LIGO Detectors and Data Analyses: Current Status and Future Prospects

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Abstract

The Laser Interferometer Gravitational wave Observatory (LIGO) is a network of first generation interferometric detectors aiming to make the first direct observations of gravitational waves. This paper surveys the status of commissioning and data analyses of the initial LIGO as well as the plans for the future.

1. Status of LIGO

LIGO [1] is comprised of two experimental sites in the US; one is in Hanford, WA and the other one is in Livingston, LA. The detectors use kilometer-scale Michelson interferometry to measure the fractional differential change $\Delta L/L$ in the distances of two orthogonally positioned pairs of masses [2]. Such changes are expected to occur upon the passage of a gravitational wave. The fractional distance change $\Delta L/L$ between two such pairs of perpendicularly arranged masses defines $h(t)$, the *gravitational wave strain*. This is a direct measure of the strength of the local spacetime distortions (which is the gravitational wave itself) folded with coefficients of order unity that depend on the direction of the wave source and the orientation of the interferometer [3]. The Hanford site hosts two such interferometers of 2km and 4km baseline. The Livingston site hosts a single 4km long interferometer. A 10W Nd:YAG laser operating at $1.06\mu m$ is used as the light source. After extensive stabilization the light is directed toward the beam splitter and from there to the two perpendicularly arranged arms. The test masses at either end of each arm form a resonant Fabry-Perot optical cavity [2] where light "builds up" by bouncing back and forth multiple times before returning to the beam splitter. An additional partially transmitting mirror is placed between the laser and the beam splitter aiming to increase the light power that circulates in the interferometer. This is referred to as "power recycling" and reduces significantly the noise due to photon counting statistics (shot noise) [2].

The construction of the LIGO detectors is essentially complete. Following civil works in 1996-2000, the "first lock" of the Hanford 2km interferometer was achieved in October of 2000. Since then several engineering runs interleaved with commissioning work took place. This effort was aimed to (a) bring the three interferometers to their final optical configuration (b) reduce the interferometers' noise floors and (c) pave the way to the first science observations. The progress of this effort can be seen in figure 1 where the spectral noise amplitude for the Livingston 4km interferometer is shown. Among the commissioning achievements has been

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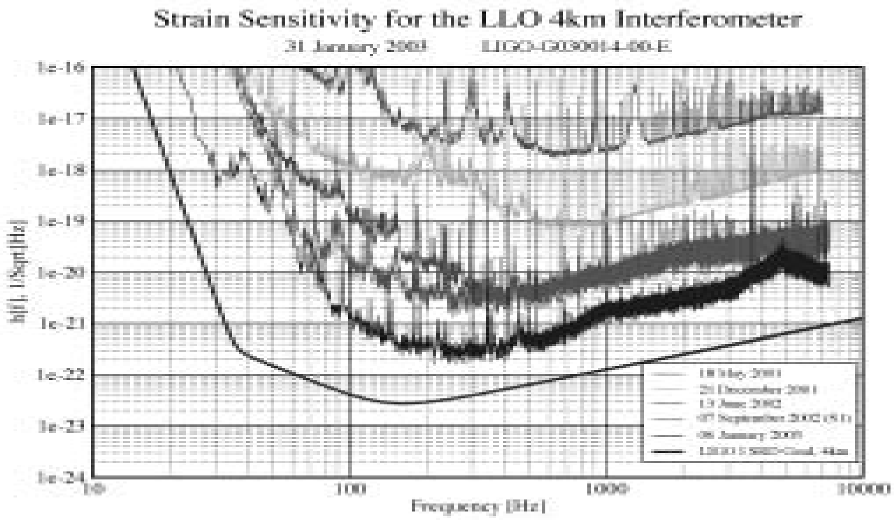

Fig. 1. Sensitivity of the Livingston 4km interferometer (LLO) in terms of equivalent strain noise amplitude density.

the "locking" of the acquisition for up to 66 hours and with power recycling factors of order 40. There is approximately an order of magnitude improvement in strain sensitivity needed in order to reach the LIGO science design requirements. We expect to achieve this by 2004. Among the tasks we will be addressing are the completion of the wave front sensing and beam centering control systems, further reduction of electronics noise and electromagnetic interferences as well as working on the overall optical efficiency of the interferometers. A higher than expected anthropogenic seismic activity at the Livingston site results in excitation of the seismic isolation system resonances near 2Hz. This prevents that instrument from running during most of the daytime. We plan to install an active seismic isolation system at the Livingston detector by 2004 in order to improve its duty cycle.

A major milestone in the instruments' commissioning and operation was the first science run (S1) that took place in the summer of 2002. The total observation time of S1 was 408 hours in 95.7 of which all three interferometers were in coincidence. S1 represents the longest and most sensitive operation of broad-band interferometers in coincidence. S1 was followed by a second science run (S2) from February 14 to April 14, 2003. Observation time was increased by a factor of 4 and the detectors were roughly ten times more sensitive than in S1. Through the commissioning and planning of data runs the operation of LIGO has been coordinated with other long baseline interferometers around the world. LIGO's S1 was in coincidence with the GEO-600 detector (`http://www.geo600.uni-hannover.de`) in Germany while S2 was in coincidence with the TAMA-300 detector (`http://tamago.mtk.nao.ac.jp`) in Japan. An earlier engineering run in 2002 was in coincidence with the ALLEGRO resonant detector (`http://gravity.phys.lsu.edu`) at Louisiana State University.

2. LIGO Data Analyses

Within the LIGO Science Collaboration (LSC, `http://www.ligo.org`), data analysis efforts are organized in four working groups. These working groups follow the general categories of source types that we are pursuing: burst-like, inspiral, stochastic and continuous. Given the sensitivities of the instruments during S1 no detections were expected from the canonical sources of gravitational radiation. The searches we pursued established the methodology we expect to follow in the analysis of the data from future running; we also interpreted the S1 searches in terms of setting upper limits. Although these observational limits in gravitational radiation represent in most cases significant improvements from previous ones it will be future running of the instruments that will bring them in an astrophysically interesting regime. Detailed publications describing thoroughly the analysis techniques and the limits obtained are in the final stage of preparation. In this section we will summarize the highlights from the S1 analyses.

The search for burst-like events focused on short (<1s) transients of unmodeled waveform with enough strain amplitude in LIGO's sensitive band (∼100-1500Hz). *Time domain* as well as *time-frequency domain* [4] search algorithms were employed to identify single-interferometer events. The coincidence of these events among all three detectors was then required. The search has set a 90% upper limit of 1.4 per day on the rate of gravitational wave bursts at the instruments which when interpreted in the context of detection efficiency for ad hoc waveforms implies sensitivities in the range of $h_{peak} \sim 10^{-17} - 10^{-16}$. Contrary to the bursts, the search for binary inspirals is characterized by our ability to approximate the expected signal waveform by a post-Newtonian expansion. For S1 we have considered low mass binaries in the 1-3$M_{\odot}$ range in order to generate a bank of templates for which we performed a *matched filter* [5] search. The search was sensitive to coalescing binary stars in the Milky Way and the Magellanic clouds and has established an observational 90% upper limit on their rate of $R < 138$ per year per Milky Way Equivalent Galaxy.

Stochastic background of gravitational radiation may have cosmological or astrophysical origin [6]. It is revealed as random, weak radiation impinging continuously upon the LIGO detectors. We have performed a search for such a signal on the assumption to be isotropic, unpolarized, stationary and Gaussian. Moreover, we have assumed the energy density in stochastic gravitational waves per logarithmic frequency interval normalized to today's closure density of the universe to be a constant $\Omega_{gw}(f) = \Omega_0$. The *cross-correlation* of the 2km Hanford detector with the 4km Livingston one yields a 90% upper limit for $\Omega_0 h^2{}_{100} < 23$ where h_{100} is the Hubble constant in units of 100km/sec/Mpc. Finally, we pursued a search for the emission of continuous gravitational waves from rotating neutron stars. The mechanism we considered responsible for the continuous emission from these stars is attributed to small distortions of their shape away from axisymmetry. We have used complimentary *time* and *frequency domain* search methods [7] coupled respectively to *Bayesian* and *frequentist* approaches to look for such signals. These methods were used to set upper limits on the continuous wave amplitude h_0 emitted by the known pulsar J1939+2134. In this search we have used data not only from the three LIGO detectors but from the GEO-600 as well. The 95% upper limit on h_0 is 1.0×10^{-22} and for the emission model we considered it constraints J1939+2134's ellipticity at the level of $\epsilon < 7.5 \times 10^{-5}$.

3. Future Prospects

The LIGO detectors are expected to reach their design sensitivity within 2004 following which we will initiate a data taking period with an integrated observation time of at least a year. This is expected to be achieved by the end of 2006 and it will exploit the full scientific reach of the initial LIGO. Around 2007 we intend to start the installation of a second generation LIGO instrument [8] that will have a sensitivity improved by at least a factor ten. Current research across the LIGO laboratory sites as well as participating institutions of the LSC is addressing the technology needed in order to achieve this improvement. An active seismic isolation system will be used to push back the seismic cutoff from its current value of ~50Hz to 10Hz. Internal thermal noise (dominant in the 50-300Hz region) of the mirrors and their suspension systems will also be greatly reduced by the use of materials of at least two orders of magnitude higher quality factors. Sapphire will be employed in the construction of test masses while fused silica suspension wires will be replacing the currently used steel ones. The shot noise limited response of the interferometers at the high frequency end will be reduced by increasing the laser power to 180W and achieving power recycling factors of the order of 80. Finally, the ability to reshape the noise of the instrument and tune its frequency and bandwidth of maximum sensitivity will be achieved by adding a *signal recycling* [2] mirror between the beam splitter and the dark port photodiode thus allowing us to tune the interferometers to specific sources.

4. Acknowledgments

The LIGO Laboratory is supported by the US National Science Foundation under awards PHY-9210038 and PHY-0107417.

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