Modeling LIGO Data Analysis

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The Laser Interferometer Gravitational Wave Observatory (LIGO) will search for direct evidence of gravitational waves emitted by astrophysical sources in accord with Einstein's general theory of relativity. State of the art laser interferometers located in Hanford, Washington and Livingston Parish, Louisiana will unambiguously measure the infinitesimal displacements of inertially isolated test masses which convey the signature of these gravitational waves. The initial commissioning of LIGO will consist of three interferometers operating in coincidence to remove spurious terrestrial sources of noise. These initial LIGO interferometers will search for gravitational wave signatures with very low event rates and low detection signal to noise ratios out to distances as great as 300 million light years. Data will be collected continuously from the three interferometers at rates as high as 16 megabytes per second. Data analysis for LIGO ranges from the extremely simple for the case of intense short duration supernova bursts which will rely on site to site communications to share data used in coincidence, to state of the art parallel and distributed computing utilizing several hundred nodes to detect the chirp signals from neutron star/black hole binary systems, to petaflop computers of the future needed by the all-sky periodic source surveys.

Key words: LIGO; interferometer; gravitational radiation; astrophysics; data analysis; modeling; distributed computing; wide area network

1 Introduction

The Laser Interferometer Gravitational Wave Observatory (LIGO) is presently under joint development by the California Institute of Technology and the Massachusetts Institute of Technology and funded by the National Science Foundation. LIGO's scientific goal is the broadband detection and analysis of gravitational waves of cosmic origin in the tens of hertz to tens of kilohertz region. Understood sources of these waves include coalescing binary systems of neutron stars and black holes, black hole quasi-normal modes, supernovae, pulsars and a stochastic background (the gravitational analog to the microwave background). Beyond these sources await many great surprises as this new class of instrument opens a never before viewed window on the cosmos.

Initially LIGO will be configured as a Michelson interferometers with Fabry-Perot arm cavities and a recycling cavity [1]. The interferometers are being designed to detect RMS motions between the perpendicular arms as small as 10^{-18} meters [2]. To achieve this level of sensitivity, a high power stabilized Nd:YAG laser will provide input to each recycling mirror. All optical components contributing to the sensitivity of the instrument will be suspended as pendula and isolated seismically to reduce coupling to sources of thermal noise and ground motion. The optical path lengths of the interferometer will be maintained by a servo-system, keeping the interferometer phase locked on a particular dark fringe at the gravitational wave port.

LIGO data will be collect from roughly 3600 channels at sampling rates ranging from 2 to 16K samples

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per second. These channels will compliment the gravitational wave channel with environmental, and housekeeping information. The total data collected from each interferometer is estimated at over 5 megabytes per second. The data will be packed into units called frames which carry a complete representation of the data for one or two seconds. This frame data is archived to tape and directed to the data analysis system, where detection challenges begin.

2 LIGO Data Analysis

Gravitational waves couple to the differential length of the interferometer arms. The signal observed at the gravitational wave port is proportional to this length difference. The amplitude of the signal will depend on the characteristics of the source and its relative orientation to the arms of the interferometer. Gravitational waves from a distribution of matter are dominated by the quadrapole moment. The gravitational strain from a source in the Virgo cluster with a distribution of mass on the order of $M_\odot$ (one solar mass), moving at a few tenths of the speed of light would at most produce a strain amplitude of $\sim 10^{-20}$. As a result, LIGO data will typically have very low signal to noise ratios.

The most promising source for gravitational waves for LIGO comes from the inspiral of binary systems composed of neutron stars and black holes. The waveforms for such systems are well described by post-Newtonian approximations [3]. This allows for the application of optimal Wiener filtering on the data. This method involves a weighted matching of the known waveforms to the data. The inspiral will have frequency content observable to LIGO from tens of hertz to a few kilohertz. The number of templates needed to carry out the inspiral search is given by

$$\mathcal{N} \simeq 2.4 \times 10^5 \left(\frac{\mathcal{L}}{0.1}\right)^{-1} \left(\frac{M_{min}}{0.2\mathrm{M}_\odot}\right)^{-2.7} \left(\frac{\hat{f}}{200Hz}\right)^{-2.5} \tag{1}$$

where $\mathcal{L}$ is the excepted fraction of signals lost in the analysis, M_{min} is the mass of the smaller of the binary companions, $\mathrm{M}_\odot$ is one solar mass, and $\hat{f}$ is the frequency at which the interferometer is most sensitive (roughly 140 Hz for the initial LIGO interferometers) The computing resources required for this search are dominated by Fourier transforms and roughly scale as

$$\mathcal{P} \simeq 90 \times 10^9 \text{ FLOPS} \left(\frac{\mathcal{L}}{0.1}\right)^{-1} \left(\frac{M_{min}}{0.2\mathrm{M}_\odot}\right)^{-2.7} \left(\frac{\hat{f}}{200Hz}\right)^{-1.5}. \tag{2}$$

A search for such objects with component masses as low as $0.2\mathrm{M}_\odot$ would require an estimated 6.1×10^5 templates with an associated computing performance of 150 GFLOPS to keep up with the data from a single LIGO interferometer.

Rotating neutron stars having asymmetries about their axis of rotation will emit weak quasi-periodic gravitational waves. The method of detection for these sources involves re-sampling several days of data to correct for Doppler and source spin-down effects and then Fourier transforming the data and performing peak detection on frequency bins below a few kilohertz. A complete search involves dividing the sky into roughly 10^6 patches to correct for the Doppler shift at a high enough accuracy to limit the signal power to a single frequency bin associated with a data stretch of order 10 days. This would require computing performance at the teraflop level. Including spin-down effects in the search is expected to increase this into a petaflop class computing problem [5].

Other sources of gravitational waves such as supernovae and stochastic background do not require the same scale of computers. The detection technique with these sources involves a coincidence measurement of data collected from both LIGO sites. These will only require a communication of the gravitational wave port data and a composite data quality channel. The data will be time tagged using Global Positioning System (GPS) to guarantee proper coincidence. Since the frequency bandwidths of interest for these sources is typically a few kilohertz, the demands on communication are minimal.

Sources of gravitational radiation that have not been characterized will require robust techniques that provide detection of waveforms that are poorly understood. Candidate techniques currently being studied include multi-taper and wavelet methods.

3 Conclusions

LIGO data analysis of expected sources of gravitational waves is being characterized and the magnitude of the computing requirements needed to carry out searches for these sources has been modeled. The predictions made by these models indicate that LIGO data analysis will require several hundred gigaflops of compute power for the binary inspiral searches and similar performance for a targeted pulsar search. The all sky survey for periodic sources requires compute power in the petaflop regime when spin-down effect are included on integrations times of order ten days. This could be scaled back to teraflops by reducing the integration time to roughly a day, but at the expense of signal strength. Proto-type analysis systems designed to test the fundamental algorithms to be utilized in the analysis are currently being implemented on parallel computing platforms at Caltech. The proto-type analysis will enhance the understanding and allow scaling of the data analysis specifications to the level required to reach LIGO's scientific goals.

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