LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
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Technical Note **LIGO-T22xxxxx–** 2022/07/29

2022 LIGO SURF Interim Report 2: Emissivity Engineering for Radiative CryoCooling

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1 Introduction/Motivation

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 Progress: Moving from Simulated to Real Data

Since the first interim report, steps have been taken to develop a more complicated model of the Megastat system. By implementing the code from the scipy solve_ivp numerical solver in report 1 and building upon of the parabolic curve MCMC code previously developed (see interim report 1), this model uses a simulated cooldown curve modeled by an ODE (including random noise) for a test mass surrounded by a spherical shell.

Ideally, the MCMC code would fit the ODE to the temperature data by performing the numerical integration. However, this is challenging to code. Therefore, providing the data and the first derivative of the data is an intermediate step that directly links the previous parabolic model to the ODE cooldown model. By providing both the data and it's first derivative, MCMC is estimating parameters the same way that it would for an algebraic equation by evaulating an array of 'x values,' or the cooldown data, and 'y values,' or the first derivative of the cooldown data.

This intermediate program numerically calculates the first derivative for each point on the simulated cooldown curve. The array of slopes and the simulated data are used to fit for the emissivities of the test mass, enclosure, and heat leak. The enclosure and heat leak translate to the inner and outer shield of the real system.

2.1 Simulated Cryostat

Before running the MCMC on real data, it was important to observe how the program handled simulated data with known parameters. These data were created by adding noise to the numerically calculated solution to the differential equation for the net heat transfer between the test mass and its environment with an initial value of 295 K. Solutions to Equation 1:

$$mc_p\frac{dT_1}{dt} = \frac{\sigma A_{tm}(T_2^4 - T_1^4)}{\frac{1}{\epsilon_1} + \frac{A_{tm}}{A_e}(\frac{1}{\epsilon_2} - 1)} + \frac{\sigma(T_3^4 - T_1^4)}{\frac{1-\epsilon_1}{A_{tm}\epsilon_1} + \frac{1}{A_{tm}F_{13}} + \frac{1-\epsilon_3}{A_h\epsilon_3}}$$

were used to model the net radiative heat transfer, where Table 1 defines the variables for the system.

Variable	Meaning
m	Test mass in Kg
c_p	Specific Heat (function of temp)
T_1	Temperature of the test mass
T_2	Temperature of the Inner Shield
T_3	Temperature of the Outer Shield
σ	Stefan Boltzmann Constant
A_{tm}	Surface Area of the Test Mass
A_e	Surface Area of the Enclosure
F_{13}	View Factor from test mass to heat leak
ϵ_1	Thermal emissivity of the test mass
ϵ_2	Thermal emissivity of the enclosure
ϵ_3	Thermal emissivity of the heat leak

Figure 2 shows how information from the data did not add very much new information for the MCMC walkers. This is evident from observing how the walkers explored the prior space and how closely the prior distributions matched the posterior distributions. The walkers did not converge well and generally explored the entire region given in the prior, as evident in the trace plots in Figure 2. The posterior distributions almost perfectly matched the priors, meaning that the data were not providing enough information for MCMC to properly estimate new parameters. It is interesting to note that the posterior distributions

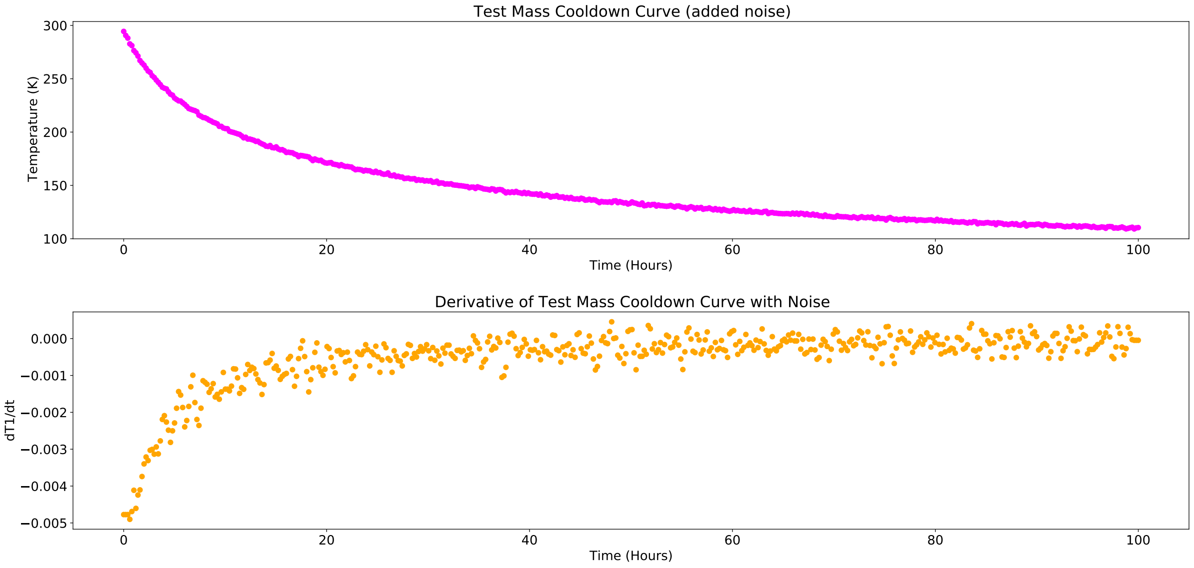


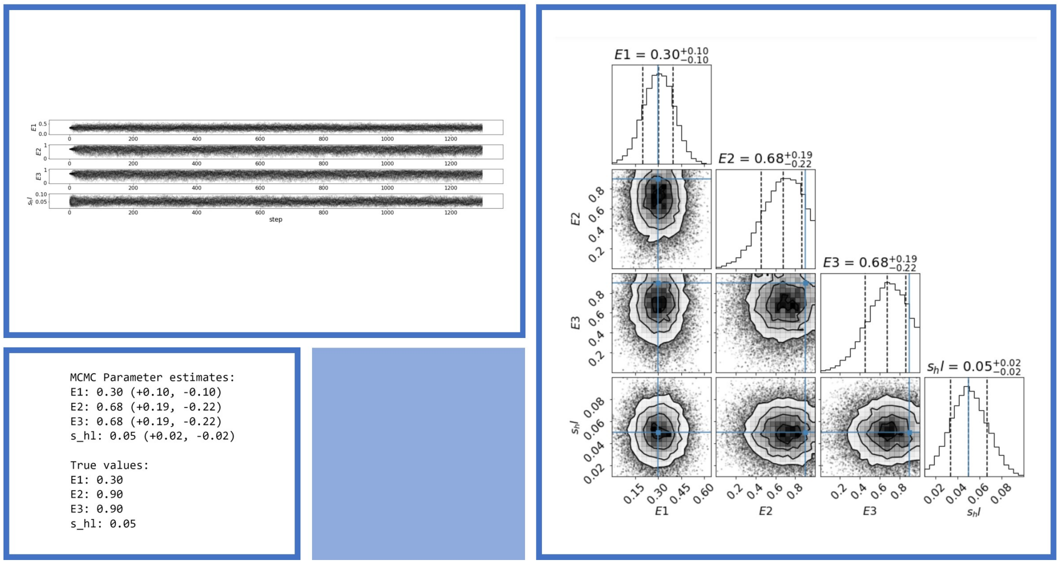
Figure 1: *Top:* The simulated data for a test mass cooldown. *Bottom:* The manually computed (unsmoothed) derivative of the cooldown data.

for the emissivity of the inner shield and the heat leak (E2 and E3 respectively in Figure 2) moved in the opposite direction of the true value. This could be because the derivative of the cooldown curve was computed manually without any smoothing (Figure 1). This meant that the derivative was very noisy, and could have effected how the MCMC found posterior distributions. When moving to real data, this issue was fixed by implementing a scipy smoothing method for computing the derivative to reduce noise.

2.2 Real Data

Using real data from cooldowns on 01-07-2022 and 15-07-2022 of a glass and silicon wafer respectively, the emissivities of the wafers, the inner shield, the outer shield, and the effective side length of the heat leaks (approximating as a square) were estimated. These data provided the new challenge of using MCMC to estimate parameters for a system where the emissivities of the wafer and the surrounding was not known to high accuracy. In these models, the temperatures of the inner and outer shield were functions of time from the raw data, meaning that the theoretical curve for the test mass cooldown reflected the actual cooldown (Figure 3). With these data, the unknown emissivities and the size of the heat leaks was modeled.

The improvements from the simulated model to the real data meant that MCMC was able to find new posterior distributions that did not necessarily match the priors. Figure 4 shows how the posterior distributions did not match the priors with respect to E1 and E2. However, parameters E3 and s_{hl} matched the prior distributions very closely. This is evidence that there is a bug in the code, as discussed in the challenges section. Despite these setbacks, this is a step forward to being able to use MCMC to reliably model parameter estimation of this system.



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MCMC Parameter estimates:
E1: 0.30 (+0.10, -0.10)
E2: 0.68 (+0.19, -0.22)
E3: 0.68 (+0.19, -0.22)
s_hl: 0.05 (+0.02, -0.02)

True values:
E1: 0.30
E2: 0.90
E3: 0.90
s_hl: 0.05
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Figure 2: *Top Left:* The trace plots for the simulated data show the walkers exploring the whole parameter space. They did not converge well on a new value not given by the priors. *Bottom Left:* The true values of the emissivities and the heat leak aperture with uncertainty. *Right:* The corner plots for this run reveal that the posterior distributions are very similar to the prior distributions for the values where it was fed the correct priors. For the parameters where the prior distribution was off center from the real value, the posterior was slightly different. Interestingly, it moved in the opposite direction of the true value (refer to bottom left).

3 Challenges

3.1 MCMC

In Interim Report 1, the dominant issue with MCMC implementation was because there was strong coupling between the parameters, meaning that it was impossible to distinguish between the values of each emissivity. This meant that it was possible to fit for the product of the emissivities, but not each repective value. However, this coupling became less problematic when modeling the real system, where the emissitvities can be distinguished from each other because of the scaling factor on ϵ_2 in Equation 1.

Although the MCMC program currently runs, it is not finding accurate parameter estimations (Figure 4). There are a number of reasons for this. The prior distributions should be more accurate and the smoothing in the derivative of the cooldown data needs to be optimized. It will be beneficial to find the optimal number of intervals to smooth over to create an accurate yet less noisy curve to feed the MCMC. Based on the fact that the walkers are not converging for parameters E1 and E2 (Figure 5), it is theorized that there is a bug in the log likelihood function as well. Indentifying and removing this error will allow MCMC to search for and converge on an area of highest probability. This problem most likely arose when converting the code from a simulated data set to implementing real data (most likely

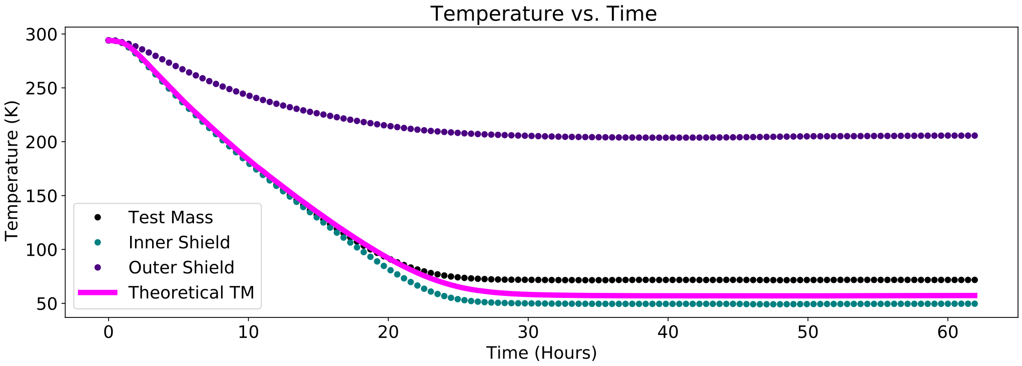

Figure 3: The cooldown curves of the test mass, inner shield, and outer shield with the theoretical curve for the glass wafer cooldown on 01-07-2022. This particular iteration shows that the theoretical curve is computed with a heat leak term that is too small, hence the downward shift.

calling the wrong parameter somewhere). With these changes to the MCMC program, it will hopefully be possible to estimate the emissivity of the glass and silicon wafer.

4 Future Work

- Locate and fix the bug in the likelihood function.
- Adjacently develop a least squares curve fitting program for proof of concept for finding the correct parameters. Use this model to learn more curve fitting in general and prove that there are optimal parameters for this system.
- After fixing bugs in the model, use it to simulate error propagation for different parameters.
- In the lab, calibrate and install a new RTD for for Megastat cold head.

5 Acknowledgments

Thank you to Professor Rana Adhikari (Experimental Gravitational Physics, LIGO Lab Caltech), Radhika Bhatt (graduate student, Adhikari research group), and Christopher Wipf (Experimental Gravitational Physics, LIGO Lab Caltech) for their support in this project as mentors. I also appreciate and acknowledge the National Science Foundation Research Experience for Undergraduates program, the California Institute of Technology, and the LIGO Summer Undergraduate Research Fellowship for this opportunity.

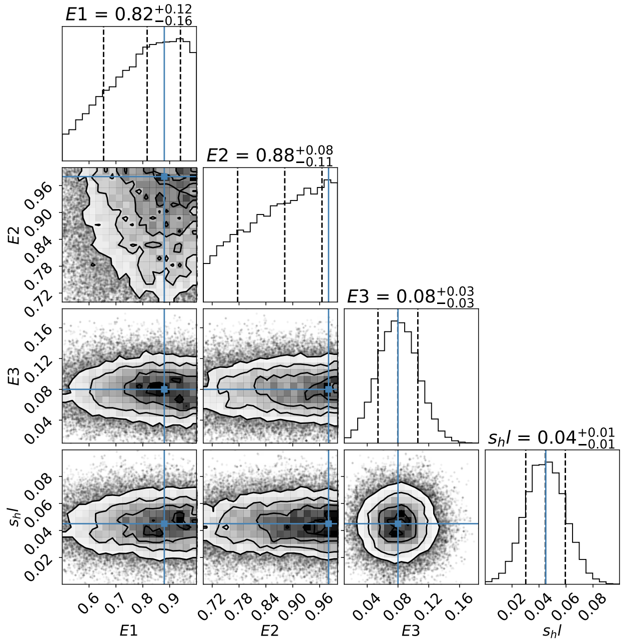

Figure 4: The corner plots for the glass wafer show that the parameter estimation is not yet perfected. It is concerning that the posteriors for E3 and s_{hl} match the prior distributions but the other parameters' posteriors do not.

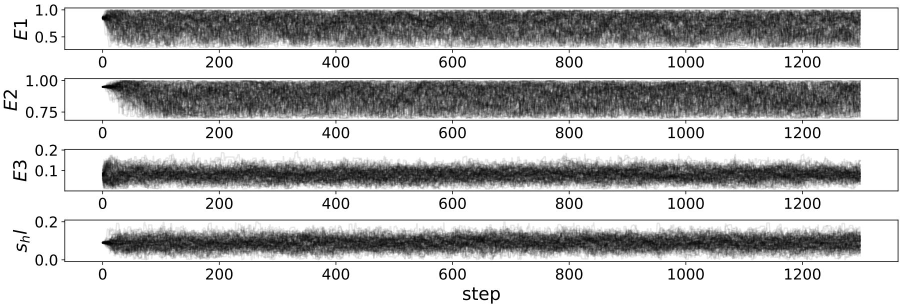

Figure 5: The trace plots for an iteration of the parameter estimation on the glass wafer cooldown show that the walkers for E1 and E2 are not converging. This is evidence that the MCMC code is not able to locate areas of highest likelihood.

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] M. Pitkin, An example using emcee, 2018, Accessed: 7-11-2022, Available: http://mattpitkin.github.io/samplers-demo/pages/emcee/

[6] I. Martinez, Radiative View Factors, (http://webserver.dmt.upm.es/ isidoro/tc3/Radiation %20View%20factors.pdf)

[7] The ideas for this report were based off of discussions with Professor Rana Adhikari (Experimental Gravitational Physics, LIGO Lab Caltech), Radhika Bhatt (graduate student, Adhikari research group).