Modeling Corrections to the Fabry-Perot Cavity for the Calibration of Advanced LIGO Instruments

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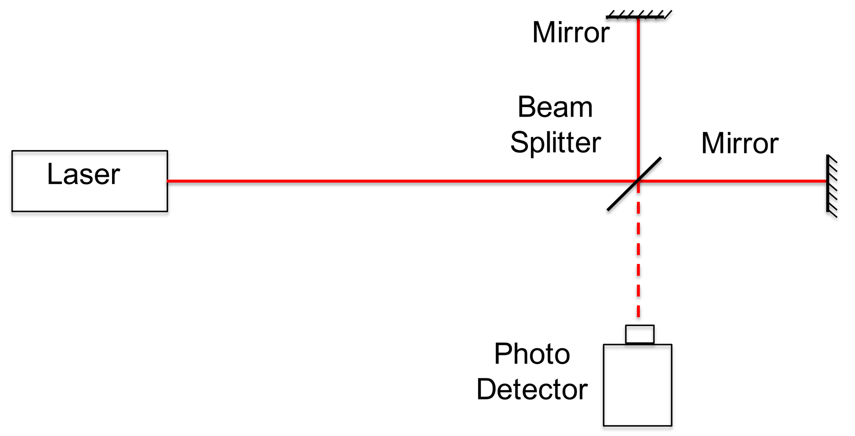
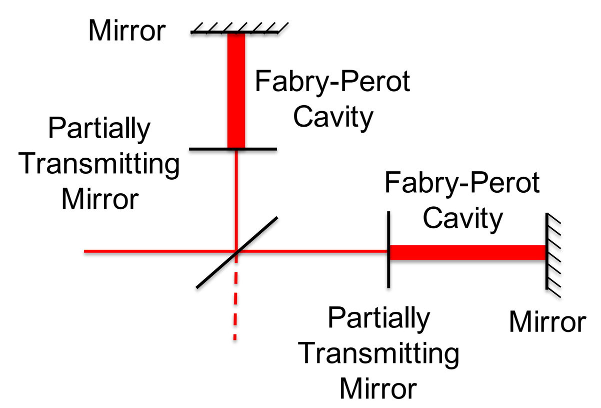
LIGO Background

The LIGO (Laser Interferometer Gravitational-Wave Observatory) scientific collaboration works to directly detect the presence of gravitational waves in the universe. A gravitational wave is a ripple in spacetime predicted by the theory of general relativity. The asymmetric motion of large masses such as black holes and neutron stars produce ripples in spacetime that propagate through the universe at the speed of light. LIGO uses large Michelson interferometers to detect small distortions in spacetime between stationary hanging masses. A Michelson interferometer consists of a laser which is separated into two identical perpendicular beams by a beamsplitter. The light from the laser then travels down the two arms of the interferometer where it reflects off of mirrors to travel back to the beamsplitter and form an interference pattern at the detector. Small changes in the length of the beam arm cause changes in the interference pattern at the detector, allowing gravitational waves to be measured.

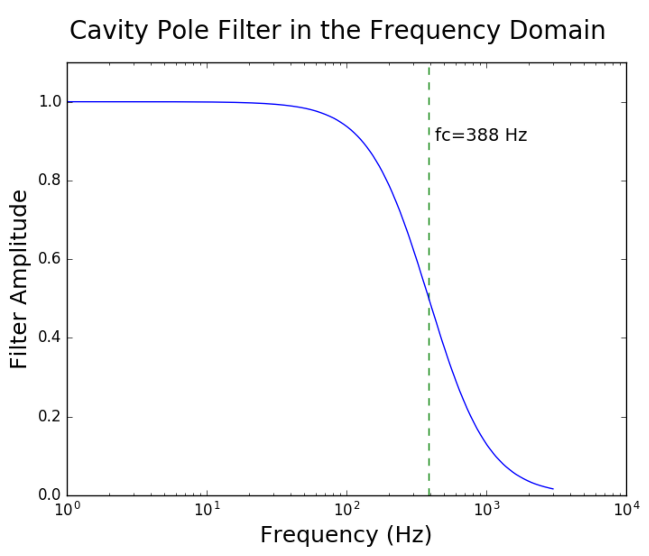


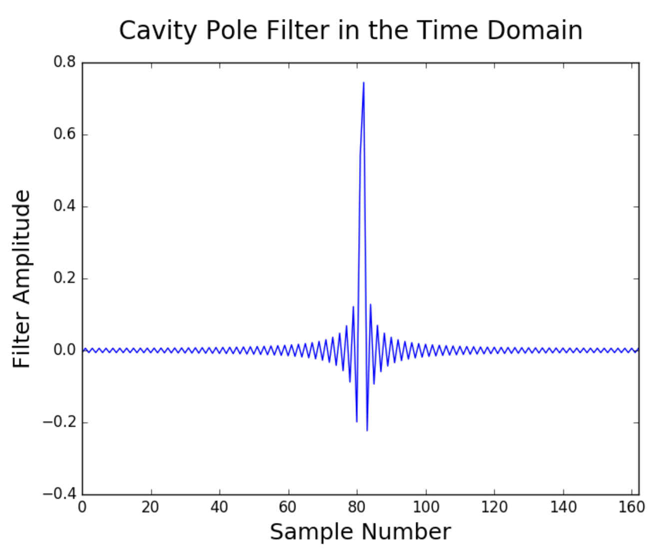
The Fabry-Perot Cavity

The interferometer is sensitive to even the most minute distortions. The raw data must be calibrated using filters the model the physics of the interferometer. This project is interested in modeling the Fabry-Perot cavity filter as a function of time. The Fabry-Perot cavity is used to increase the effective beam length of the interferometer and consists of a partially transmitting mirror causing light to bounce back and forth between the mirror and the end of the arm. The folding of the beam path at resonant frequency causes a build up of constructive interference resulting in a standing wave which is extremely sensitive to any changes in beam length.



LIGO loses sensitivity to gravitational waves at frequencies higher than the frequency of the inverse of the light storage time in the Fabry-Perot Cavity (f_c). The purpose of the Fabry-Perot filter is to model the decrease in sensitivity that the detector has to frequencies above this threshold. The Fabry-Perot filter is a low pass filter in the frequency domain which is used to filter out signals from the data with frequencies higher than that of the Fabry-Perot Cavity (f_c).





Project Goal

As shown below, the cavity pole frequency changes over time. The goal of this project is to create and implement a method which periodically updates the Fabry-Perot cavity filter of the LIGO interferometers as the cavity pole frequency changes. This results in a reduced error for the calibrated LIGO data and decreases the error for estimating the characteristics of the sources of gravitational waves.

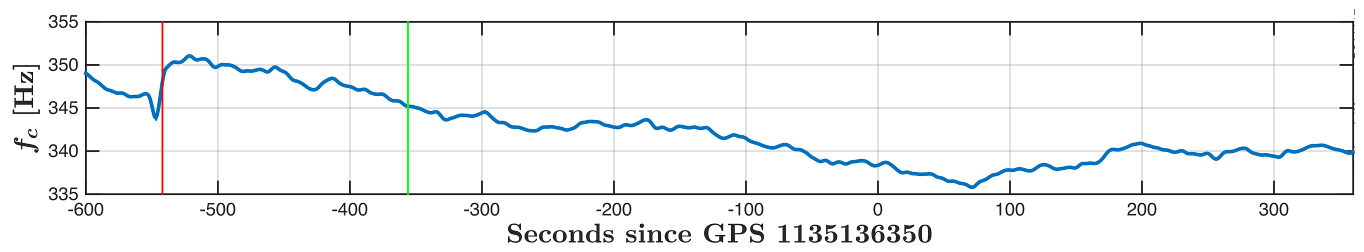
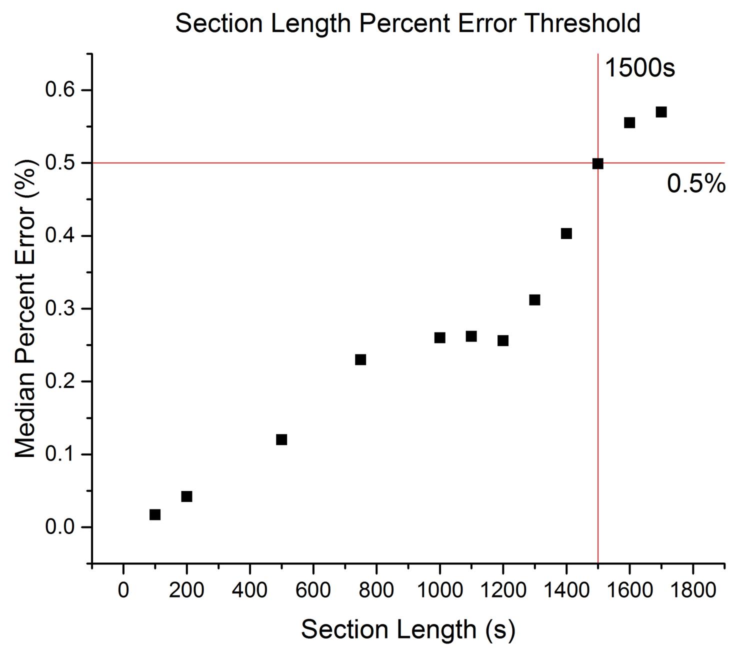


Image credited to Sudarshan Karki

Preliminary Findings

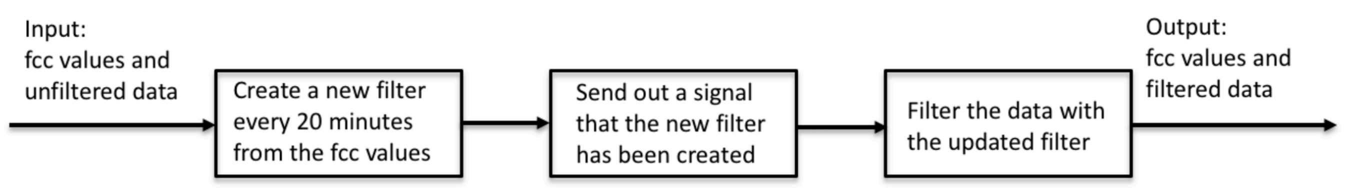
The Fabry-Perot filter needs to be updated often enough to not result in more than a 0.5% difference from the ideal filter. In order to determine when this threshold is reached, the filtered data with the filter updated at different time intervals was compared to filtered data with the filter updated as often as possible. The percent error of the data due to the update lengths is shown below.



From this graph it was determined that the Fabry-Perot filter should be updated every 20 minutes which corresponds to every 1200 seconds. This value was shown to be safely below the 0.5% median error threshold.

Pipeline

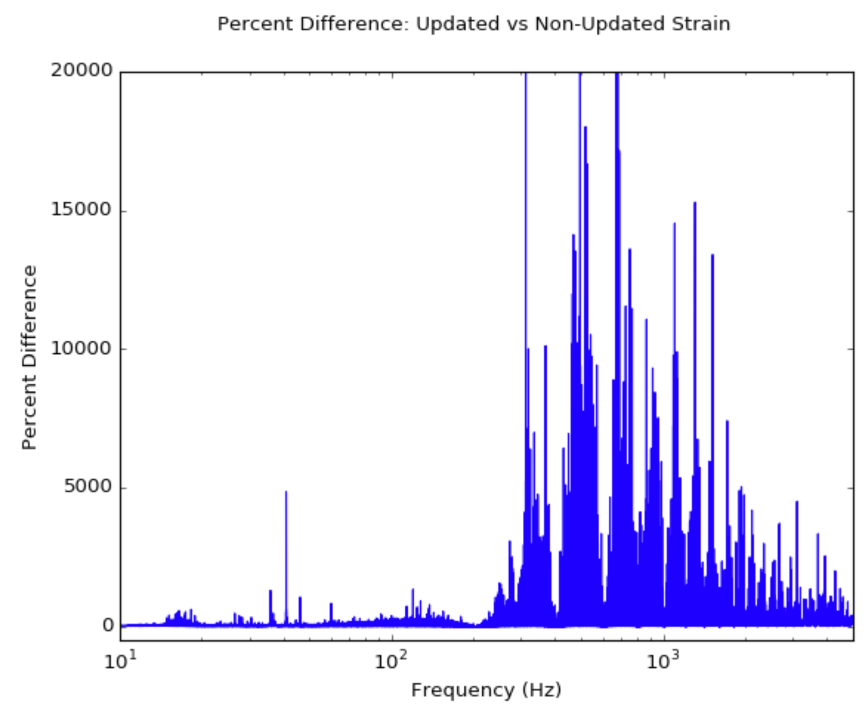
In order to update the cavity pole filter, I incorporated the method of constructing new filters into the calibration process. This was done using code from the Gstreamer library which is designed to send data in real time down the elements of an established pipeline such as the simplified pipeline shown below.



This pipeline takes in current fcc values and partially calibrated data from the LIGO detector and sends it down the pipeline, which creates a new filter every 20 minutes. A signal is then sent out telling the element that filters the data that a new filter has been created. And so, every 20 minutes a new cavity pole filter is created and implemented into the calibration process.

Conclusions

It was determined that the Cavity pole filter should be updated every 20 minutes to achieve a median percent error of less than 0.5%. This should greatly reduce error in the calibration process, particularly at high frequencies. The change to this filter was then implemented in the calibration pipeline. The graph below shows the percent difference in strain between updating and non-updating filters.



We can see that the greatest difference in the updated versus the non-updated strain occurs at higher frequencies. This is to be expected, since the correction made in the cavity pole filter update has the most effect on high frequency signals.

Future Work

The next steps for this project are to further characterize the effects of updating the cavity pole filter. We wish to identify to what extent updating the cavity pole filter improves the overall calibration error, particularly for high frequencies. On a larger scale, we wish to develop a process in order to determine how much calibration error is acceptable in order to achieve LIGO's science goals in both search and parameter estimation.

Acknowledgements

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