Radio Frequency Noise Reduction in the LIGO Hanford Observatory

Matthew O. Withers
Department of Physics and Engineering
Washington and Lee University

Mentor: Dick Gustafson
Co-Mentor: Keita Kawabe

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Introduction

Gravitational wave detection at LIGO's Hanford Observatory (LHO) and Livingston Observatory (LLO) has played a major role in increasing the scientific community's confidence in the predictive abilities of Einstein's theory of general relativity, which, via a series of derivations performed by Einstein himself in 1916, suggests that super massive accelerating objects should produce wave-like effects within the fabric of spacetime [1]. Their initial detection of signal GW150914, which was produced by two merging black holes, marked the first direct detection of gravitational waves [1]. Furthermore, both observatories continue to detect gravitational wave signals, allowing astronomers to routinely detect significant astronomical events, even those that do not routinely emit electromagnetic radiation.

Both LHO and LLO are, in principle, advanced Michelson interferometers (IFOs), devices used to detect and precisely quantify small changes in length by allowing two perpendicular laser beams to combine and form an interference pattern [2] [3]. The design team building both LHO and LLO's IFOs was challenged to produce devices that could detect changes in length on the order of 1000 times smaller than the width of a single proton [2]. Three primary factors contribute to an IFO's ability to detect smaller and smaller changes in length. First, as the distance traveled by the laser beams increases so too does the sensitivity of the device [2]. At 4 km in length, the arms of LHO and LLO are exceptionally long; in fact, they measure longer than any other interferometer ever built. The team further increased the distance traveled by each laser beam by placing a standard Fabry-Perot interferometer within each arm. The Fabry-Perot interferometer causes each beam to oscillate 280 times within each arm before finally emerging for combination with the other beam. Thus, the arms of LHO and LLO are effectively 1120 km in length [2].

Second, the sensitivity of an IFO is also dependent upon the power of the input laser beam [2]. LIGO's IFOs operate at an unprecedented 750 kW of optical power. Such a high power level is achieved not by increasing the power of the laser itself but by including a power recycling mirror within the interferometer configuration. This recycling mirror sends any reflected light directly back into the interferometer, greatly increasing the number of photons present, which contributes directly to an increase in optical power [2].

Finally, the sensitivity of the detector, and especially its resolving power, is directly related to the amount of noise present in the system [2] [4]. Because LIGO's detectors are so sensitive, they can detect vibrations that we usually consider inconsequential. Events such as seismic activity and the natural vibrations of the many mechanical components that contribute to each observatory are of even greater concern [4]. This research project will focus on determining ways to continue to reduce noise in LHO.

Objectives

My research project will begin with a quantitative examination of several classes of noise currently present in the signal detected by LIGO's Hanford Observatory. After characterizing these noise sources, I hope to propose and investigate potential techniques and design modifications aimed at eliminating them from the system. Two main noise sources are currently of the utmost concern. The first is a class of radio frequency (RF) noise that arises within the observatory's interferometer cavities. Understanding RF noise and examining potential techniques for its reduction is important because it could cause a significant decrease in the resolving power of the observatory. Additionally, RF noise could also be a contributor to some of the glitches in the interferometer's control system. These glitches sometimes result in a break in the lock of device's seven IFO cavities. When the lock breaks, the entire system requires nearly an hour to return to normal operational conditions. Due to the observatory's inability to record data during these hour-long recovery periods, LHO currently operates at a duty factor of approximately 70%. If RF noise is truly the main factor driving the breaks in IFO cavity lock, its elimination could drastically increase the duty factor, thus improving the observatory's rate of data output.

The second source of noise occurs at the low-frequency end of the observatory's output signal (i.e., between 20 and 80 Hz). Within this region, analysis of the observatory's output noise is greater than all of the identified noise added together. Furthermore, existing noise models, which work exceptionally well at higher frequencies, have very little success in explaining this noise source. I hope to complete a thorough quantitative analysis of this noise source. The results of this analysis will be especially helpful in determining a list of candidate sources for the signal. With a list of candidates established, further work will include more directed efforts (either analytical or experimental, as appropriate) to narrow down this list and begin considering plausible methods of elimination.

Approach

I anticipate that my research will be centered around four primary activities. First, my mentor has indicated that one of the primary sources of RF noise at LHO may be a voltage leak (most likely between 1 to 100 mV, but perhaps less than 10 μV) in the cables used to supply 1 V_{rms} to precision RF control drivers found within the IFO. These drivers operate at various frequencies, including, but not limited to, 9.1 MHz and its harmonics. Their primary function is to control the length and alignment of the IFO's seven resonant cavities to a precision on the order of 10^{-20} m. The noise increase due to this voltage leak may be on the order of the RF noise that is currently plaguing LHO's signal.

Solving this voltage leak problem will most likely require a physical examination of the transmission cables bringing power to and from the RF control drivers. The examination will focus on looking for damaged cables, as well as any other electronic configuration that could be contributing to the voltage loss. Because LIGO will be in observation mode during my research period, these physical inspections will likely occur during weekly four-hour maintenance periods and perhaps during additional commissioning time should the laboratory decide to place the device offline to resolve other problems related to the IFO.

The second activity will focus on examining an unexplained class of glitches in the IFO's RF signal generators. One potential origin of these glitches is related to the GPS signal used to coordinate the RF signal generators. Currently, the GPS signal is causing the generators' time coordination to wander in phase by ±50 ns over the course of approximately 50 s. This value is a lower-end estimate; the wandering could be much greater.

Investigating these RF signal generator glitches will most likely require a physical examination of the generators themselves. This will occur via a series of table-top experiments, in which I test and troubleshoot each component in a spare RF signal generator. A thorough review of the software used to coordinate the GPS signal and the RF signal generator may also aid in this process.

The third activity will investigate non-linearity in some of the IFO's electronics systems. This non-linear behavior causes pure sinusoidal signals to transform into a comb-shaped profile, with harmonics found at approximately 10% of that of the carrier wave. This profile transformation could be contributing to the signal noise and the glitches observed in the RF control drivers and RF signal generators. While little is currently known about this non-linear behavior, I anticipate investigating it by performing Fourier analysis of the signal (most likely in MATLab), which will help deconstruct the signal into its constituent components. Once the constituent components are known, I will be able to make predictions about which physical components are the most likely sources of the profile transformation.

Finally, the fourth activity will consist of a quantitative analysis of the unexplained low frequency noise present in the LHO system. This investigation will also begin with Fourier analysis, which will help to simplify the noise into individual components. With these components extracted, I will be able to compare to other known noise sources, revealed both from LIGO's previous work but also from other fields and experiments, to begin making progress toward diagnosing the origin of the noise.

Project Schedule

Date	**Activity**
6/16/19	Arrival in Pasco, WA
6/18/19 - 6/21/19	Initial Orientation
6/24/19 - 7/12/19	Research Part I
7/15/19 - 7/19/19	Midterm Presentation Preparation and Report Writing
7/22/19 - 8/16/19	Research Part II
8/19/19 - 8/22/19	Final Presentation Preparation and Report Writing
8/23/19	Final Presentation
8/24/19	Departure

References

[1] Abbot B. P. *et al.*, *PRL.* **116**, 061102 (2016).

[2] LIGO's Interferometer. Pasedena: LIGO Caltech; [accessed 9 May 2019]. `https://www.ligo.caltech.edu/page/ligos-ifo`.

[3] What is an Interferometer? Pasedena: LIGO Caltech; [accessed 9 May 2019]. `https://www.ligo.caltech.edu/page/what-is-interferometer`.

[4] Martynov D. V. *et al. Phys. Rev. D* **93**, 112004 (2016).