noise budget. The black trace denoted "DARM" is the measured displacement noise of the interferometer, and the thick dashed line "SRD" is the same as "LIGO I SRD Goal, 4km" curve in Fig. 2. Everything else shows the amplitude of corresponding noise sources projected into the displacement noise. It is not within the scope of this paper to discuss these in detail, but the most important part of this plot is that the detector noise is fairly well understood. Above 200 Hz, the noise is dominated by the shot noise (blue broken line, "Shot"). At frequency lower than 50 Hz, there is no single dominant noise source.

There is a small frequency range between 50 and 100 Hz where the detector noise is not totally accounted for, which shows as a discrepancy between "DARM" and "total" line in the figure. There are several hypotheses about the origin of this unknown additional noise which is still under study.

Figure 4 is the histogram of the binary inspiral range of LIGO detectors over the entire run. Several peaks in each of the detectors represent the fact that there were several "commissioning breaks" to improve the sensitivity and reliability of the instruments during the run.

Figure 5 is weekly duty factor chart for S5. As you can clearly see, LIGO's reliability improved over time during the run. Although there are day-to-day fluctuations due to various reasons, all in all triple coincidence duty factor (red in the figure) of about 0.6 was maintained except the

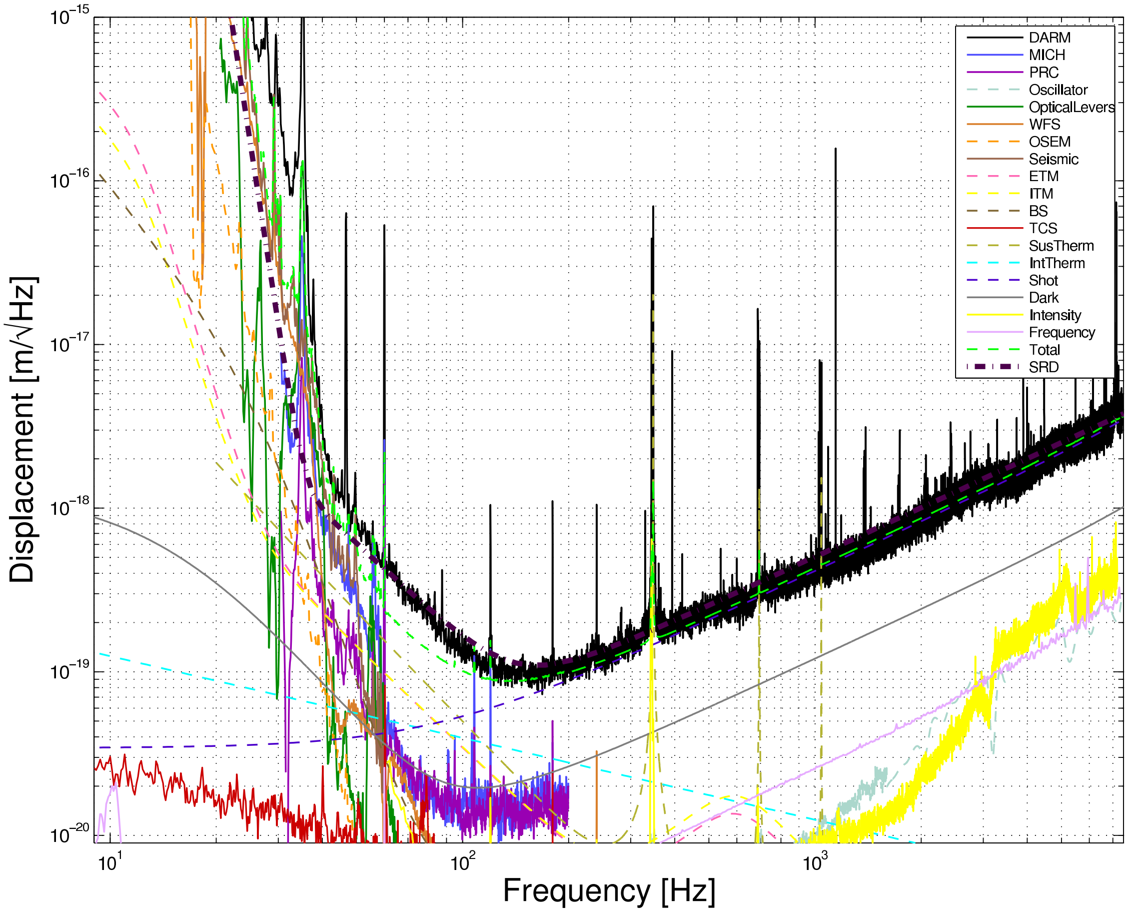

Figure 3. Projection of various noise coupling to the displacement sensitivity of H1 detector. DARM: Displacement noise of the H1 instrument. MICH and PRC: Noise of the auxiliary servo controlling the Michelson part and the power recycling cavity part of the interferometer. Oscillator: Local oscillator noise. OpticalLevers and OSEM: Noise of servos locally damping the angle and position of the mirrors. WFS: Noise of the wave front sensors controlling the angle of the mirrors. Seismic: Noise caused by seismic excitation. ETM, ITM and BS: Actuator noise of End Test Masses, Input Test Masses and Beam Splitter. TCS: Noise coming from thermal compensation system. SusTherm and IntTherm: Thermally excited motion of the wires suspending the mirrors and the internal resonant modes of the mirrors. Shot: Shot noise. Dark: Noise of the main detection electronics chain. Intensity and Frequency: Intensity and frequency noise of the laser. Total: Root sum square of all of the noise. SRD: See Fig. 2.

early part of run and commissioning breaks.

3. Science Results

The data obtained in S5 is still being analyzed by search groups in LIGO Scientific Collaboration (LSC). Though no GW has been detected yet, upper limits for various sources have been set using the data from S4 and earlier runs.

In the targeted search of continuous GW from 78 known radio pulsars in S3 and S4, the strain upper limit as small as 2.6×10^{-25} and the ellipticity as small as 10^{-6} were established

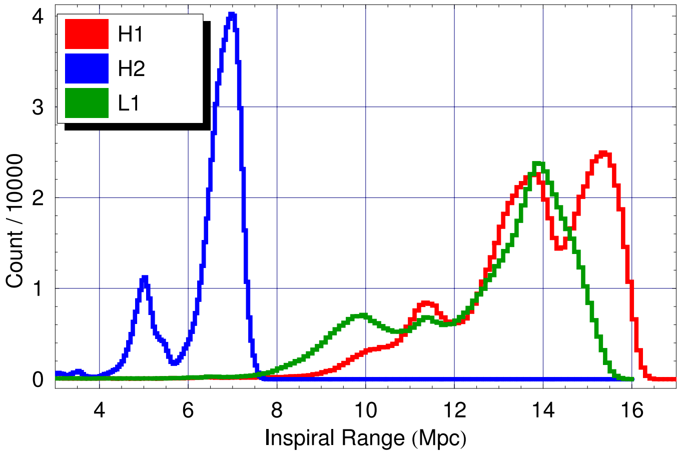

Figure 4. Histogram of binary inspiral range for the entire S5 run. Different peaks represent different periods of the run separated by several "commissioning breaks" to improve the detector performance.

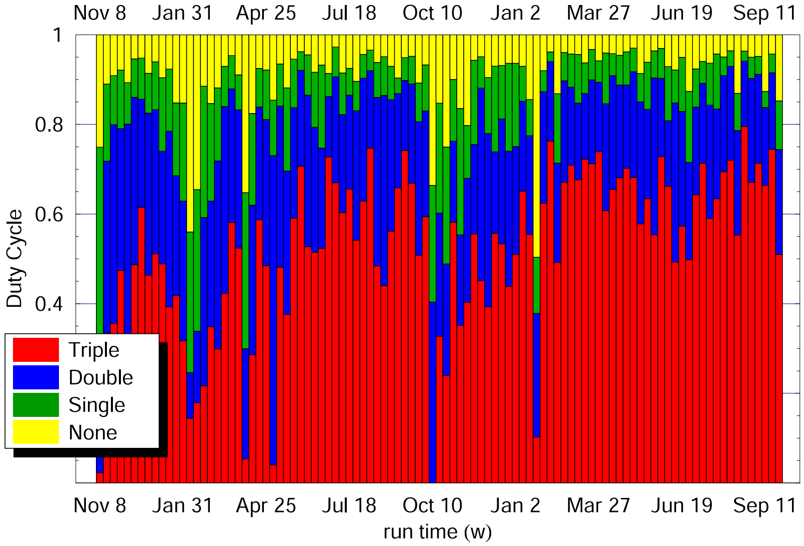

Figure 5. Duty factor chart for S5. Each vertical bin corresponds to a week. Each color shows the time LIGO was operating with three detectors (red), two (blue), only one (green) or none (yellow).

with 95 % confidence level[5]. Also non-targeted all-sky continuous wave search was conducted for S4 with the best upper limit 4.23×10^{-24} near 140 Hz with 95 % confidence level[6].

For binary inspiral events, upper limit rates for primordial black hole binaries in the mass range of 0.35 to 1 solar masses, neutron star binaries in the range of 1 to 3 solar masses, and stellar black hole binaries in the range of 3 to 80 solar masses were derived from S4 and S3 data. They were 4.9, 1,2 and $0.5/\mathrm{yr}/L_{10}$ respectively with 90 % confidence level, where L_{10} is 10^{10} times the blue luminosity of the Sun.

For short bursts with unknown waveform, the sensitivity of LIGO in S4 for root-sum-squared amplitude of the gravitational strain was from 10^{-21} to $10^{-20}/\sqrt{\mathrm{Hz}}$ for 50 % detection efficiency[7]. Also a targeted search for burst GW associated with the SGR 1806-20 hyperflare was conducted[8], resulting in $h_{\mathrm{rss}} = 4.5 \times 10^{-22}/\sqrt{\mathrm{Hz}}$ upper limit with 90 % confidence.

For stochastic background, the 90 % upper limit of $\Omega_{\mathrm{GW}} < 6.5 \times 10^{-5}$ was obtained using S4 data in the frequency range of 51–150 Hz assuming a flat spectrum[9], where Ω_{GW} is defined as the energy density spectrum of GW normalized by the critical energy density of the universe as $\Omega_{\mathrm{GW}} \equiv (\mathrm{d}\rho_{\mathrm{GW}}/\mathrm{d}\ln f)\,\rho_{\mathrm{c}}^{-1}$. For frequency range 850–950 Hz, $\Omega_{\mathrm{GW}} < 1.02$ was obtained from S4 correlation analysis of L1 and resonant bar antenna ALLEGRO[10]. Also all-sky upper-limit maps for two different source strain power spectrum models were generated using S4 data[11]. The upper limit for a flat strain power spectrum was between $8.5 \times 10^{-49}\mathrm{Hz}^{-1}$ and $6.1 \times 10^{-48}\mathrm{Hz}^{-1}$ depending on the sky location with 90 % confidence level.

For a complete list of publications, readers are encouraged to visit LSC web page[12] and follow the “Observational Results” link.

4. Enhanced LIGO and Advanced LIGO

After S5, LIGO 4km detectors are upgraded to increase the sensitivity by about a factor of two, which would cover about a factor of 8 larger volume than initial LIGO within detection range. Some of the key elements in this program called Enhanced LIGO[13] are early adoption of the technologies developed for even more ambitious program called Advanced LIGO. Such technologies include a high power laser module with output power of more than 30 W, and what is called “DC” readout scheme (as opposed to radio frequency modulation-demodulation technique of initial LIGO) combined with an optical resonator called output mode cleaner. Commissioning of Enhanced LIGO starts in winter 2007. Upon successful commissioning of Enhanced LIGO, another science run (S6) is anticipated in 2009.

Advanced LIGO is a program to achieve roughly a factor of 10 improvement in strain sensitivity or a factor of 10^3 improvement in volume coverage over initial LIGO. We expect to realize this by increasing laser power further, using larger mirrors with smaller absorption and smaller scattering, better seismic isolation, and new optical scheme, among other things. Advanced LIGO commissioning is planned to start in 2011.

5. Conclusion

During its fifth science run, LIGO acquired more than one year of triple coincidence data. The sensitivity of all instruments reached and exceeded design. Despite the fact that S5 data is still under study and no gravitational wave was detected yet, LIGO already set many upper limits for various sources. Enhanced LIGO is already in commissioning phase. A factor of two improvement in sensitivity is expected, with roughly a factor of eight larger volume in detection range than initial LIGO, before the Advanced LIGO starts.

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