LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Technical Note **LIGO-T1800224–v0** 2018/07/07

Thermal State of LLO Test Masses: Mirror Degradation Monitor

Project Proposal

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1 Introduction

The Advanced LIGO detector is composed of a Michelson interferometer with 4 km Fabry-Perot optical cavities that function as the arms of the interferometer. These cavities utilize high-reflectivity fused silica mirrors that interact with high power laser beams. These mirrors are referred as the input test mass (ITM) and the end test mass (ETM) of each arm. Each cavity has an optical power that ultimately will reach 800 kW and a small portion of this power is absorbed by test masses and then converted into heat. A thermal transient is created in the mirrors when the arm cavities control systems are locked.

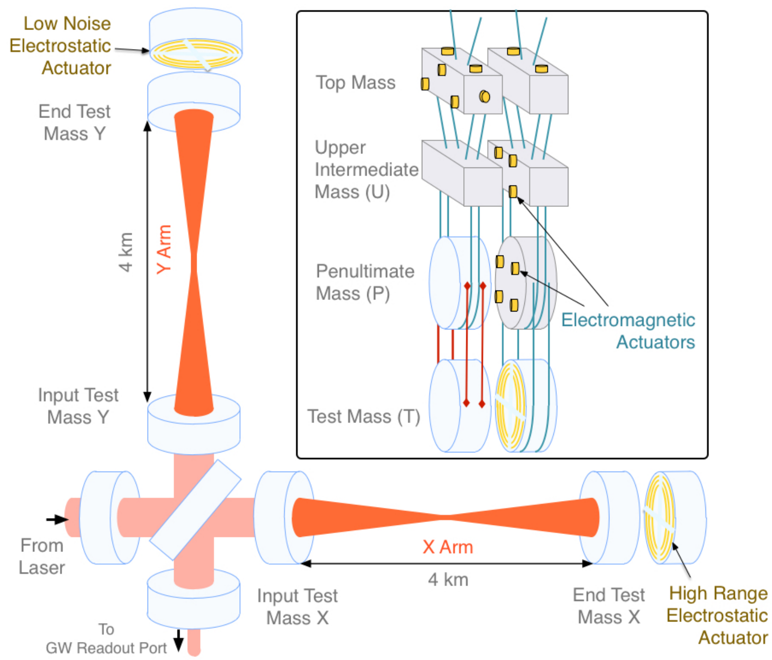

Figure 1: Diagram of an Advanced LIGO interferometer with Fabry-Perot cavities. [3].

There are two main effects that dominate the interferometers behavior due to the thermal transient. The first effect is known as thermal lensing which is caused by a change of refractive index through the thermo-optic effect. A reduced sensitivity of the interferometer can result from this process causing aberrations that contribute to a deterioration of mode matching between the many optical cavities of the interferometer. The deterioration of mode matching will reduce the optical gain and thus reducing sensitivity of the interferometer.

The second effect is the high-reflectivity coatings of the test masses being deformed from thermal expansion. A change of the radius of curvature (ROC) of the mirror is the first order deformation and this shifts the frequency of the transverse optical modes (TEM) resonant in the cavity. This changes the tuning conditions for parametric instabilities. As the mirror warms there is a relatively small increase in the mechanical mode frequencies due to the small positive thermal dependence of the Youngs modulus of the mirror substrates.

Parametric instabilities arises when the frequency spacing between the fundamental mode and a TEM mode equals the mechanical mode frequency. The interferometer can become inoperable and unstable if this condition is met.

This is a problem that needs to be addressed and investigated. Work has been completed by LIGO researchers to design and develop strategies aimed to minimize the role of these issues on the detector sensitivity. This is a problem I want to work on since the effects of these issues can have a more severe impact with the use of higher laser power. I will work on helping with the modeling of the test masses and help monitor the coating absorption of Livingstons test mass arms to provide a source of identifying coating damage or contamination. The paper, Thermal modelling of Advanced LIGO test masses discusses how LIGO researchers have built a thermal model of the test masses that applies shifts in mechanical mode frequencies as a probe for the overall temperature of the mirror. This paper provides information on estimates of the coating absorption of the ETMY of the Livingston detector. I plan on continue working on using the model for ongoing absorption monitoring to help provide early warning for potential contamination or degradation of test masses. I would also like to help track mechanical mode frequencies that might be relevant for parametric instability mitigation strategies. [1]

2 Objectives

My main goals are to apply the model described above to develop a method to build a Kalman filter to work on extracting useful information such as coating absorption from the available monitors. A Kalman filter is created by using the state-space methodology described in the Pure state space model of thermal effects paper by Aidan F. Brooks. [1] After carefully reading the paper, I know that my goal is to work on understanding why the thermal lens have one particular time evolution over another. The fitted response of the LIGO optics was produced by combining both COMSOL simulations and observations. His paper also focuses on wavefront distortions which are measured by the Hartmann Wavefront Sensor (HWS). A wavefront sensor Hartmann filter has already been implemented and I will be producing an eigenfrequency Kalman filter. I strive to include the eigenfrequencies to have verifying information and specifically when there is no Hartmann Wavefront Sensor. As a result, the wavefront distortions are a vital output of the Kalman filter.

Through my project, I will accomplish the creation of a Kalman filter that will help extract useful information about coating absorption and other measures from the available monitors. I will be working with COMSOL models and learning how to analyze them to extract information. I will also be using the LIGO CDS system that allows me to get data from the interferometer archives, where the normal interface is Matlab or Python. Furthermore, I will build state-space models and calculate step-function response and its derivative the impulse response and then creating state-space variables in order to arrive at a final model. This model can also encode the transient response of the acoustic modes of the test masses. I will then analyze data such as the self-heating response and ring heater response. The responses I obtain will be based on both empirical data obtained by using the COMSOL models and through the encoding of a Kalman filter to obtain a fitted response of the thermal lenses in LIGO optics. My starting conditions will be based on using the COMSOL models created and using the work completed by Brooks paper to continue working on modifying the state-space model. I will generate models for the test mass temperature as a function of ambient temperature, ring heater power and cavity optical power. Then I will compare the models to measured test mass eigenfrequency data from the interferometer.

3 Approach

Given that I have ten weeks to work on this project, I have divided my time to three main sections composed of extracting prior information from COMSOL models and analyzing the behavior, creating a Kalman filter that focuses on extracting coating absorption information, and finally working on testing my filter to see if the information it gathers provides a reasonable explanation. I have estimated the first component of looking at past data and working with the COMSOL model created to take two weeks of analysis and questions. The longest period spans five weeks and involves the theory, calculating, and formulating of a Kalman filter that fits with the conditions set from prior work. Finally, I have set the last three weeks to be focused on testing the filter and working on fixing problems I come across when extracting data. I will also dedicate the last week on creating a final report and organizing my findings to be presented.

4 Work Plan

Below I have created a schedule for my ten-week period at LIGO Livingston with the principal activities and events that I have in mind to accomplish in this given time.

Weeks 1-2: June 19-24

- Arrive at LIGO Livingston site on Tuesday June 19th
- Familiarizing myself with the thermal state COMSOL models and in general with my area of research for the upcoming weeks
- Start working on Progress Report and have a meeting with my mentors, keep a journal to write daily activities and notes

Week 2: June 25-30

- Work on understanding and analyzing the COMSOL models and empirically extracting data
- Focus on organizing my plans for the Kalman filter creation
- Continue working on the written progress report and meet with my mentors, updating journal

- This is my final week to finally understand how to work with the COMSOL models and have an approved plan from my mentors for my transition into making a Kalman filter

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Weeks 3-7: July 2-August 3

- Build a state space model: Kalman filter by dedicating these five weeks to the theory, creating state-space variables, state-propagation matrix, control-input model, a final model and outputs

- Turn in my first progress report at the given due date Work on my second progress report and on an abstract, constantly meet with my mentors for help and to check on my progress

- Attend site meetings, events, and continue working on my journal Outlining final technical paper

Weeks 8-10: August 10 -24

- Complete my Kalman filter and created fitted response of the thermal lenses in LIGO optics and analyze results by creating tables of frequency vs response describing different variables such as the acoustic mode as a function of ambient temperature or by the application of power to the ring heater o Compare models to measured test mass eigenfrequency data from the interferometer

- Turn in my final progress report and work on technical report Continue attending meetings, seminars, and meeting with mentors to work on finalizing abstract, final report, and presentation

References

[1] H. Wang, C. Blair, M. Dovale Alvarez, A. Brooks, M. F. Kasprzack, J. Ramette, P. M. Meyers6, S. Kaufer, B. OReilly, C. M. Mow-Lowry, A. Freise. , *Thermal modelling of Advanced LIGO test masses.*. Class. LIGO Document. 26 Apr (2017).

[2] S.C. Tait, I.W. Martin, C. Blair, R. Jones Z. Tornasi, A. Bell, J. Steinlechner, J. Hough,S. Rowan. *Optical Absorption of Ion Plated Coatings and Instantaneous absorption at LLO.* $https://dcc.ligo.org/DocDB/0150/G1800531/001/LVC_2018.pdf$ (2018).

[3] CALIBRATION OF THE ADVANCED LIGO DETECTORS FOR THE DISCOVERY OF THE BINARY BLACK-HOLE MERGER GW150914, *Thermal Modelling*. LSC.

[4] A. Brooks, *Pure state space model of thermal effects.* LIGO-T16xxxx-v1-D (2018).