LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Technical Note **LIGO-T2300146–v1** 2023/07/13

Developing spatially-tunable adaptive optics for LIGO

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1 Introduction

Gravitational waves (GW) were first predicted by Albert Einstein in his General Theory of Relativity. Their first direct detection was in 2015 by the Laser Interferometer Gravitational-wave Observatory (LIGO), through the response of free test masses (mirrors) to the strain of spacetime.

Increasing stored power in the LIGO interferometers decreases quantum shot noise at high frequencies [2]; however, this gives rise to undesirable thermally-induced distortions due absorption of power. Absorptions in the coatings of the test masses results in a radial temperature gradient [2], causing unwanted lensing effects and surface deformations. These in turn cause wavefront distortions, reducing the amplification of the gravitational wave signal and increasing noise at the readout photodiode. Such distortions are currently compensated by the Thermal Compensation System (TCS).

Uniform absorption refers to the absorption of the main laser beam caused by a spatially invariant absorption coefficient across the high-reflectivity surface of the optic. [3] TCS is designed to compensate for uniform absorption. Non-uniform absorption involves higher spatial-frequency absorption caused by features such as point absorbers, or non-uniform coating absorption and emissivity. Such non-uniform absorption induces distortions causing power to scatter from the fundamental mode into higher order spatial modes [3], which can be enhanced or suppressed by arm cavity gain.

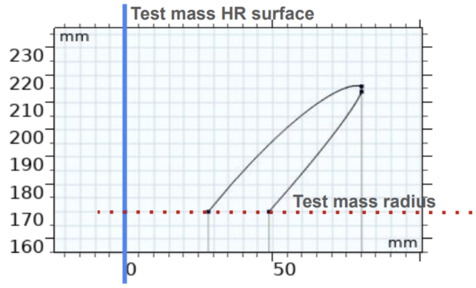


Figure 1: FroSTI Reflector System Design [5]

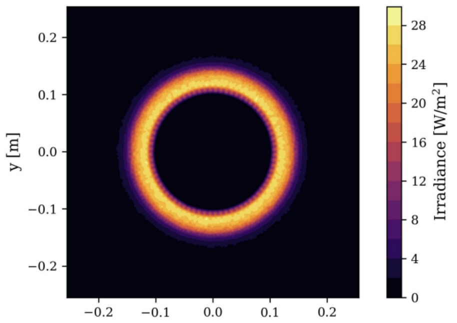


Figure 2: FroSTI Radiance Profile [5]

The front-surface-type irradiator (FROSTI) is a prototype actuator designed for aLIGO which consists of a ring heater mounted in front of the test masses. FROSTI's initial de-

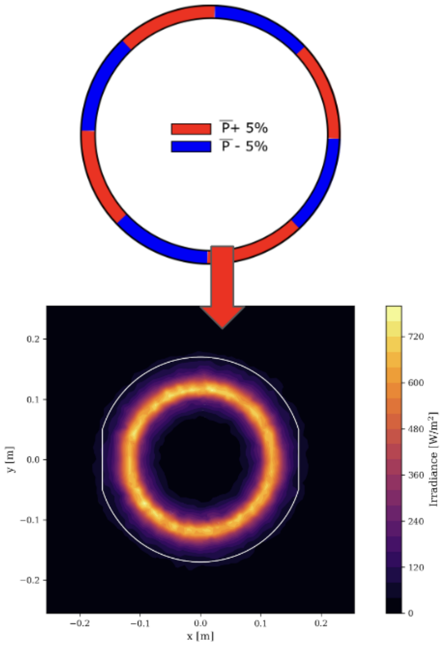


Figure 3: FroSTI Radiance Profile with Variance in Individual Heating Units [4]

sign targets the enhanced loss of the fundamental mode to the 7th order mode by point-absorbers[4] and will also compensate for the non-spherical surface deformation due to coating absorption. FROSTI uses the asymmetric elliptical profile to deliver IR radiation effectively to the mirror surface (Figure 1). FROSTI demonstrated its ability to constrain radiation radially (Figure 2) but does not constrain rays azimuthally (Figure 3). Simulations of the FROSTI system, consisting of multiple heating units, show that varying radiation across individual units does not produce an exact correspondence of heating in target regions.

2 Section 2: Objectives and Approach

The objective of this project is to address the non-uniform absorption-induced distortion by designing new FROSTIs to generate more complex and precise heating profiles. The project aims to modify the current FROSTI design to improve localization of radiation in target regions (improving radial and azimuthal confinement) while also maintaining an efficient and realistic heater arrangement.

- Current ray tracing simulations of FROSTI are simplified by reducing the geometry to a quarter of a revolution and a straight line extruded model.
- The distribution of heat from the simplified heating units are then analyzed to determine the best figure of merit for the reflector system confinement optimization.
- Necessary design alterations of individual heating units will be identified by optimizing individual segment power.

- Once the optimal reflector system design for a single heating unit has been identified, then the entire ring heater can be simulated.
- A Monte Carlo simulation will be performed to show the distribution of residual distortion (rms) after optimization.

3 Section 3: Challenges and Progress

3.1 Challenges

Challenges I've experienced in the past weeks have been primarily surrounding familiarity with the COMSOL interface. I've gained experience with the simulation progress and have identified the most common problems and mistakes I run into when setting up/running a study. I've also experienced challenges on interpolating the COMSOL data for ease in my analysis. I've identified the most appropriate interpolation method (SciPy's LinearNDInterpolator) for COMSOL mesh data.

3.2 Progress

I have familiarized myself with the COMSOL modeling software, specifically the geometrical optics/ray tracing modules, and with the current FROSTI design/simulations. I've confirmed the current radial confinement of the initial FROSTI design (Figure 4).

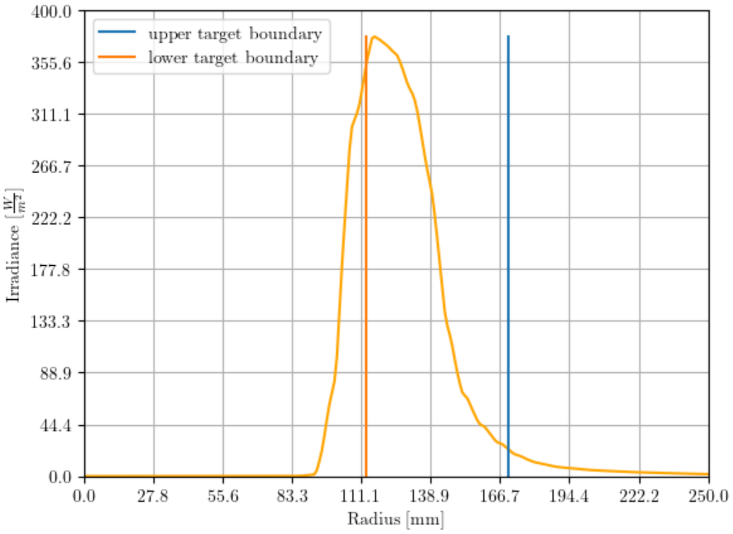


Figure 4: Average Radial Distribution of FROSTI (Full) Model

I've modified the current FROSTI model by reducing it from a fully-revolved heater to a quarter revolution (one out of four simulated heater elements). I've also modified the quarter-revolution heater to a straight line model by extruding the elliptical profile.

When simulating the quarter-reduced model (Figure 5), there is an decrease in both radial and azimuthal confinement. This decrease is similarly represented in the straight line model (Figure 6).

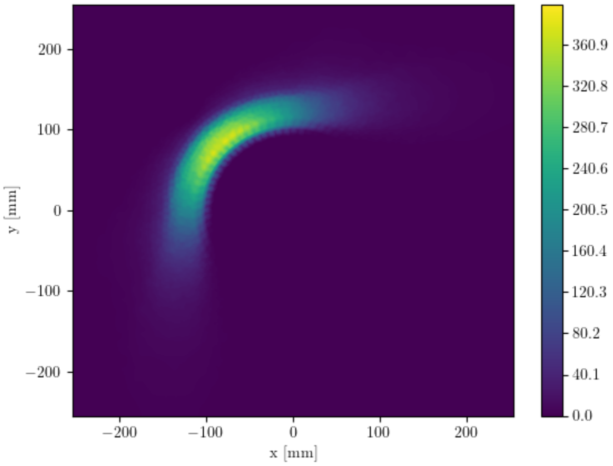


Figure 5: Quarter Revolution FROSTI Model Surface Irradiance [$\frac{W}{m^2}$]

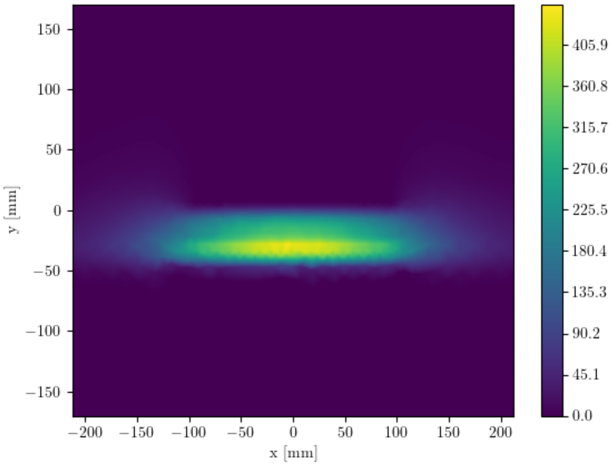
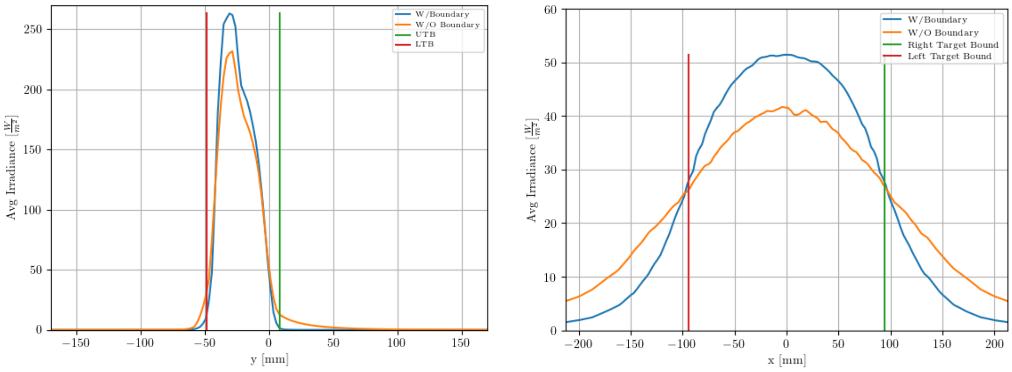


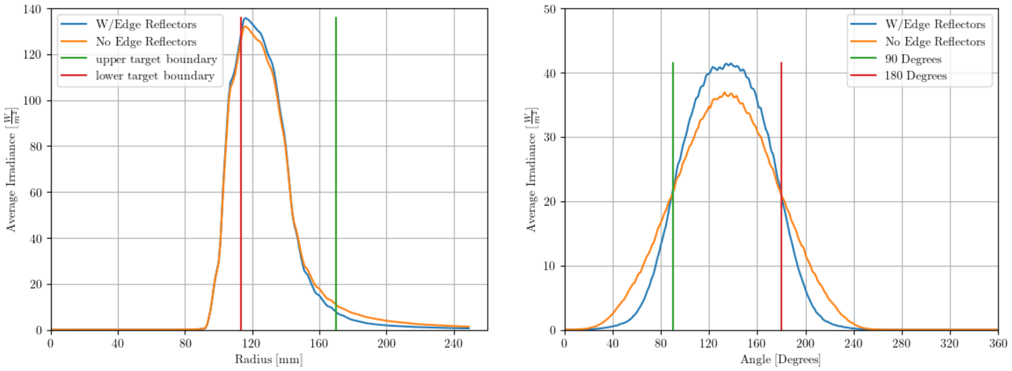
Figure 6: Quarter Extruded FROSTI Model Surface Irradiance [$\frac{W}{m^2}$]



(a)

(b)

Figure 7: (a) Vertical and (b) Horizontal Distributions of Irradiation for the Quarter Revolution Model.



(a)

(b)

Figure 8: (a) Radial and (b) Angular Distributions of Irradiation for the Quarter Revolution Model.

Possible figures of merit for both models have been identified. For the quarter revolved model, the figures of merit are the average radial and azimuthal distributions of irradiance. For the straight line model, they are the average vertical and horizontal distributions of irradiance. These figures of merit for the straight line model are being evaluated now by simulating reflecting boundaries on the edge of the reflector (Figures 7a and 7b).

The quarter revolution heater model also has been simulated with edge reflecting boundaries and compared with the unbounded version (Figures 8a and 8b).

The straight line figures of merit will continue to be evaluated with different edge reflector surfaces, such as parabolic or elliptical.

4 Section 4: Future Goals and Potential Challenges

Goals for the upcoming weeks of the program include:

1. Continuing simulations of the straight line model with alternative lengths and surface boundaries.
2. Beginning and continuing simulations of the quarter revolved model with different surface boundaries (concurrently with straight line modifications).
3. Identifying proper figures of merit for analyses through above geometry modifications.
4. Applying most promising geometry modifications to the full FROSTI design and evaluating their performance.

Potential challenges include the design of the non-flat edge reflectors; practicing with extruding parabolic and elliptical surfaces from the reflector's cross-section will be necessary. It also may be challenging to identify the most optimal characteristics of the non-flat reflectors (most specifically the curvature/extent outward).

4.1 Updated Timeline

Week 4: Continue to explore geometry modification design space of straight line reflector with average vertical/horizontal distributions as figures of merit. Simulate effects on radiation spread from modifying the length of the bounded straight line reflector, and from different types of edge reflector surfaces. Begin making geometry modification edits and analyses of the same nature to the quarter rotated bounded model. Begin to simulate eighth rotated model and add modifications based on findings from straight line/revolved quarter models.

Weeks 5 and 6: Finalize modeling reflector system designs for single-heating unit models (finish by start of Week 6). Apply any required single-heating unit design modifications to full FROSTI design.

Weeks 7 and 8: Evaluate new full heater with modifications. Make adjustments to full heater design and analyze for possible improvements.

Week 9: Test confined FROSTI design with Monte Carlo generated non-uniform distortion and evaluate actuator efficacy in minimizing residual wavefront distortion.

Week 10: Finalize and consolidate presentation materials.

References

[1] Rana X Adhikari, et al., *Gravitational Radiation Detection with Laser Interferometry.* arXiv:1305.5188 (2014).

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[4] Huy Tuong Cao, et al., *Development Status of HOM Ring Heater.* LIGO Presentation, UCR Physics and Astronomy, 2022.

[5] Huy Tuong Cao, et al., *Updates on FroSTI for use in LIGO.* LIGO Presentation, UCR Physics and Astronomy, 2023.

[6] Lun Jiang, Roland Winston, *Asymmetric Design for Compound Elliptical Concentrators (CEC) and its geometric glux implications.* Proc. SPIE 9572, Nonimaging Optics: Efficient Design for Illumination and Solar Concentration XII (2015).

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[8] Roland Winston, et al., *Nonimaging optics: a tutorial.* Advances in Optics and Photonics, Vol. 10, Issue 2, pp. 484-511 (2018).