Offline noise subtraction for Advanced LIGO

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Abstract. The Advanced LIGO detectors recently completed their second observation run. Here, we utilize auxiliary sensors that measure various noise sources, and use them to remove those noise contributions from the gravitational wave readout data that is used for estimation of astrophysical parameters of gravitational wave progenitors. This noise removal is particularly significant for the LIGO Hanford Observatory, where the improvement in sensitivity is greater than 20%.

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1. Introduction

Advanced LIGO's [1] detections of gravitational waves [2, 3, 4] have broken open a new view of the universe, allowing us to learn about astrophysical sources such as binary black holes. As work continues toward reaching the ultimate sensitivity of Advanced LIGO, we look forward to more detections of gravitational waves (GW), and learning more about their progenitors [5].

Laser interferometers can suffer from a large number of different noise sources. LIGO's goal is to be limited primarily by fundamental noise sources such as quantum shot noise, quantum radiation pressure noise, and Brownian thermal noise. However, Advanced LIGO's first observation runs have been limited at some frequencies by technical noises [6, 7]. Many of these noise sources are well understood, and further work will hopefully eliminate them from contaminating the GW readout. However, due to the already exquisite sensitivity of the LIGO detectors, most of these technical noise sources and their effect on the GW channel cannot be measured until the interferometers are in a low noise observation-ready state. The balance between infinite tuning of the detector, the lead time for hardware upgrades, and the desire to observe for GWs is a difficult one. For the second observation run from November 2016 - August 2017, the LIGO Collaboration chose to run with somewhat elevated noise in one of the interferometers, while making plans to address those sources of noise prior to the third observation run.

In the meantime, many of these technical noise sources, once identified, can be ameliorated if they affect the GW channel in a linear way and are witnessed by an independent sensor. This noise removal can enhance the sensitivity of the LIGO Hanford detector to GWs by more than 20 % for the second observing run. At this time, the noise subtraction is done in post-processing, so the searches that identify and determine the significance of any transient GW candidates do not have the benefit of this noise reduction. However, all other analyses that are performed later do benefit. This significantly improves our ability to estimate the parameters of the astrophysical source of a compact binary coalescence, including its sky location, masses, and many others.

Additionally, the removal of narrow-in-frequency lines in the sensitivity spectrum is beneficial for the search for continuous wave (CW) GW sources. Due to the long duration of the signals, the frequency of the observed gravitational wave signals are shifted by the rotation of the earth and motion of the earth around the sun. A narrow spectral line in the gravitational wave detector (calibration lines or power line harmonics for example) therefore has a greater impact in the search for continuous gravitational waves than in searches for transient signals. Currently, the CW searches ignore relatively wide frequency bands around each spectral line. The nature of the

CW searches' long integration times means that they do not run in low latency. Thus, any line removal done in post-processing is beneficial to the search, as well as any later understanding of source properties.

Section 2 will briefly describe the sources of several noise sources that can be removed. Section 3 will discuss the method for calculating the subtraction coupling functions and the witness sensors used to subtract each noise source.

2. Technical noise sources

After the first Advanced LIGO observing run from September 2015 - January 2016 the LIGO observatories, one in Hanford, WA and another in Livingston, LA, underwent a series of upgrades [7]. The Handford observatory focused on increasing the amount of laser power circulating in the interferometer, which required using a high power oscillator (HPO) [8]. The cooling water required for the HPO flows through pipes sitting on the laser table, which also hosts optical elements for beam shaping, impression of radio frequency sidebands, and steering. The water flow causes vibrations on this table, and the laser beam bounces off the mirrors that pick up these vibrations. The size of the laser beam is also fluctuating, likely due to the turbulent water flow directly over the laser amplification crystals [9].

In addition, during Advanced LIGO's second observing run, it was discovered that one of the core mirrors in the long arm cavities at the Hanford observatory has a point absorber on its surface, which causes the shape and index of refraction of the mirror to change as a function of laser power incident on its surface. LIGO has a thermally actuated adaptive optics system [10] which can help compensate for effects that are axially symmetric about the beam axis, but this point absorber is several mm from the center of the mirror and so cannot be compensated for. The presence of this optic deformation and thermal lens couples beam jitter and beam size noise into the GW readout channel. The point absorber is not visible by eye, and cleaning the surface of the optic was unable to remove the absorber, so this optic will be replaced prior to the start of the third oberving run.

Together, the higher beam jitter and size noise of the laser beam and the point absorber on the mirror increasing the coupling of beam motion to the gravitational wave channel, the sensitivity of the LIGO Hanford Observatory was significantly worse than expected for the second observing run.

The LIGO Livingston Observatory did not utilize their HPO during the second observation run, and so required much less cooling water to flow through pipes on the laser table. Instead, during this time the Livingston Observatory was focused on finding and mitigating various noise sources, such as scattered light and coupling of noise through analog electronics. This bifurcation of effort is common with the two LIGO interferometers, enabling the parallelization of learning about new challenges that each hardware upgrade (like the use of the HPO) brings.

Other noise sources that affect interferometer sensitivity at both LIGO sites include power mains lines that couple through various analog electronics, and calibration lines applied to monitor any time dependance of the calibration of the interferometer.

Frequencies below a few tens of Hertz can also have noise introduced from control forces being applied to mirrors to control the resonance condition of the interferometer. In addition to the 4 km long arm cavities, the LIGO detectors have optical cavities in the central part of the interferometer whose lengths must be controlled to keep the interferometer at its linear operating point. The sensors used for these auxillary length degrees of freedom have worse shot noise limited sensitivity than the GW channel itself; this shot noise becomes imposed as actual length noise of the auxillary cavities by our feedback control. Some of this auxillary length noise can contaminate the DARM signal. The online control system decouples 2 of these 3 length degrees of freedom from the GW readout channel, but this decoupling is not perfect and does not address the third degree of freedom, so some noise can still be removed in post-processing. The other type of control signal that readily contaminates the main GW readout is angular control of the mirrors that make up the long arm cavities. While the control required for these angular degrees of freedom is at frequencies below those to which LIGO is sensitive to GWs, due to our finite ability to cut off high frequencies in the control signals, some finite actuation is present at frequencies relevant to GW detection. If the actuation node of the mirror actuators is not co-located with the laser beam, any angular motion of the mirror will look like a cavity length change, with a coupling factor proportional to the distance between the beam position and the actuation node.

Figure 1 shows the low-latency noise amplitude spectral density (ASD) of the LIGO detectors, and estimates of the noise contribution from each of the categories described above.

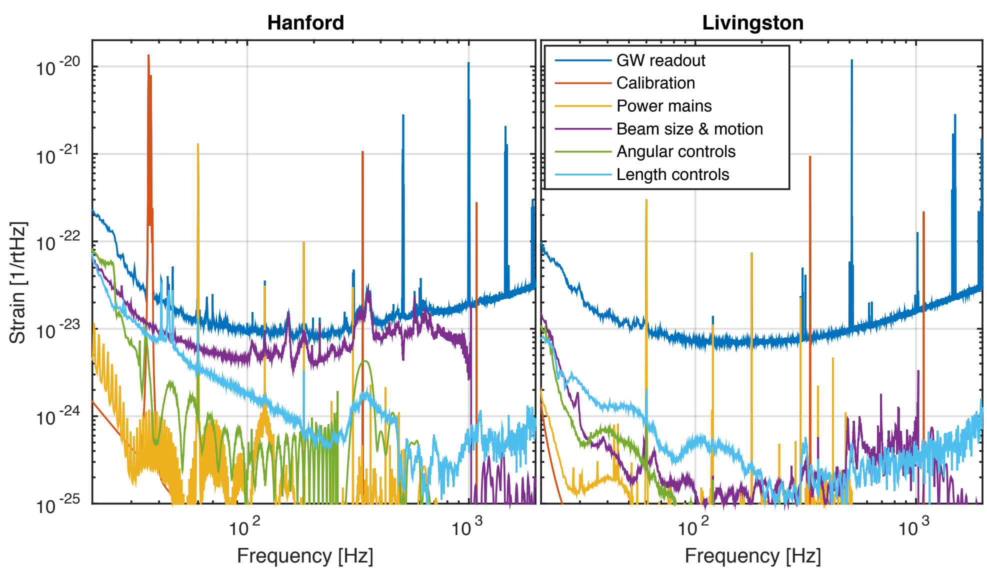

Figure 1. Noise amplitude spectral density of the Advanced LIGO detectors (dark blue), Hanford in left panel and Livingston in right panel. Other traces are estimates of the contributions of various noise sources to the overall spectrum: calibration lines (red), power line and harmonics (gold), beam motion and size noise (purple), angular control (green), and auxiliary length control (light blue). These spectra are estimated using 1024 s of data starting on 25 June 2017 at 08:00:00 UTC, a time when both LIGO interferometers were online and in an observation ready state.

3. Noise subtraction

We use the optimal Wiener method [11] to estimate the coupling function between each noise source and the GW channel. This method determines how best to manipulate an auxiliary witness sensor's data such that when it is subtracted from the primary target signal (here, the GW channel) the mean-square-error of the primary channel is minimized. To do this, we define an error signal

$$\vec{e} = \vec{d} - \vec{y}, \tag{1}$$

where $\vec{d}$ is the noisy target signal and $\vec{y}$ is the approximation of $\vec{d}$ from the independent witness sensor. This is given by

$$\vec{y} = \vec{w}^{\mathrm{T}}\vec{x}, \tag{2}$$

where $\vec{x}$ is the measurement of the external disturbance from the witness sensor, and $\vec{w}$ is the finite impulse response (FIR) filter that we will solve for. The figure of merit (ξ) that we use for calculating the Wiener filter coefficients in this case is the expectation value of the square of the error signal,

$$\xi \equiv E[\vec{e}^{\,2}] = E[\vec{d}^{\,2}] - 2\vec{w}^{\mathrm{T}}\vec{p} + \vec{w}^{\mathrm{T}}R\vec{w}. \tag{3}$$

Here, $E[*]$ indicates the expectation value of $*$, $\vec{p}$ is the cross-correlation vector between the witness and target signals, and R is the autocorrelation matrix for the witness channels. When we find the extrema of Equation 3 by setting

$$\frac{d\xi}{dw_i} = 0, \tag{4}$$

we find

$$R\vec{w}_{\mathrm{optimum}} = \vec{p}. \tag{5}$$

Equation 5 finds the time domain filter coefficients which minimize the RMS of the error $\vec{e}$ by optimizing the estimate of the transfer function between the witness sensors and the target signal. The error signal is now an estimate of the signal in $\vec{d}$, without any noise.

This method was utilized on LIGO data in 2010, for low frequency seismic noise [12]. Following this, the method was used to create feed forward filters which were used online in 2010 [13]. This and other method was also used offline to remove noise from auxiliary degrees of freedom from LIGO's initial-era sixth science run [14, 15].

The Wiener method is able to handle several witness sensors simultaneously by extending R and $\vec{p}$ in the above equations, even if they see some amount of signal from the same noise source, as long as the information in the auxiliary sensors is not identical. This prevents over-subtracting a source of noise, and eliminates the need to carefully chose the order of subtraction if the witness sensors are used in series.

As this method works to minimize the root mean square (RMS) of the target channel, it is useful to remove narrow spectral lines from the data before attempting to subtract the broadband noise sources. For the calibration lines we use the digital signals that are sent to the various actuators as our auxiliary channels. Since we know that these signals sent to different actuators are not correlated with one another, we subtract them in series. For the power mains line at 60 Hz we use a digitized signal that comes directly from monitoring the voltage supplied to our analog electronics racks. While we monitor the voltage at all locations that host analog electronics for the interferometer, we empirically chose the one signal at each site that removes most of the 60 Hz line. In the future, we may consider utilizing more of these signals, particularly for subtraction over longer periods of time.

To measure the beam jitter motion we use a set of three split photodiodes, each with four sections. One of the photodiodes is placed on the laser table, and monitors the beam motion and beam size just after the laser itself. This diode has a central circle, and a ring of three equal-sized segments surrounding the central region. The other two split photodetectors monitor the vertical and horizontal motion of the beam rejected by the input mode cleaner cavity which spatially filters the laser beam before it enters the main interferometer. The signals from these photodiodes are all passed to the Wiener filter calculation algorithm together. The inversion of this matrix (R^{-1} when Equation 5 is solved for $\vec{w}_{\text{optimum}}$) is computationally intensive, and is the main time-limiting step in the noise removal process.

For both the angular and length control noise sources we use the digital control signals that are sent to the mirror actuators as the witnesses.

Figure 2 shows the improvement that can be made in the LIGO interferometers' noise ASD, as a function of frequency. Note that the LIGO Hanford detector is compromised by the technical noise sources discussed above more significantly than is the LIGO Livingston detector, and so sees much more dramatic improvement. Notable spectral lines such as those at ∼500 Hz and harmonics cannot be independently witnessed with currently existing hardware, and so cannot be subtracted. A measure of the improvement in each interferometer can be summarized by the increase in horizon distance the detectors can see a certain GW signal with a pre-defined signal to noise ratio. For both canonical binary black hole $30\,M_\odot$-$30\,M_\odot$ mergers as well as canonical neutron star $1.4\,M_\odot$-$1.4\,M_\odot$ coalescences with a signal to noise ratio of 8 the Hanford detector improves by more than 20% while the Livingston interferometer only improves by about 0.5% using this measure.

Several checks can be done to confirm that this noise removal procedure does not affect any gravitational wave signal present in the data. Most of the noise sources have no possibility of containing any gravitational wave information, therefore cannot remove any actual signal. For example, the power mains monitors, calibration lines, and beam motion photodiodes do not contain any GW signal. For other witness sensors such as length of the short Michelson, we can calculate that the GW signal there is a factor of 1.2×10^{-5} smaller than in the main GW readout channel [16, 14, 17], so should only impact the GW signal up to 0.0012%.

4. Conclusions

We have shown that post-processing noise subtraction is effective for the Advanced LIGO gravitational wave detectors, particularly for the Hanford Observatory which is limited by known technical noise sources over a wide range of frequencies. This sensitivity improvement significantly enhances our ability to extract astrophysical information from our detected signals. Work is ongoing to quantify this. The improvement in sensitivity shown roughly doubles the volume of the universe in which the Hanford interferometer can detect gravitational waves.

5. Acknowledgements

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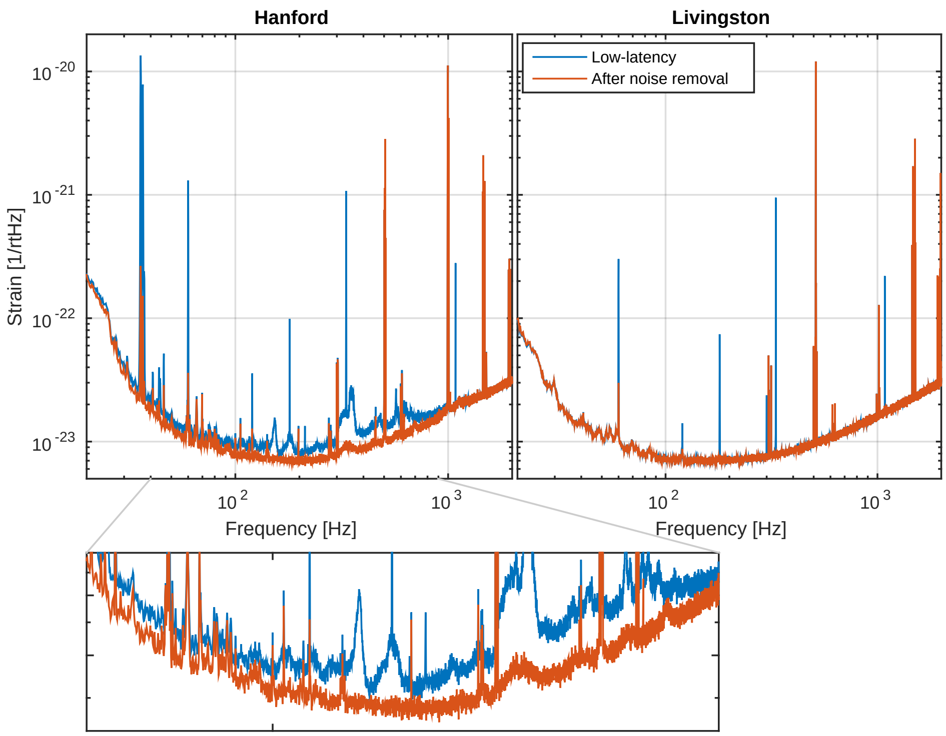

Figure 2. Noise amplitude spectral density improvement of the LIGO detectors, Hanford in left panel and Livingston in right panel. Low latency data used to identify GW candidates and determine their significance shown in blue traces. Interferometer noise ASD after post-porcessing noise removal shown in red traces. Inset is zoom of Hanford data. These spectra are estimated using 1024 s of data starting on 25 June 2017 at 08:00:00 UTC, a time when both LIGO interferometers were online and in an observation ready state.

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