LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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SURF Progress Report 1

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1 Introduction

The project will involve gravitational wave detection with the LIGO project at Caltech. The goal of LIGO is to detect and study gravitational waves, which are as yet undetected fundamental prediction of general relativity. Specifically the work will be on calibrating the gravitational wave strain data channel on the new Advanced LIGO detectors. In particular I will be developing a model focusing on the optical response part of the sensing chain element. I will also be involved in work on the detection model as a whole. The team I will be working with has been making great progress at developing a detailed model of the detector with the Simulink/Matlab programs. My contribution will be to examine how real world changes to the detectors will affect the calibration in an error propagation study, as well as work to improve the digital filters used in the model. This will improve the performance of the detector when brought into operation as well as ensure that real world changes are measured well enough to achieve accurate calibration.

As for the gravitational waves themselves, I have learned that they are fundamental predictions of general relativity. They consist of waves of space-time curvature created by accelerating quadpoles. They are transverse waves that arent readily scattered or absorbed due to the relative weakness of the gravitational force. Any time mass accelerates it creates gravitational waves, even if its something as small and slow as a bird flapping its wings. However, these gravitational waves are too small to detect. The sources that LIGO hopes to detect are astrophysical sources capable of producing much larger waves with more energy. These include, but are not necessarily limited to, collisions of binary neutron stars, supernova, spinning neutron stars, and the cosmic gravitational wave background left over from moments after the big bang. These waves are thought to propagate at the speed of light. If it turns out that they do not it would imply that the fundamental force particle of gravity, the graviton, has mass. Further studies of the gravitational waves could reveal an entire scope of science determining their causes and characteristics as well as use in gravitational wave astronomy.

ALIGO uses 4km dual recycled Fabry-Perot Michelson interferometers to detect these waves. With a 200W laser and the resonance of the cavities it is possible to bottle up about 800 mega-watts within the arms. This makes the arms incredibly sensitive to the smallest change in the position of the end test mass which would put the cavity off resonance. When this happens the total destructive interference at the dark port is interrupted and some light leaks through. This light is measured to provide the actuation functions of the arms the data they need to move the mirrors back into resonance. This also provides the signal of the passing gravitational wave.

The differences between ALIGO and the initial LIGO include, but are not limited to the following. The sensing system uses different electronics and DC readout. The actuator for Advanced LIGO contains a complex quadruple pendulum and the optical plant is now a more complex dual-recycled interferometer. Additionally, calibration done in the time domain will have to be much more detailed than initial LIGO. It also uses FIR filters based on IIR models. These changes and more will be elements to understand and study in the progression of the project and development of new filter designs. Also, a greater understanding of the physics of general relativity and gravitational waves will be helpful in pursuit of these goals.

2 Objectives

The goal of this project is to improve the model for the gravitational wave detector in Advanced LIGO. The focus will be on modeling the sensing function and the digital filters, which describes how the interferometer responds to differential changes in arm lengths and how that response is digitized. The first step consisted of learning how to work in the modeling environment as well as understanding the model itself. This was achieved through various online tutorials for Matlab/Simulink provided by the Mathworks website as well as direct experimentation with the model developed by Jeff Kissel. The next step was to learn as much as possible about the principles of LIGO and gravitational waves. This is an ongoing process throughout the summer as it is important to not only access the output of the model but also to understand what it means. Up to the writing of this report, enough information on the subject has been learned to begin producing plots from the model and available equations. Ideally, enough will be learned to intuitively interpret changes in the data as a result to model perturbations as this will lead to more effective use of the model and other resources. Moving forward, the goal will be to understand the feedback of the digital filter by plotting each filter bank individually and observing their changes in the face of perturbations to the model. This will require learning about the process and procedure of analyzing the stability of feedback systems and using what was learned to analyze the feedback systems in the model. Finally, experiments will be undertaken with the goal of making a more effective and efficient filter/high performance servo. The completion of this more effective filter/servo will constitute not only a successful project but also an achievement of progress towards the overall goals of LIGO.

3 Approach

The first task given was to justify the simplification of the dual-recycled Fabry-Perot Michelson into a single Fabry-Perot cavity. Then the reflectivity and transmissivity of the signal mirror were calculated using the equations:

$$r_{cm} = r_{ITM} - \frac{t_{ITM}^2 r_{sm} e^{-i\phi}}{1 - r_{ITM} r_{sm} e^{-i\phi}} \tag{1}$$

$$\phi = 2kl_s = \frac{4\pi l_s (f_{carr} + f_{sig})}{c} \tag{2}$$

$$R + T + L = 1 \tag{3}$$

$$[R, T] = [r^2, t^2] \text{(For power and energy respectively)} \tag{4}$$

The reflectivity of the signal mirror was found to be .65. Figure 1 was generated also using these equations. Figure 2 shows the current digital filer and Figure 3 shows a graph of the open loop gain [1]. The digital filter plot will be the focus of much of the project. Further progress will take the form of increased understanding of the system, generation of numerous plots helpful for both understanding and analysis, and stability studies of the system.

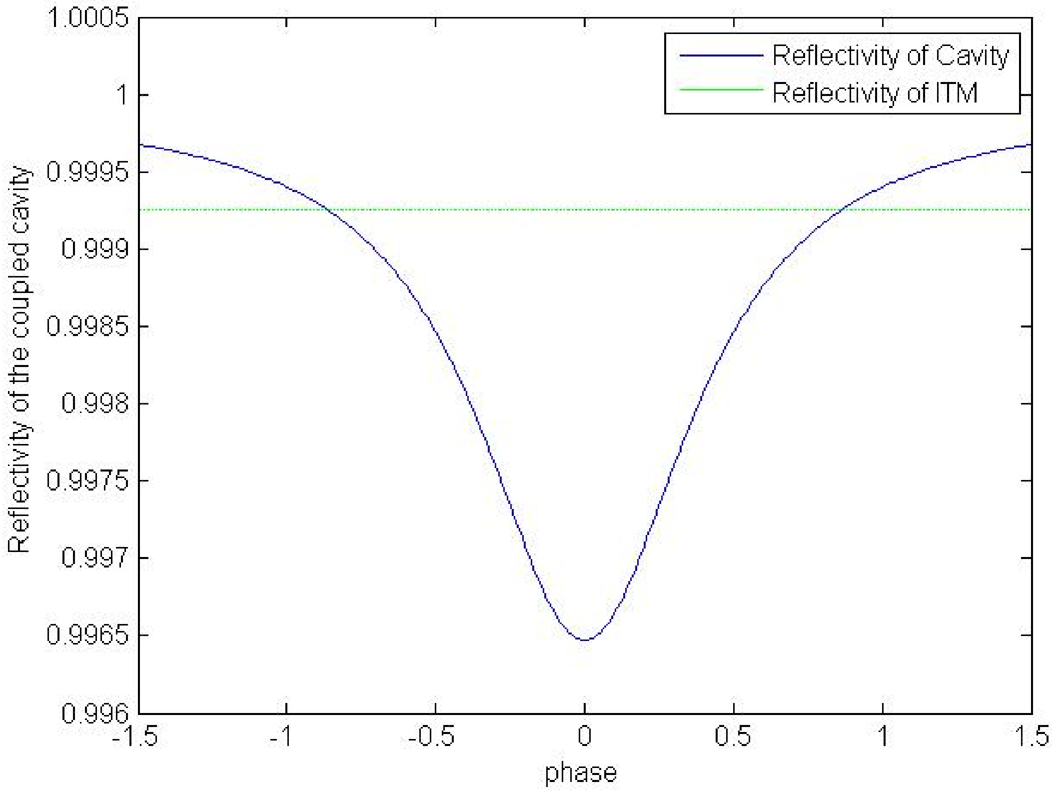

Figure 1: Reflectivity of the coupled cavity plotted against the phase.

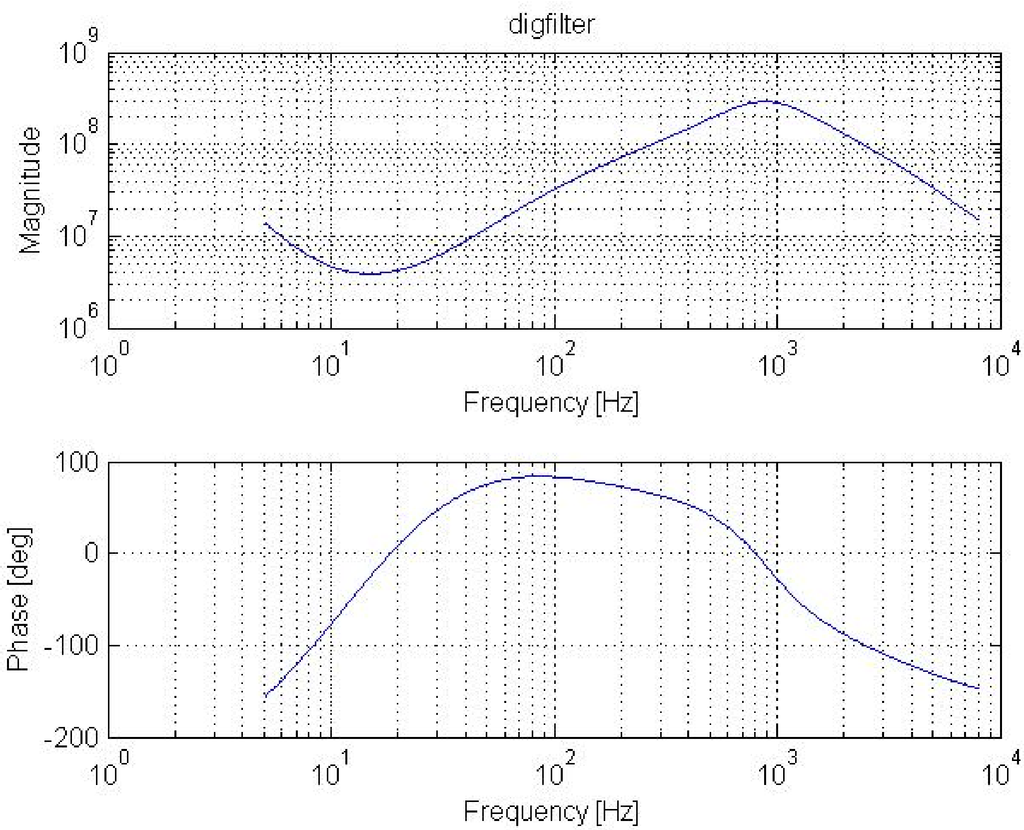

Figure 2: Digital Filter

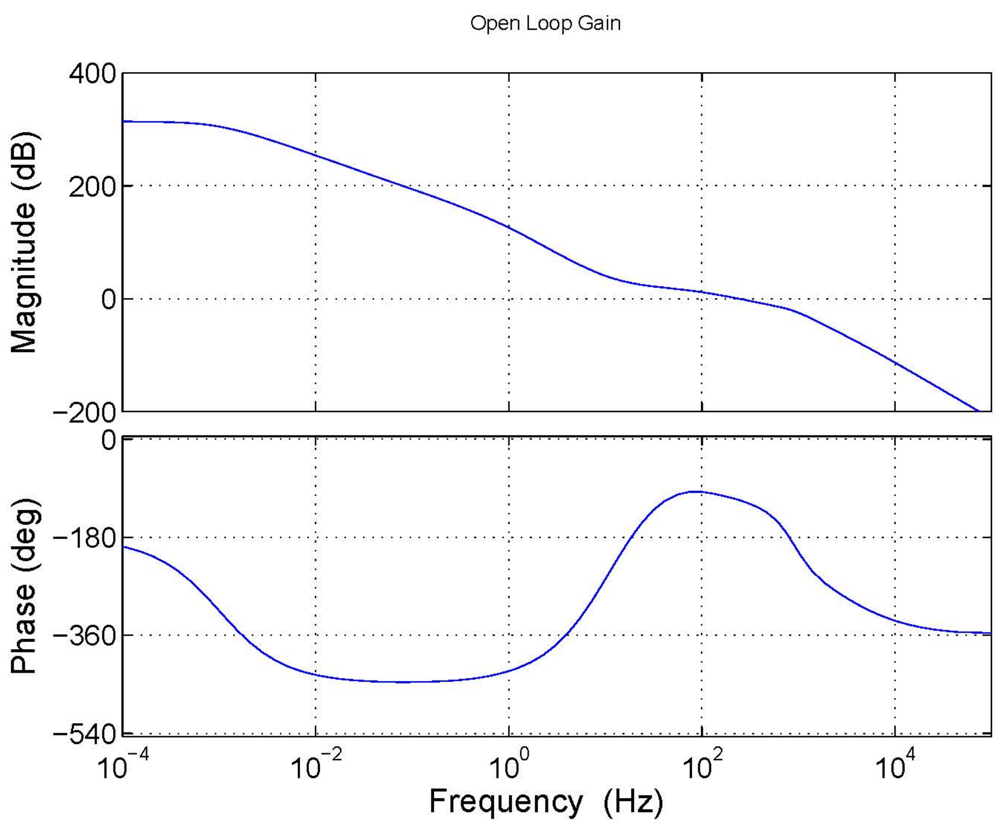

Figure 3: The open loop gain transfer function.

4 Project Schedule

1. June 19th- begin work on learning and understanding existing model
2. July 9th- Turn in first progress report
3. Characterize the calibrated detector response of the model
4. Begin introducing deviations
5. Develop improved digital filters
6. August 22nd- present final project report
7. August 23rd- end of project

References

[1] Craig Cahillane

[2] Frequency Domain Calibration Error Budget (2011),

[3] Jeff Kissel, *CALIBRATING AND IMPROVING THE SENSITIVITY OF THE LIGO DETECTORS*. (2010).

[4] Email coresspondance, lectures, and direct talks with Dr. Alan Weinstein and Jameson Rollins

[5] *Calibration of the LIGO Gravitational Wave Detectors in the Fifth Science Run.* Nucl.Instrum.Meth.A624:223-240,2010