Developing an In-Air IR Test Facility for Next-Generation Wavefront Control

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LIGO SURF Presentation

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Presentation Outline

Objectives

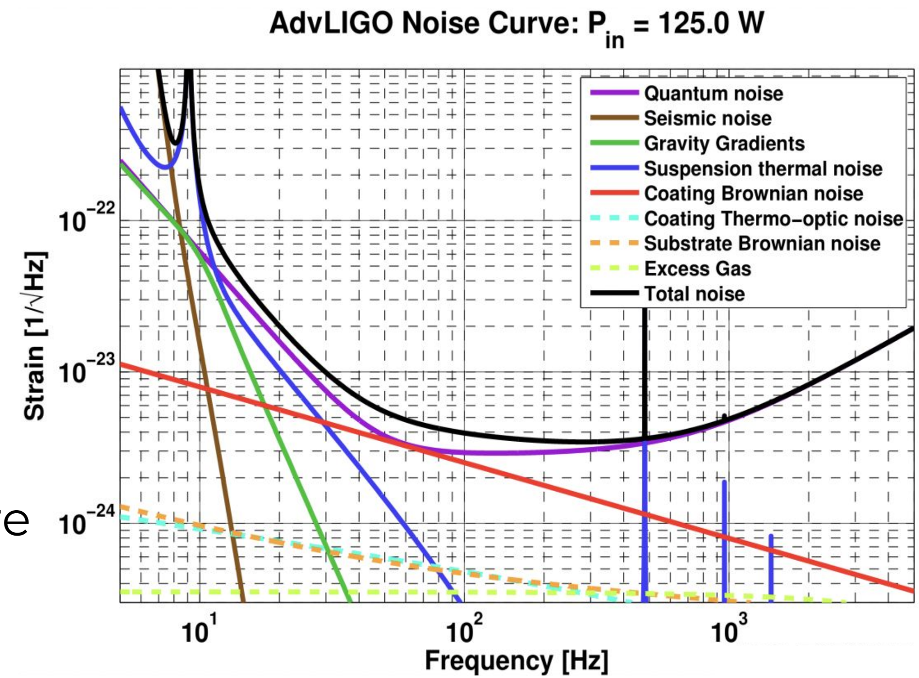
Construct an in-air optical test facility to allow for the testing of infrared adaptive optics systems.

Develop Python code to collect raw data from the infrared sensor in order to test current and future wavefront controlling technology.

Background

Motivation

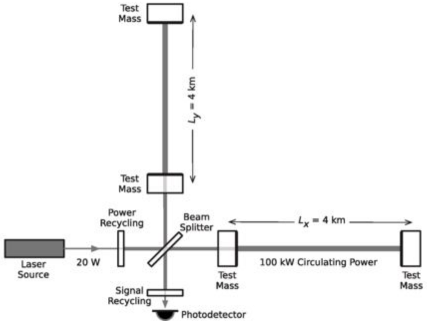
- Quantum noise domination after ~ 10^2 Hz
- Lessening photon shot noise lowers quantum noise floor
- Amplitude spectral density of shot noise scales as $\frac{1}{\sqrt{N}}$, where N = number of photons
- More laser power



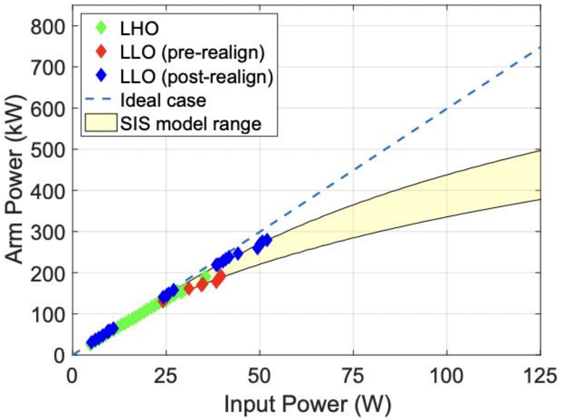
aLIGO Noise Budget Breakdown
(Hild 2017, G1200598)

Problem

- Ideally, laser is characterized by fundamental Gaussian mode
- More power deforms the test mass substrate
- Point absorbers scatter laser light into higher order modes
- Less sensitivity when losing power to higher order modes
- Arm power ≠ design power



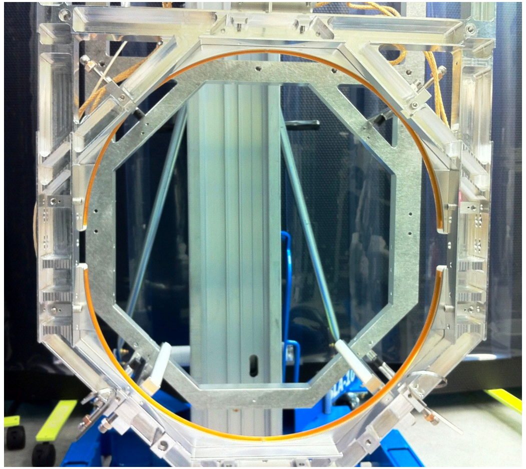
Simplified LIGO layout
(Abbott *et al.* 2016)

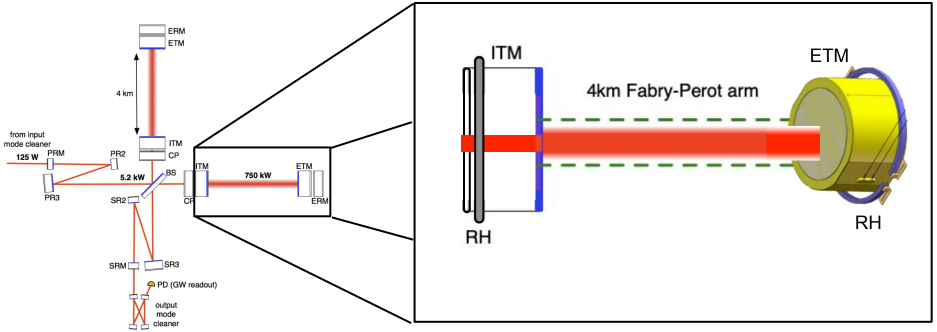


aLIGo ideal vs. actual arm power vs. input power circa 03
(Brooks *et al.* 2021, P1900287)

Current Solution: Thermal Compensation System

- Ring heaters to adjust radius of curvature
- Mismatch between ring heater correction and uniform coating absorption deformation becomes limiting
- Can’t address point absorbers



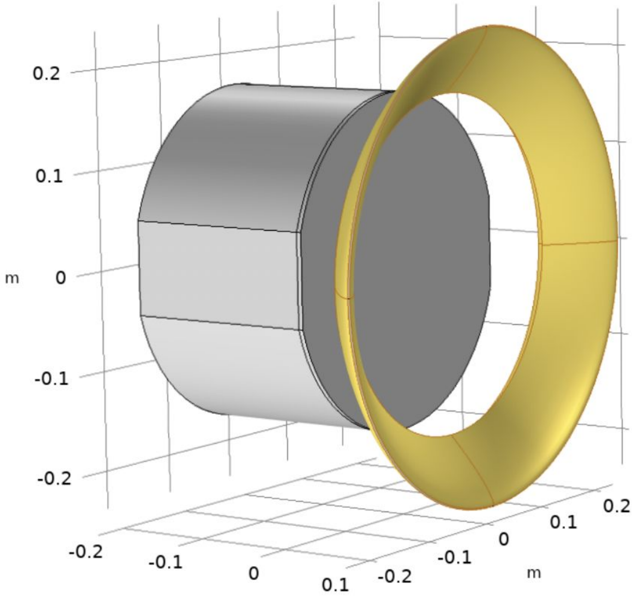


Above: Image of ring heater (orange) around large optic
(Image from https://www.advancedligo.mit.edu/aos.html)

Left: Setup of current TCS with model of ring heater actuator in place for the end test mass
(Diagrams: Brooks *et al.* 2016, arXiv:1608.02934)
(Model: Willems 2011, G1100460)

Proposed Solution

- Next gen ring heater: minimize scattering in key higher order modes (Phoebe Zyla)
- Have theoretical models of HOM ring heater → need to experimentally confirm
- **Need a way to measure the radiance profile of the ring heater on the test mass surface**



Proposed ring heater solution
(Richardson 2022, G2200399)

Path to Implementation

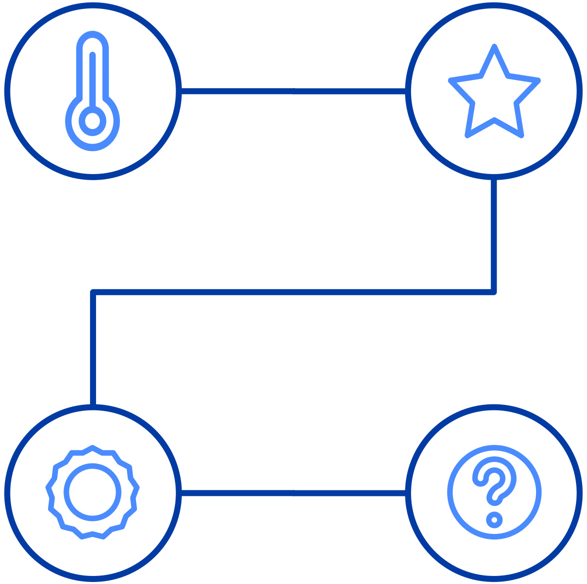
Richardson Lab

Temperature Map

- Optical system setup
- Experimental measurement: temperature

Radiance Profile

- Know geometry/materials
- Create radiance profile in Comsol (W/m^2)



Deformation Map

- Comsol models to retrieve deformation map

Simulations

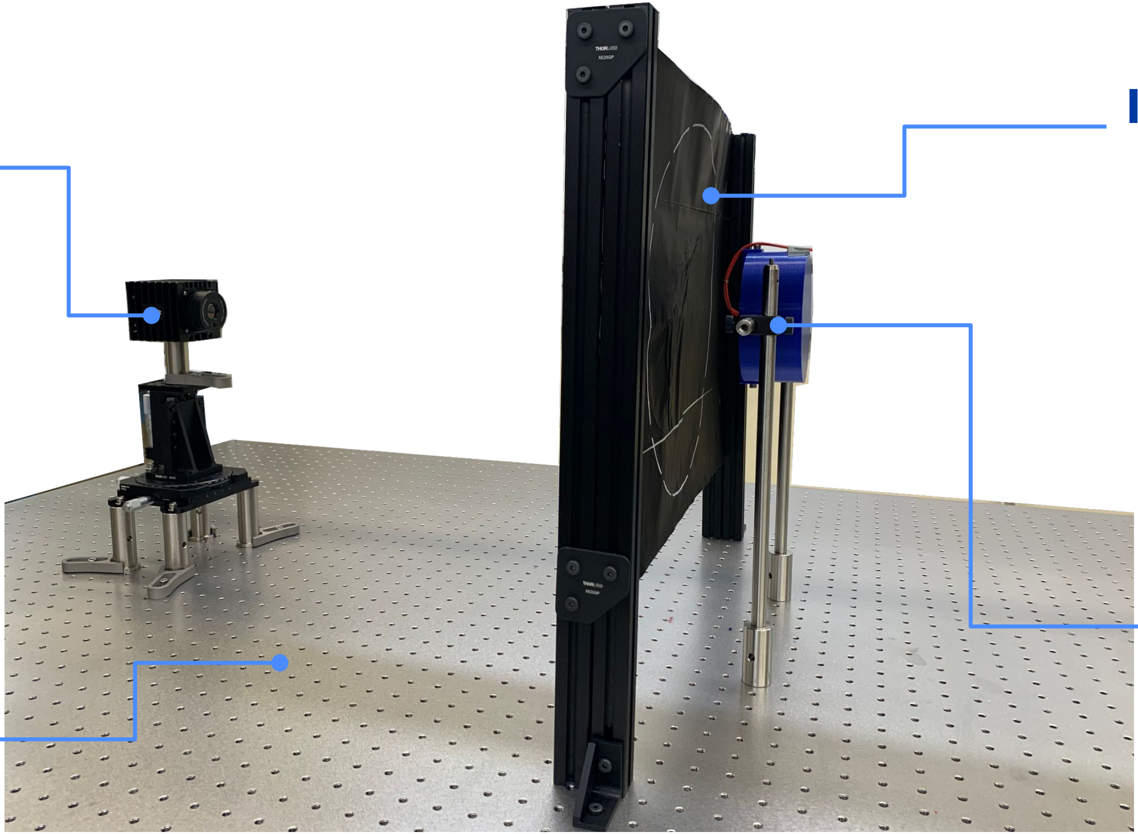
- Document how test mass deformation changes RTL, DARM sensitivity, etc.

System Setup

Optical System Setup

IR Camera
To measure power output

IR-Absorptive Thin Screen
With test mass outline



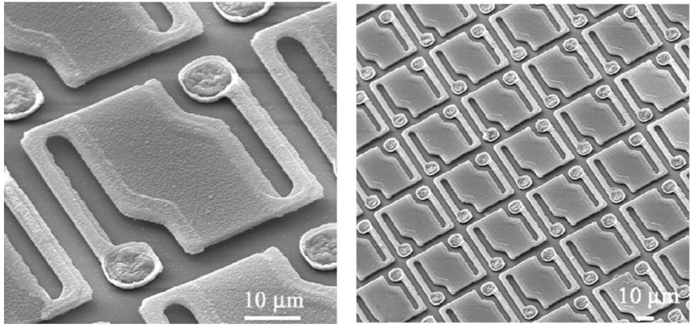
Heater System
Proof of Concept

Optical Table

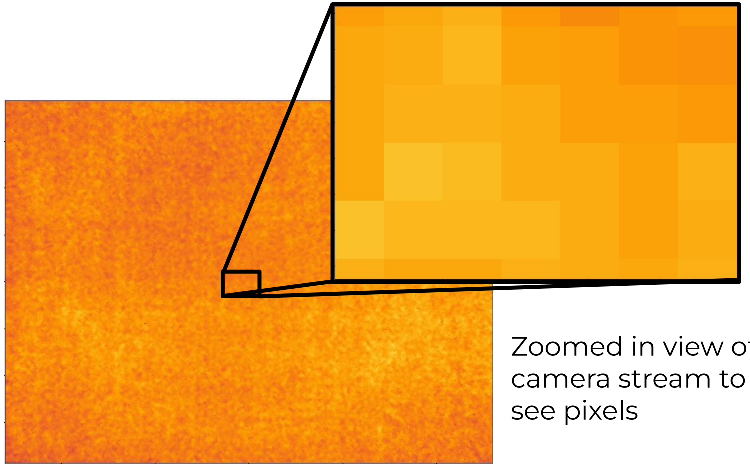
The IR Camera

FLIR A70

- Imaging Modes: Thermal and Visual
- Microbolometers
    - heat → Δ electrical resistance → raw ADC count
    - 480x640 array
- Pixel Format: Mono16 (0 to 65,535)
- **Need to convert raw counts → temperature**



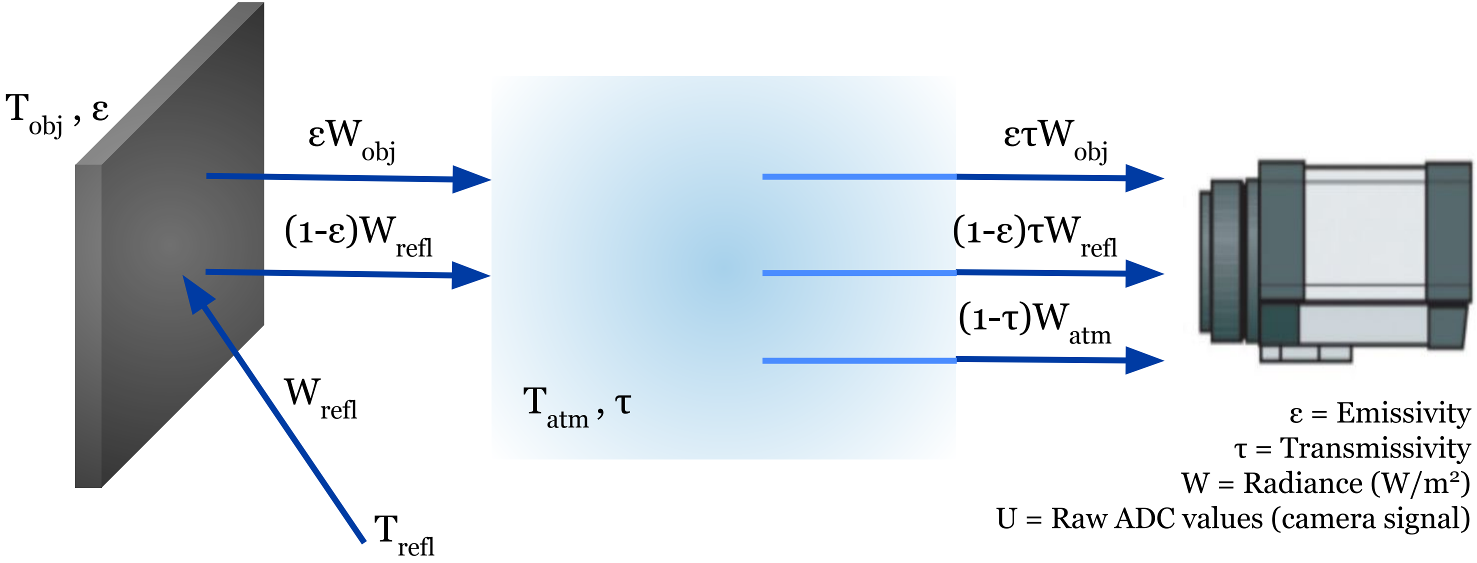
Microbolometers
(Andrushin *et al*. 2005, DOI: 10.1088/0268-1242/20/12/013)



Zoomed in view of camera stream to see pixels

Calculating Temperature

Radiation Power and Camera Signal



ε = Emissivity
τ = Transmissivity
W = Radiance (W/m²)
U = Raw ADC values (camera signal)

$$U_{obj} = \frac{1}{\epsilon\tau}U_{tot} - \frac{1-\epsilon}{\epsilon}U_{refl} - \frac{1-\tau}{\epsilon\tau}U_{atm}$$

Diagram modeled after FLIR: https://flir.custhelp.com/app/answers/detail/a_id/3321/~/the-measurement-formula

Final Equation and Input Parameters

Camera Calibration Parameters	
R	21022.24
B	1499.90
F	1.05
Offset (J_0)	19849
Gain (J_1)	20.59

User Input Parameters	
Reflected Temperature (K)	300.15
Atmospheric Temperature (K)	300.15
Object Emissivity	0.99
Object Distance (m)	0.546
Relative Humidity	1.00

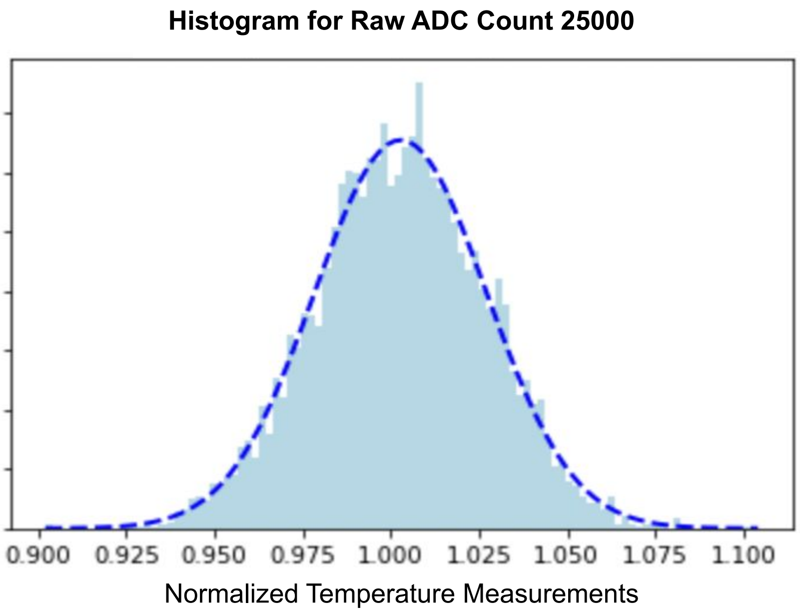
$$T = \frac{B}{ln\left(\frac{R}{(U_{obj}+J_0)J_1} + F\right)}$$

$$U_{obj} = \frac{1}{\epsilon\tau}U_{tot} - \frac{1-\epsilon}{\epsilon}U_{refl} - \frac{1-\tau}{\epsilon\tau}U_{atm}$$

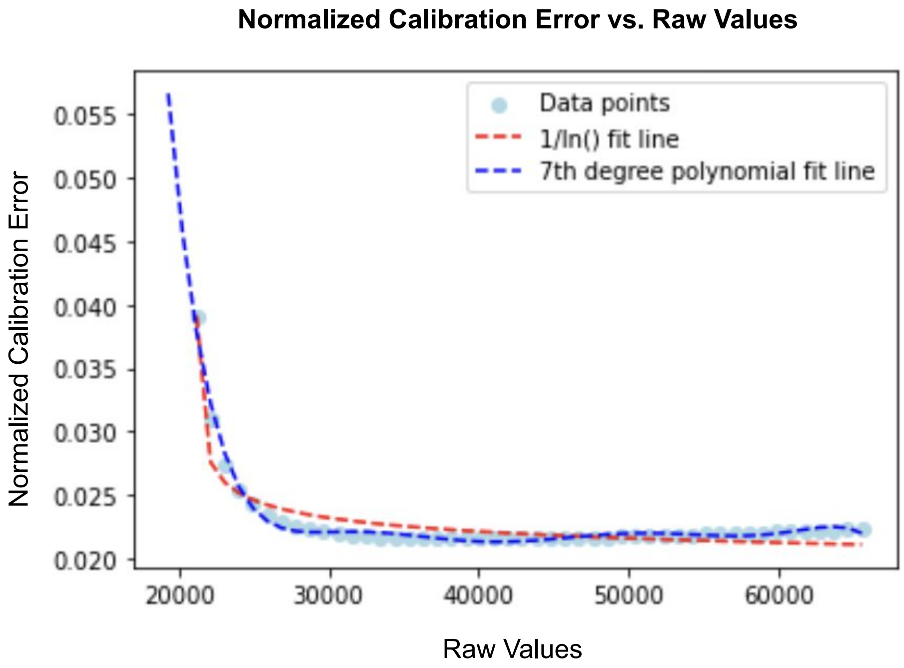
Error Evaluation

Monte Carlo Simulation

- “Actual” value and estimated deviation for each parameter → create distribution of possible values
- Use random value within distribution for each parameter
- Run the simulation many times
- Standard deviation of the outcomes is the estimated uncertainty for the measurement



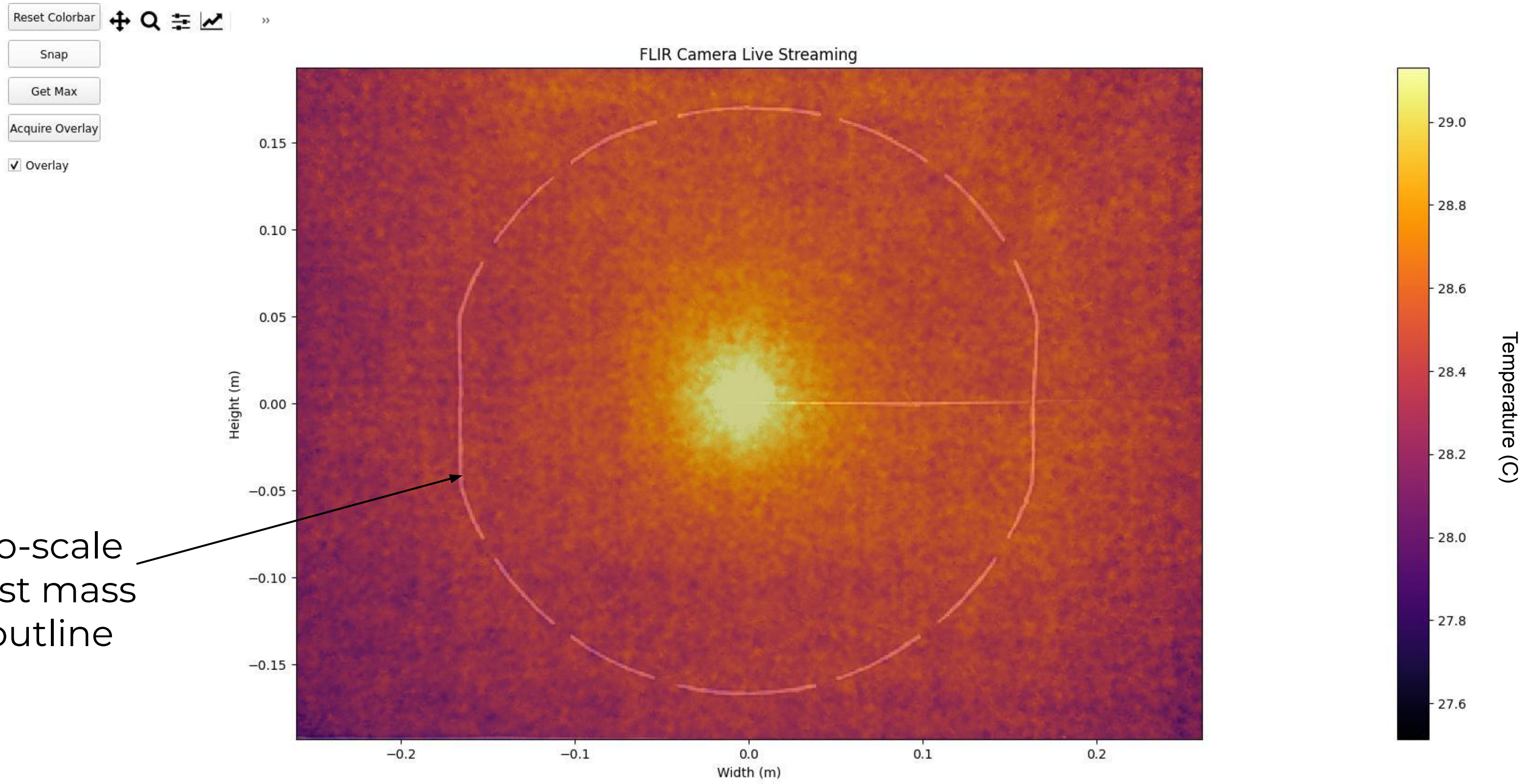
Error vs. Raw Values



- Calibration error varies based on camera's raw value
- Run simulation for range of possible raw values
- Mimics RBF function
- Error: 2% - 5%

Project Synthesis

Final Interface



To-scale test mass outline

Summary

- Final interface runs as expected
- Temperature calculations: acceptable error
- System has viable set up
- Testing the source (end to end validation): Phoebe Zyla
- Final Goal: characterizing the HOM ring heater prototype

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