Technology Development for LISA

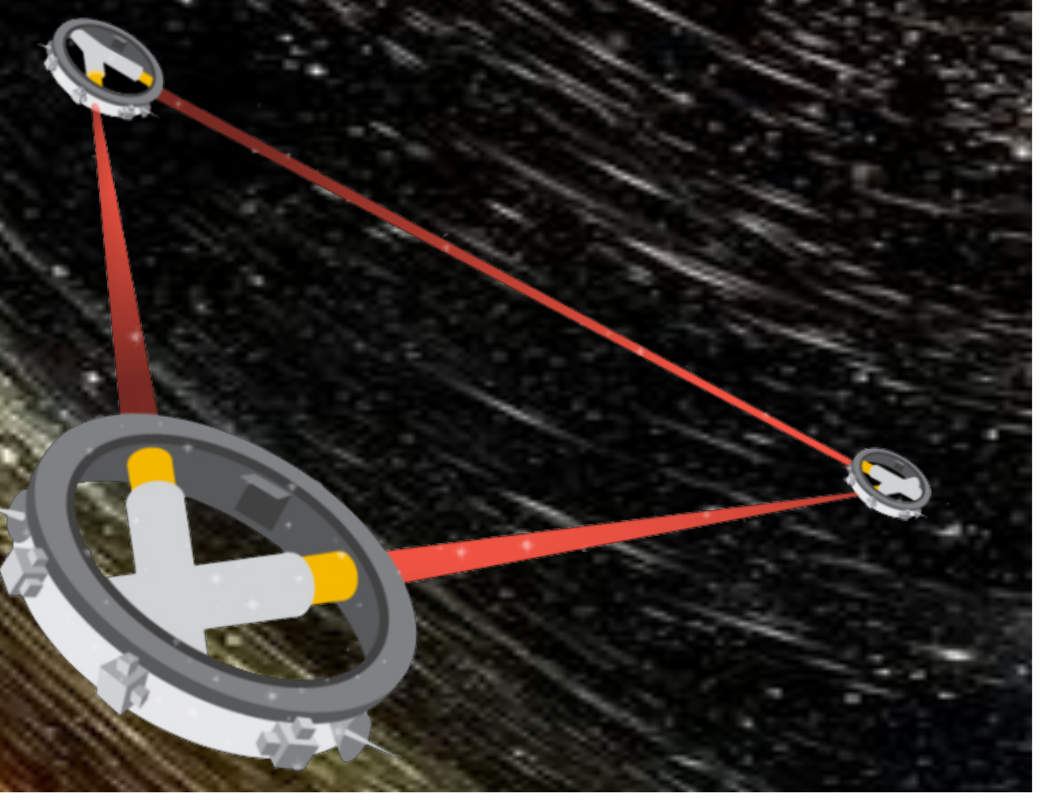
Hannah Hastings[1], Ryan Hastings[2], Hudson Loughlin[3], Shannon Sankar[4], Jeff Livas[4]
University of Pennsylvania[1], Indiana University[2], Princeton University[3], NASA GSFC[4]

Abstract

Eons ago and many lightyears away, supermassive blackholes at the centers of galaxies merged together. Obscured by interstellar dust, these extreme events have been unobservable with even the most advanced electromagnetic detectors. But now, a new generation of gravitational wave detectors will allow us to observe these events by looking at the ripples they create in space-time as demonstrated by LIGO's regent ground-based detections. The LISA gravitational wave observatory will use long baseline interferometry to measure these low frequency gravitational waves (GWs) in space as they propagate towards us from distant black hole mergers. Gravitational wave signals will be extracted by transmitting light between these satellites and observing changes in the light's phase. The observatory's strain sensitivity will be equivalent to the ability to measure a change in distance between the Earth and the Sun to less than the diameter of a proton. The low frequency of the measured signal and the large distance between the spacecraft impose unique stability requirements for the spacecraft's optics and lasers as well as light scatter requirements for the spacecraft's telescope. To reduce the frequency noise of the laser, we have frequency locked it to a thermally isolated Fabry-Perot optical cavity. Additionally, we have worked to determine the light scatter levels of a model telescope for the LISA mission including potential flight optics to determine its viability for use in a future GW observatory. This work was done in collaboration with Goddard's Gravitational Astrophysics Lab.

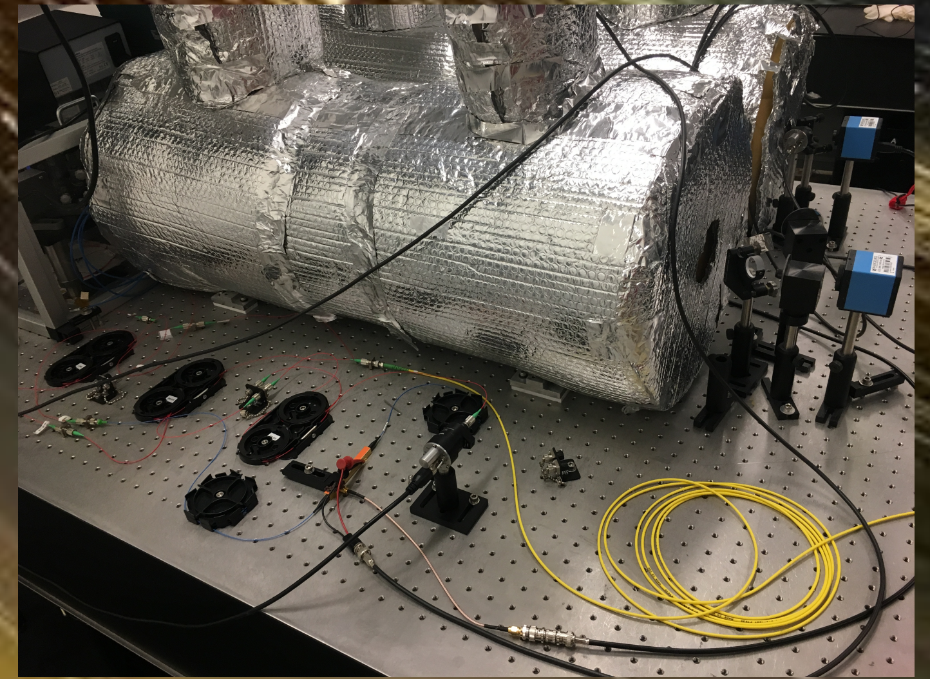
LISA

LISA (Laser Interferometer Space Antenna) is a space-based gravitational wave observatory scheduled to launch in the 2030s. LISA will observe parts of the universe that are invisible in the electromagnetic spectrum such as black holes, binary compact stars, stellar remnants, and merging massive black holes. It will be able to measure low-frequency gravitational waves (about 0.1 mHz to 100 mHz), because of its long arm length of 2.5 million km. Observations will help us study galaxy formation and allow us to test general relativity.

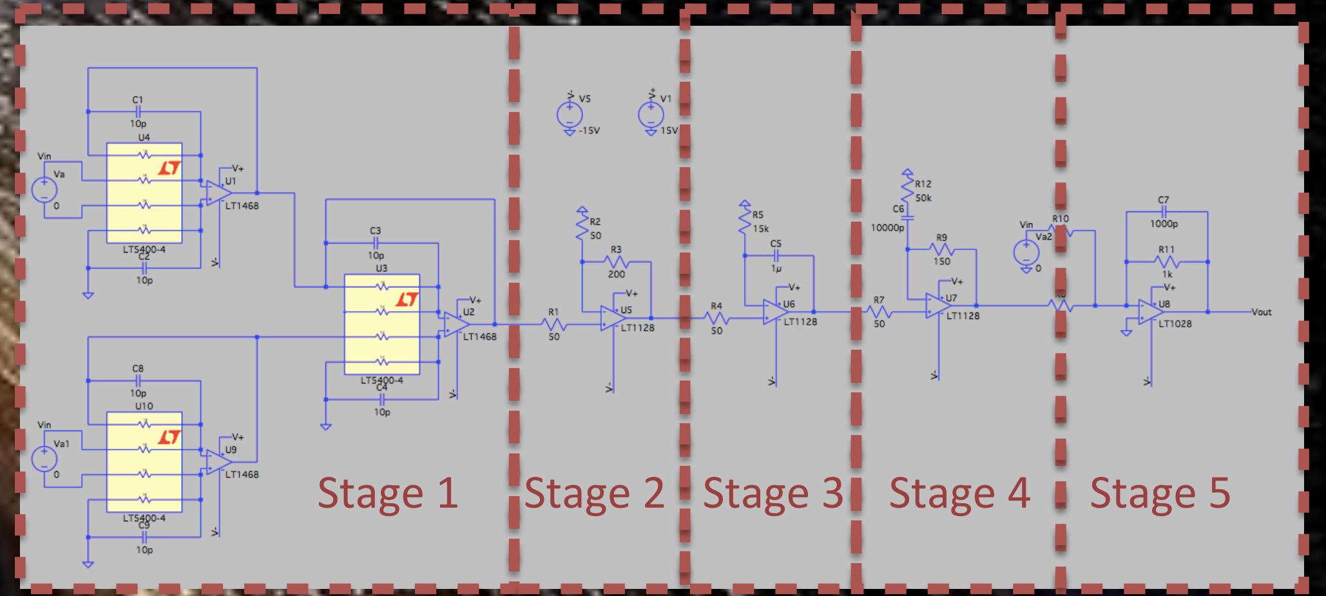


Frequency Stabilization

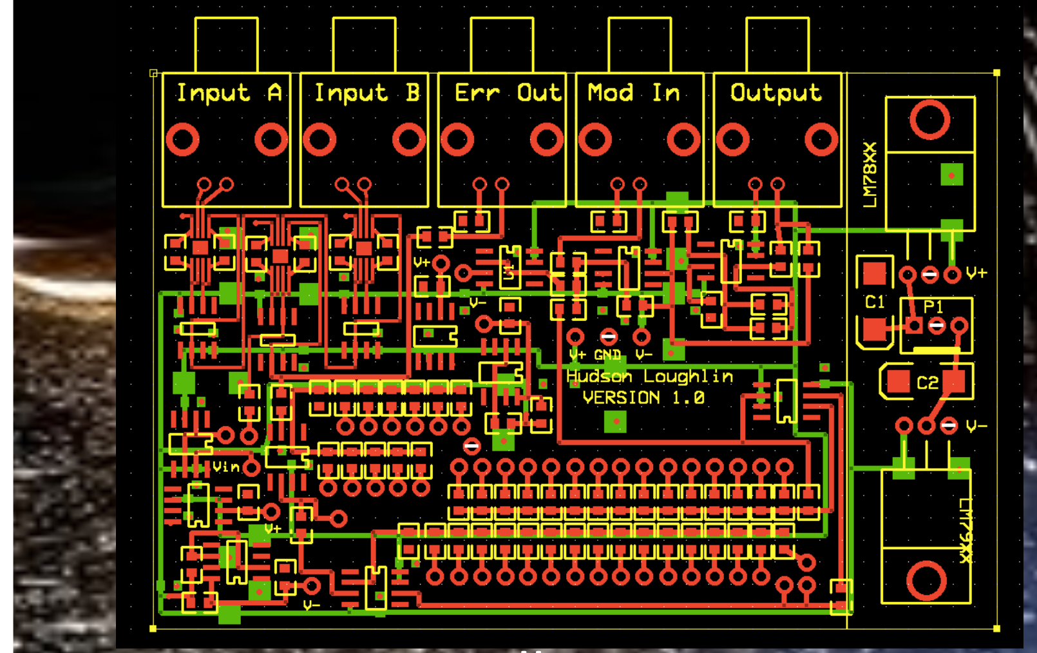
- The PDH technique allows us to stabilize a laser frequency to a reference optical cavity.
- This is done by phase-modulating the laser output, observing the light reflected from the cavity, demodulating the signal, and feeding back to the laser.



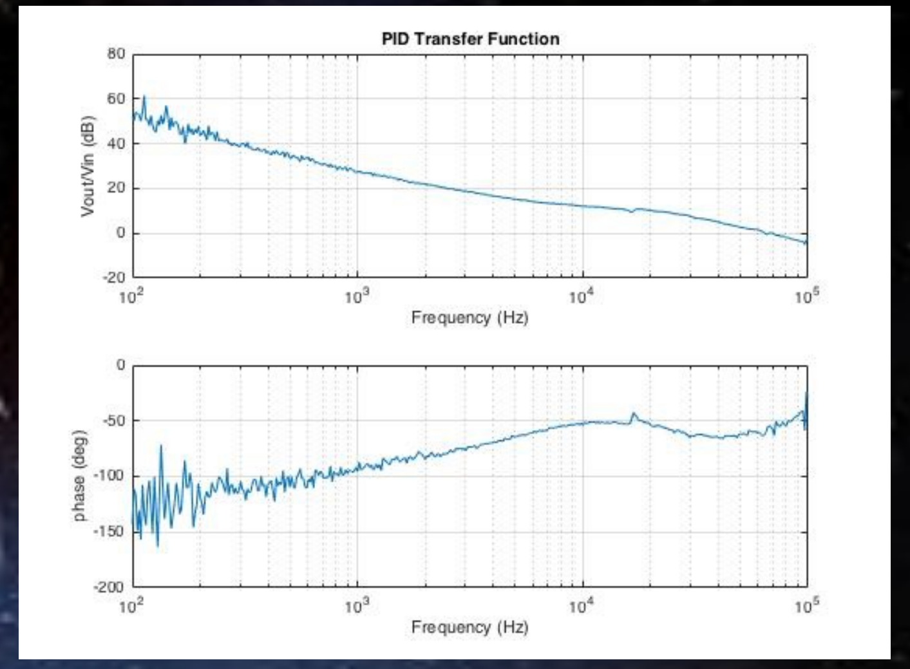
PID Controller



PID Spice Model
Stage 1:
Differential Receivers
Stage 2:
Proportional Gain
Stage 3:
Integrator
Stage 4:
Differentiator
Stage 5:
Output Offset



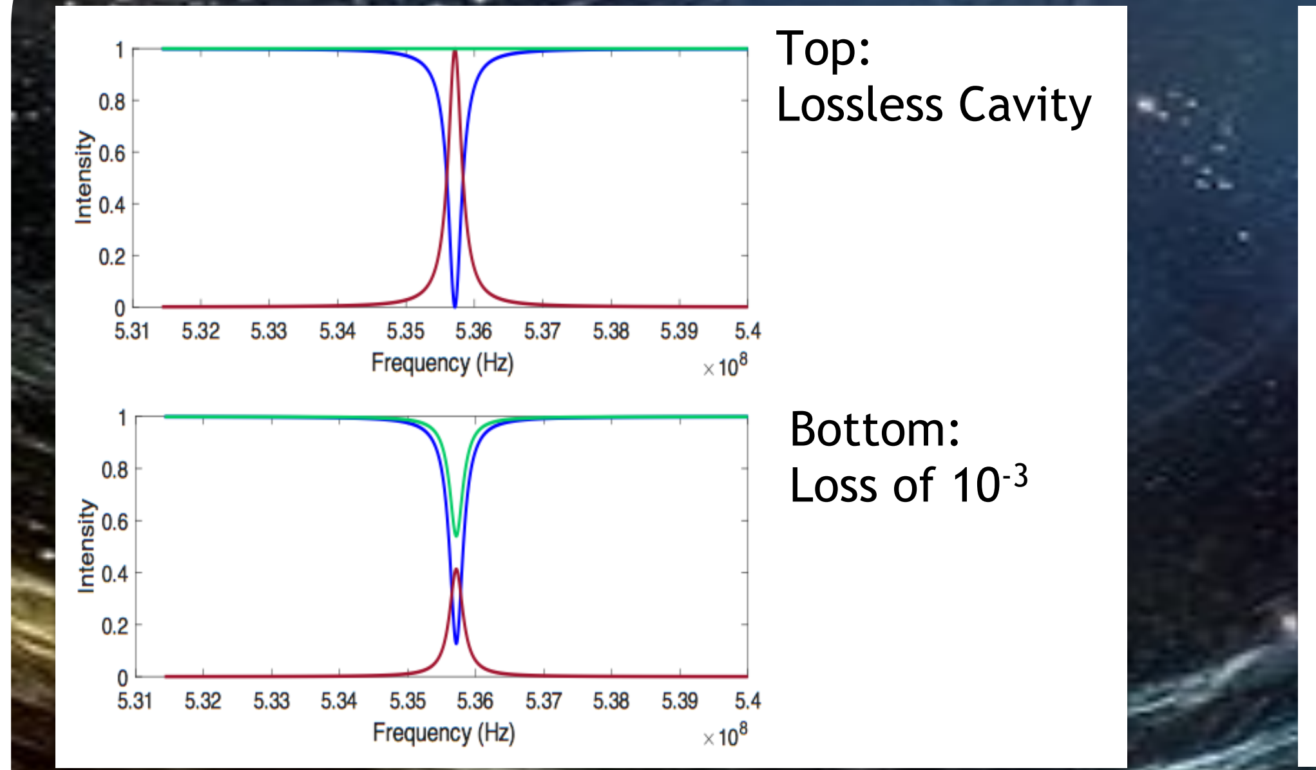
PID Controller PCB Layout



Measured Loop Transfer Function

- This controller is being used in the PDH setup to lock the laser to the cavity
- It provides similar input voltage noise and higher bandwidth than the preamp previously used in the setup

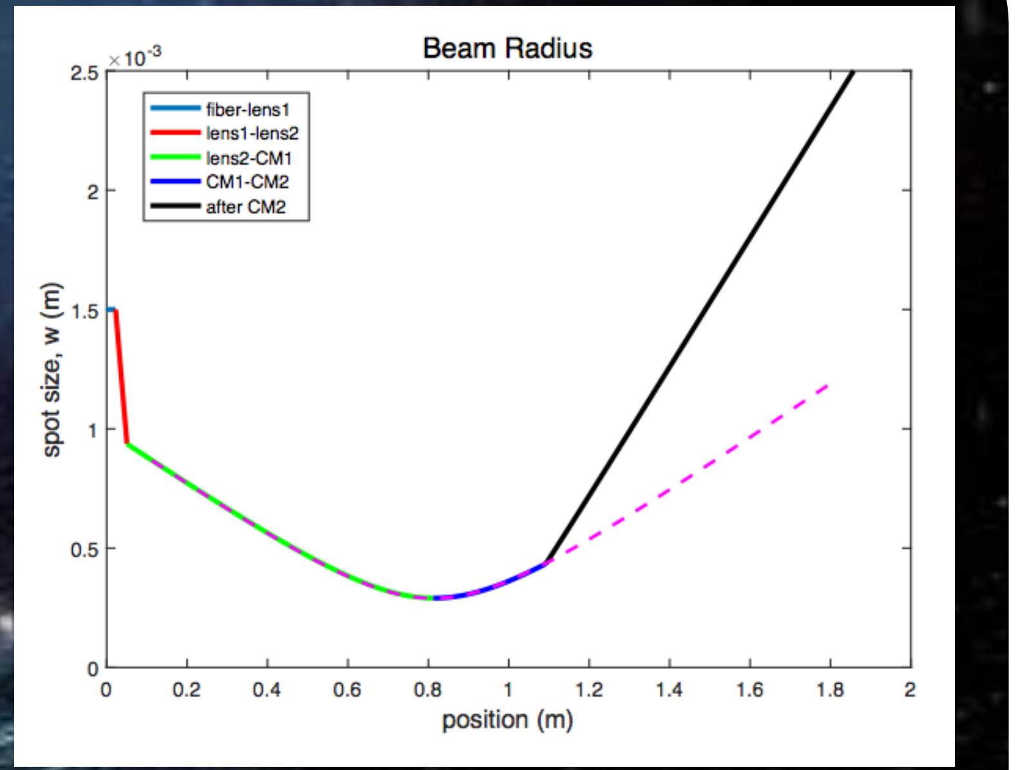
Optical Cavity Mode Matching



Top:
Lossless Cavity

Bottom:
Loss of 10^{-3}

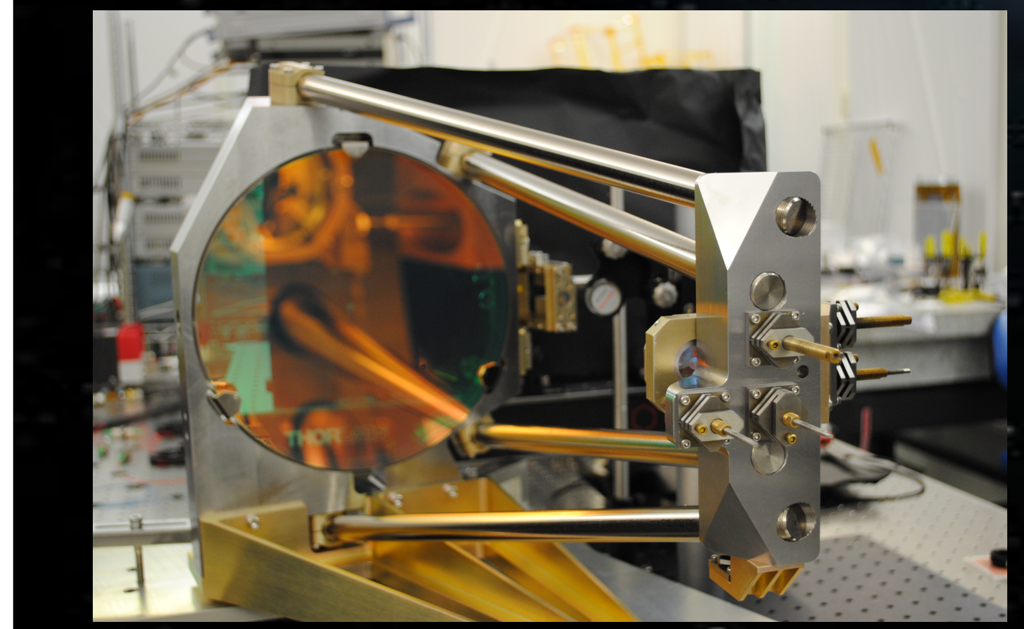
Transmitted and Reflected Power



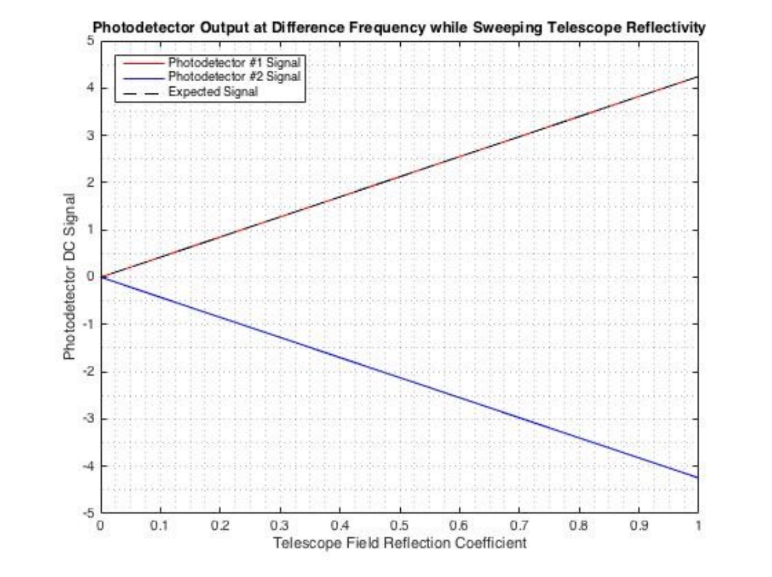
Calculated Beam Radii

Matching the shape and phase of the beam to the cavity will maximize the transmitted light. The focal length and position of two lenses in front of the cavity were varied until the radii overlapped

Scattered Light



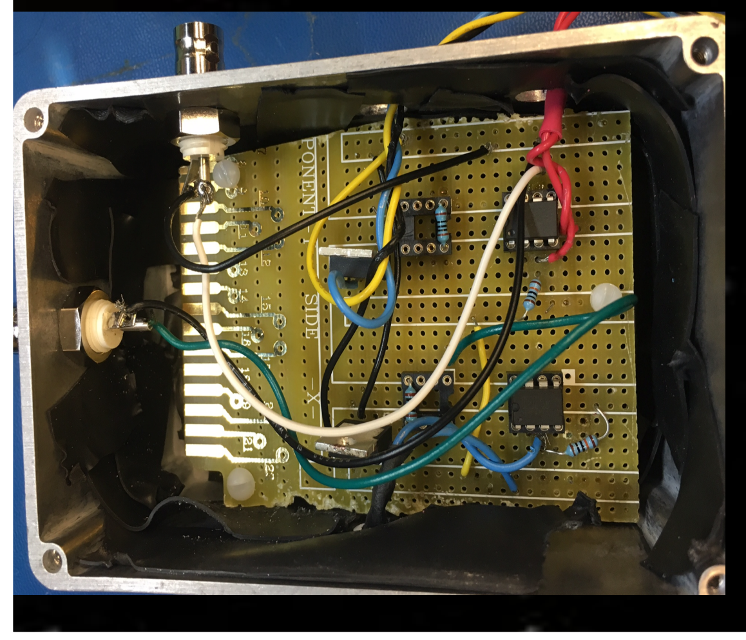
The Telescope Under Test



Results of a Light Scatter Model of the Setup

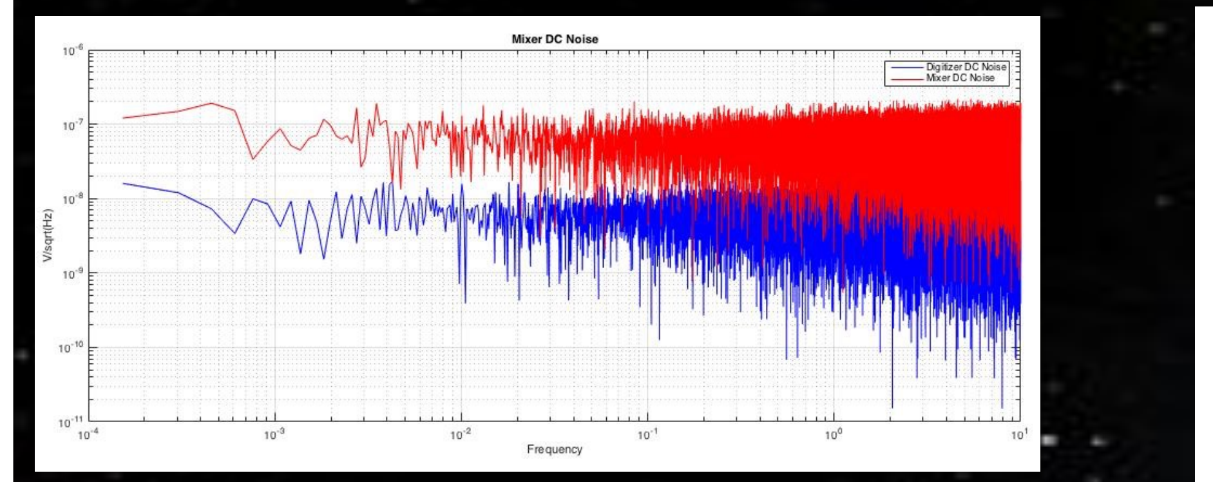
The telescope is a potential US contribution to the ESA lead LISA mission. Understanding its light scatter properties is critical to assuring its functionality

Temperature Monitor Circuit



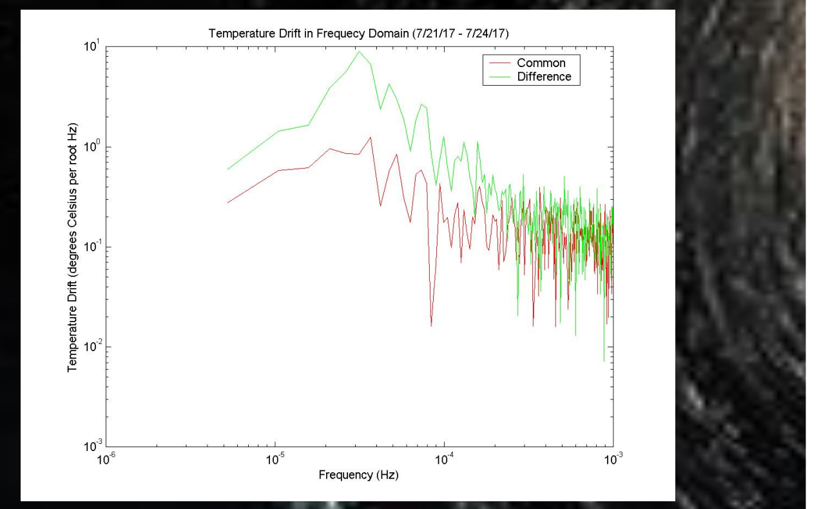
- Low frequency room temperature changes affect the optical cavity length and the back-end electronics in the setup
- A precision lab temperature measurement allows us to correlate temperature drift with other noise sources such as mixer drift

Lab Temperature and Mixer Drift



Mixer DC Offset Drift

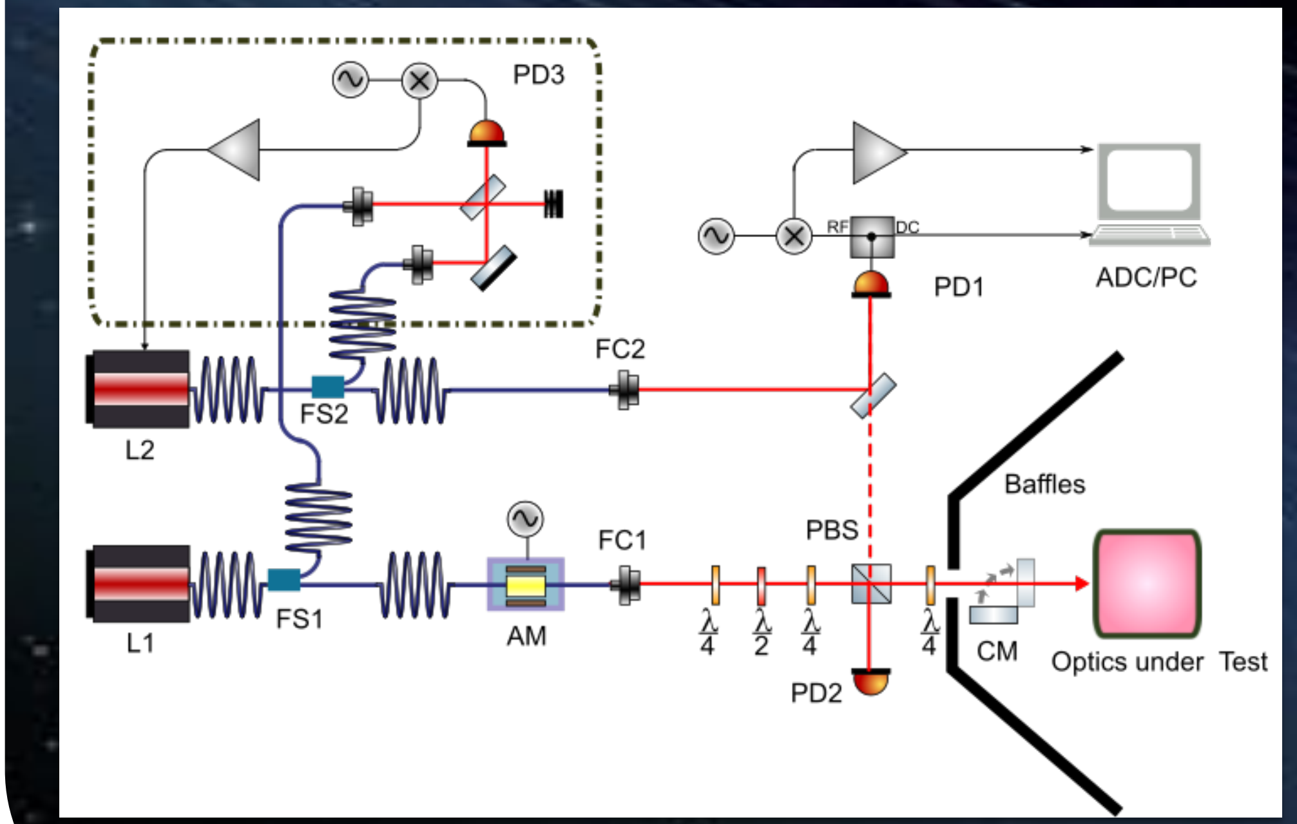
Our data shows that the output drift of the mixer is relatively low at LISA frequencies.



Lab Temperature vs Frequency

This plot shows that our temperature measurement is not impeded by noise at low frequencies.

Scattered Light Continued



Light Scatter Test Setup

The optics have been set up as shown and further alignments are in progress to reach the required sensitivity to observe the telescope's scatter into the detector

Summary

We have successfully locked a laser to the cavity using the PDH technique and have begun to improve the setup by developing and integrating back end electronics and calculating optimal lens positions to mode match to the cavity. Progress has also been made towards understanding the thermal environment of the lab and how this affects various components of the setup. Additionally, the light scatter measurement's sensitivity has been improved and the Optickle model has ensured we correctly understand the functionality of our measurement system.

Future Work

- Add temperature feedback to improve cavity lock's range
- Place lenses in calculated positions to mode match to the cavity
- Examine correlations between temperature fluctuations and mixer drifts
- Actively stabilize mixer temperatures
- Continue to improve scattered light sensitivity
- Frequency lock a second optical cavity

References

- Black, Eric D. "An introduction to Pound–Drever–Hall laser frequency stabilization." *American Journal of Physics* 69, no. 1 (2001): 79-87.
- Black, Eric. "Notes on pound-drever-hall technique." *LIGO Technical notes* (1998).
- Sankar, Shannon R., and Jeffrey C. Livas. "Initial progress with numerical modelling of scattered light in a candidate eLISA telescope." In *Journal of Physics: Conference Series*, vol. 610, no. 1, p. 012031. IOP Publishing, 2015.