LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
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2022 LIGO SURF Project Proposal: Emissivity Engineering for Radiative CryoCooling

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1 Introduction

Since the LIGO-VIRGO Scientific Collaboration's detection of gravitational waves in 2016, the field of gravitational wave astronomy has allowed for new ways to observe the physical phenomena. Collaborators hope to refine the precision of LIGO detection with further Advanced LIGO upgrades to explore new avenues in gravitational wave astronomy and multimessenger astrophysics. The LIGO Voyager version is an upgrade that will increase the sensitivity to about 700-1100 Mpc [**1**] by using cryogenic temperatures of 123 K to reduce thermal noise within the LIGO barrel. Constacio et. al. found that silicon has a high enough natural emissivity to maintain the temperature of test masses at 123K, meaning that it is an appropriate material to use in the Voyager upgrade barrel [**2**]. However, because the LIGO interferometer lasers must be very powerful (around 10W), Constacio et. al. theorized that the barrel will also require a high thermal emissivity to increase radiative coupling to its cooled environment. This will improve the cool-down time of the Voyager upgrade apparatus and help maintain the system at 123 K despite the excess heating from the laser [**2**].

Constancio et. al. showed that high emissivity coating is necessary if the laser power is greater than 6W. Therefore, it is important to test the emissivities of various materials in order to identify coatings that will sufficiently increase coupling from the excess power from the interferometer laser. The coatings will need to have emissivity between 10 - 100 um wavelength [**3**]. This will reduce the cool-down time of the system and allow for conditions to hold the system at 123K.

To determine the emissivities of various black coatings, the cool-down curves from room temperature to 123 K is monitored with respect to time using thermocouple thermometers for test masses in a cryostat chamber held at vacuum. Then, the emissivity value and propagated uncertainty can be extracted from these data by plotting emissivity against temperature [**2**]. Obtaining these data is an expensive and time-consuming process, and therefore it is beneficial to optimize this procedure and model to efficiently obtain emissivity values while minimizing uncertainty. By simulating different geometries and materials, it is possible to find a model with the lowest noise in the data by tracking how errors propagate using Markov Chain Monte Carlo (MCMC) analysis. This optimal experimental design can be applied to emissivity tests for many black coatings that can potentially be used in the LIGO Voyager upgrade.

2 Objectives

- Develop a model using radiative heat transfer equations to estimate the cool-down curves of various high thermal emissivity coating samples to potentially be applied to the barrel surface. New models may need to be developed depending on updates to the geometry of the testing environment.

- Collect cool-down temperature data using RTDs in a high-vacuum cryostat chamber to determine the temperature-dependent emissivity of a silicon wafer that is radiatively cooled to 123 K. These data will be used to improve the system/model.

- Repeat Step 2 with new materials to experimentally determine the temperature-dependent emissivity of high thermal emissivity coatings by measuring the cool-down curves of the coatings to 123K.

- Perform analysis of the data using linear regression to extract the emissivity estimates and propagated uncertainties. Implement MCMC analysis to improve the precision of these estimates.

3 Approach

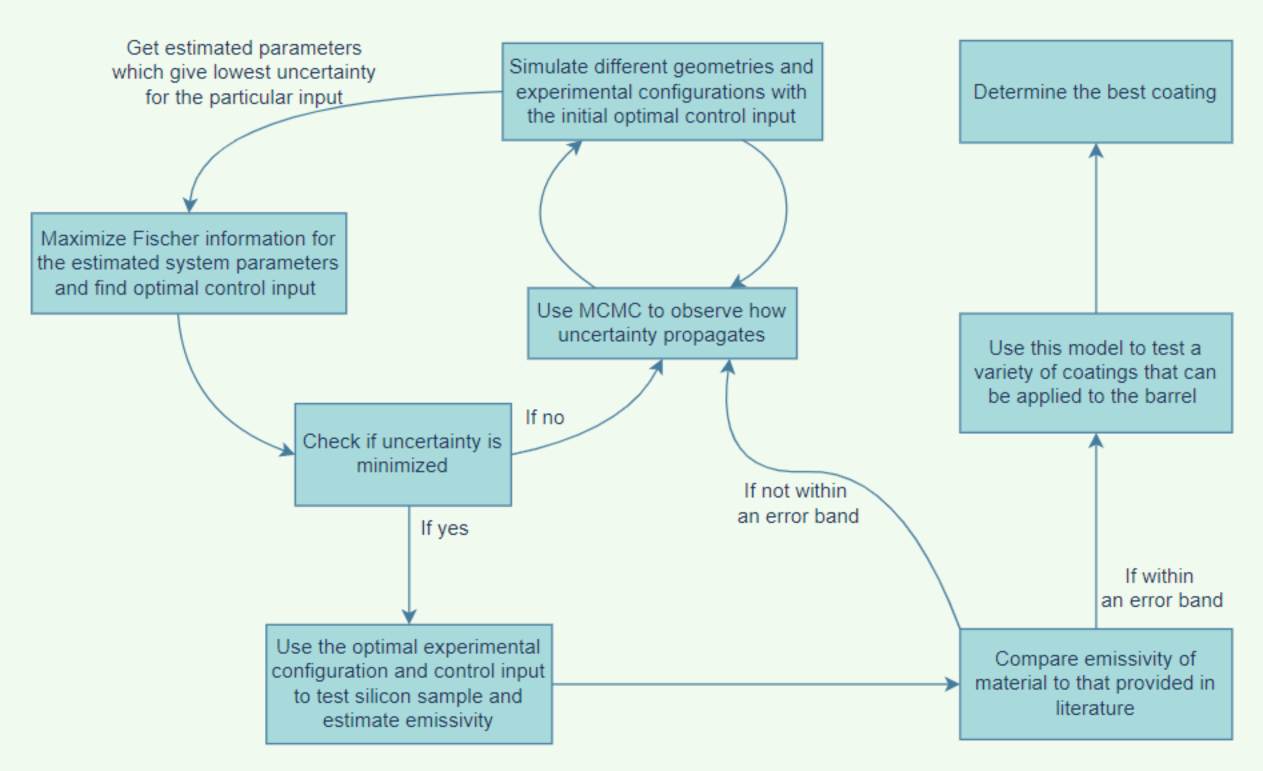

Figure 1: The experimental plan requires analyzing initial modeling repeatedly until a geometry is found with sufficiently low uncertainty. The outcome of a silicon sample test will determine if we will use the model to determine the emissivities of a variety of coatings or whether we will go back to analyzing the simulated experimental design to find a more optimal geometry. This project is in collaboration with an adjacent LIGO SURF project. Aspects of this experimental design that are in Figure 1 but not included within this proposal will be carried out by another SURF student.

3.1 Modeling the Cool-Down Curve Based on Experimental Design

Simulate experimental designs and geometries in python and use MCMC analysis to observe how simulated uncertainty propagates. Repeat the simulation with many experimental geometries to find the optimal parameters. This cycle of simulation and analysis will be repeated until a geometry/experimental design with the lowest uncertainty is determined (Figure 1).

3.2 Comparing Data to Models Using Statistical Analysis

Test the optimal model on a silicon wafer as the test material. If the measured emissivity value matches literature, then this experimental design can be implemented for further testing. If this experimental design does not match the accepted value within acceptable uncertainty, then we will return to "Modeling the Cool-Down Curve" to determine a better experimental design and further improve accuracy (Figure 1).

3.3 Implementing the Optimal Experimental Design

Use this optimal experimental design to test the emissivity of various black coatings. We can then determine the best coating from a wide range of materials. Many of these materials are not chosen yet.

4 Timeline

- **Week 1-3: Learn about heat transfer equations. Become familiar with existing models then build my own simple model for proof of understanding. By the end of Week 1, I should understand the scope of the experiment and be comfortable with the general physical principles.**
- **Week 4-5: Test model with silicon wafer and improve the model and/or parameters if necessary.**
- **Week 6-9: If the silicon test matches literature, measure the cool-down curves of Diamond-Like Black Coating, Aktar Black Coating, surface oxide layers, etc. If the silicon test does not match literature, refine the parameters and geometry based on the model by implementing MCMC.**
- **Week 10-11: Implement MCMC analysis to improve our understanding of the model.**

References

[1] V. Mitrofanov, *LIGO Voyager Project of Future Gravitational Wave Detector*, https://dcc.ligo.org/public/0139/G1602258/002/Presentation_Mitrofanov.pdf.

[2] M. Constancio and R. X. Adhikari and O. D. Aguiar and K. Arai and A. Markowitz and M. A. Okada and C. C. Wipf, International Journal of Heat and Mass Transfer, **157**, 2020.

[3] R. X Adhikari, A. Brooks, B. Shapiro, D. McClelland, E. K. Gustafson, V. Mitrofanov, K. Arai, C. Wipf, *LIGO Voyager Project of Future Gravitational Wave Detector*, https://docs.ligo.org/voyager/voyagerwhitepaper/main.pdf.

[4] Y. A. Cengel, Heat transfer: a practical approach, McGraw-Hill series in mechanical engineering (McGraw-Hill, 2003) Chap. 12.

[5] The ideas for this proposal were based off of discussions over Zoom with Professor Rana Adhikari (Experimental Gravitational Physics, LIGO Lab Caltech), Radhika Bhatt (graduate student, Adhikari research group), and Christopher Wipf (Gravitational Wave Interferometer Research Scientist, LIGO Caltech) and another LIGO SURF student, Hiya Gada. Figure 1 was designed in collaboration with Hiya.