Angular Subtraction at LIGO Livingston Observatory

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I. INTRODUCTION

In 1905, Henri Poincare considered the idea of gravitational waves, and in 1916 gravitational waves were predicted by Albert Einstein as a byproduct of general relativity. Just as accelerating charges emit light in classical electrodynamics, gravitational waves are emitted by accelerating masses. Compared to light, gravitational waves are not obstructed by matter [1].

Gravitational waves will lead to new physics and astrophysics to examine. Because it is challenging to set up an experiment with gravity (compared to the other forces), they will provide an opportunity to see more direct influences of it [2]. Additionally, predictions of general relativity can be compared to the gravitational wave data. Lastly, it will open a myriad of astronomical data, from examining black holes to probing past the cosmic microwave background. The cosmic microwave background may include a gravitational wave background, which would be evidence for inflation.

Laser Interferometer Gravitational-Wave Observatory (LIGO) is a collaboration dedicated to finding gravitational waves. It consists of two main facilities in Livingston, Louisiana and Hanford, Washington. These facilities detect gravitational waves in a way similar to the Michelson-Morley experiment. It consists of a Michelson interferometer with 4 kilometer arms which measure the deformation of space of a gravitational wave by looking for interference patterns. It contains Fabry-Perot cavities which allows the light to bounce along the arms about 280 times. It uses light recycling to increase the power of a 200W laser into a 750MW laser. The laser also travels through a vacuum and dampens out environmental vibrations both actively and passively.

After LIGO had unsuccessfully searched for gravitational waves during the 2000's, the detectors were upgraded, which was called Advanced LIGO. Consequently, in February 2016, LIGO announced that they had detected the first gravitational wave, and they announced a second detection in June 2016 [3] [4]. Both of these detections were due to binary black hole system rotating and then combining.

In order to keep the mirrors stable, LIGO uses an active dampening alignment sensing and control system (ASC) to reduce the mirror's angular motion [5]. Currently, the low frequency noise (10-35 Hz) of the LIGO Livingston instrument is limited by our angular control feedback loops. To increase detection in this frequency, the ASC should reduce the angular noise DARM coupling below 1/10th of the sensitivity (which is $6 \times 10^{-18} \frac{m}{\sqrt{Hz}}$) [5].

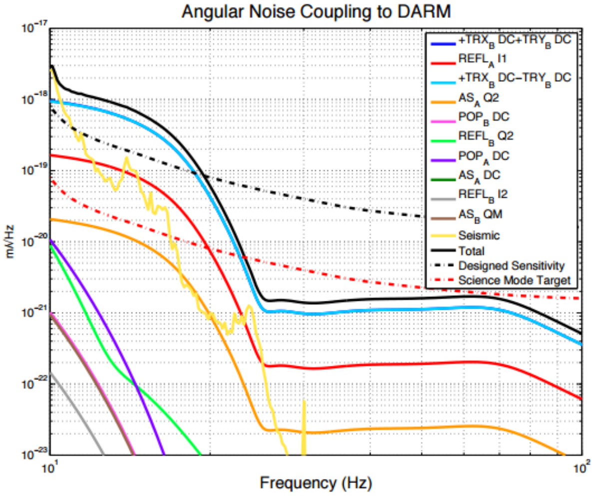

FIG. 1. The solid black line is the angle-to-length coupling noise, which should be compared to the dotted black line of the designed sensitivity. Notice the sharp uptick in angular noise 25Hz. This noise is the limiting source of noise for the detector sensitivity at lower frequencies. This figure originated in [5].

When aligning a laser on an optical axis with two mirrors, angular misalignments from the ground mode cause coupling into higher order modes [6]. By making a transverse mode, the mirror misalignment perturbations from the ground mode can be measured and corrected for [6].

Spectral subtraction is a technique that is used to filter out noise from the target signal. You assume $y(t) = x(t) + n(t)$, where y is the witness signal, x is the target signal, and n is the noise. By taking the discrete Fourier transform, the average noise for a particular frequency can be found by summing the average of the noises of that signal for frames without target signal. The target signal can then be found by taking the inverse discrete Fourier transform of the quantity of the witness signal minus the average noise [7]. This technique was used to reduce noise from Michelson motion by cutting data in 1024 second increments and applying feedforward subtraction [8].

Wiener filtering can be used to filter out noise in the interferometer. Statically, the weights of the filter can be found by minimizing the expectation value of the error squared (which occurs when $R\vec{w}_{optimum} = \vec{p}$, where p is the cross correlation vector, R is the autocorrelation matrix for the witness channels and w is the weights of the filters). The filtered result is $y = \vec{w}^T\vec{x}$ where x is the witness of the noise (in our case misalignment of the mirrors) [9]. This can be extended to online adaptive filtering by breaking up the time into intervals and letting the filter change for each time interval, using a Filtered-x Least Mean Squared algorithm [9].

II. OBJECTIVE

Angular control feedback loops limit the sensitivity of the LIGO Livingston Instrument at low frequencies (10-35Hz). We would like to reduce the angular noise by improving the suspension length-to-angle feedforward decoupling filters and implement Wiener filtering subtraction techniques to remove angular noise coming from known length sources.

III. APPROACH

At first, I will cement techniques from readings, better understand LIGO instrument's systems, and data extraction from the system into Matlab. We will practice simple feedforward exercises and apply it to real data from the instrument. We will take and analyze the data of the angular coupling. Then we will begin reducing noise with feedforward filters and Wiener filtering. We will test the results of these filters and iteratively work to improve them. Lastly we will compile the results of the filters, and I will write a report for the DCC and create a poster.

IV. TIMELINE

- **May 10th - June 20th:** Gain familiarity with techniques used by reading references provided. This includes gaining more knowledge in the following:
  - interferometric gravitational wave detector workings
  - Control systems
  - Digital signal processing and data analysis (specifically random data analysis)
  - Wiener filtering and spectral subtraction
  - Better knowledge of optics to better understand angular sensing and control
- **June 20th - June 24rd:** Learn about LIGO instrument and focus on angular control systems and incorporate knowledge gained from the readings with feedback and feedforward control systems.
- **June 25th - July 1st:** Learn about the tools to take necessary online data. Measurements templates will be created with the online LIGO tool DTT or generated with Matlab depending on the progress.
- **July 2nd - July 15:** We will on taking online measurements, importing data into Matlab, and analyzing the measurements. We are particularly interested in measuring the coupling from each angular signal into our gravitational sensing readout. This will be done by sending swept sine or white noise functions into digital excitation channels to actuate on the optics in angle. We will use the differential arm sensor (DARM) to sense the coupling. We will also measure the coupling from the length degrees of freedom to the angular sensors to create a simple noise budget by projecting the ambient noise.
- **July 16th - July 22nd:** Work on solutions to implement on the detector, by using feedforward lessons from week 1, and more advanced Wiener filtering techniques. The measured transfer functions will be fit in the frequency domain to simulate projected noise, and subtract it from the end channel.
- **July 23rd - July 29th:** We will test those techniques after making appropriate filter design. We will implement the filters into the instrument and measure the improvement in the DARM coupling. We will send again digital excitations to measure the new coupling and construct a new noise budget
- **July 30th - August 12th:** Based on the previous results, we will repeat the procedure and design new filters if the coupling reduction is not satisfying or we will look for further improvement by trying other feedforward techniques. A clear summary of the results should be started to make sure we got all the necessary measurements to assess the residual coupling. If time allows, the student could also start a model of the noise budget to validate the results.
- **August 13th - August 19th:** Write a report to be posted in the DCC and create a poster to present their results (check what are the Caltech REU requirements). The last week(s) will be dedicated to the finalization of the documents.

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