LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Implementing A Frequency Control Loop for the 40m Prototype Arm Length Stabilization System; First Progress Report

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1 Introduction: The LIGO Detector

Gravitational waves are a component of Einstein's theory of General Relativity, which have not, as of yet, been directly observed. The detection, observation and characterization of these waves are the primary goals of the LIGO detector.

The waves manifest themselves with disturbances in spacetime, causing miniscule changes in length. These modulations, when detected, are on the scale of $10^{-18}m$ [1]. With independent variables on such a small scale, it is necessary to employ a highly sensitive instrument–in this case, a laser interferometer, diagrammed in Figure 1.

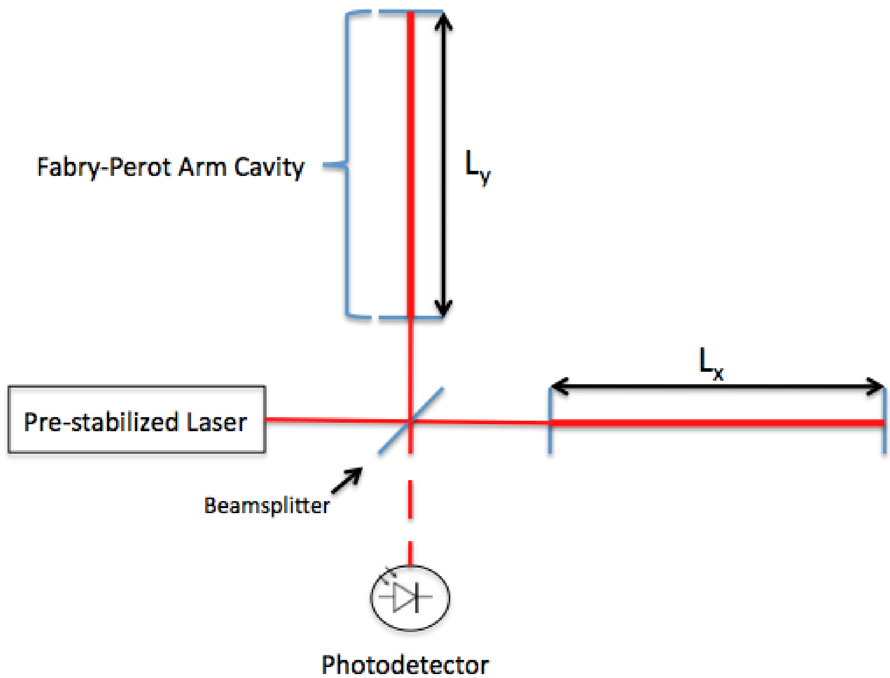

Figure 1: Laser interferometer with Fabry-Perot arm cavities.

Since the laser light is perfectly in phase with itself when it enters the arm-cavities, the only thing that could shift the phase difference between beams is a difference in arm length $(L_x - L_y)$. Thus, we can observe changes on the scale in which we need to. Measurements are taken by way of observing interference patterns produced by the recombined beam.

The Fabry-Perot arm-cavities, as opposed to the more traditional simple arms, allow us to generate greater arm lengths, and thus increase sensitivity, which increases in proportion to arm length.

In addition to the Fabry-Perot arm cavities, the detector implements power recycling cavities at the vertex of the detector, which effectively amplify the optical power of the PSL, improving the shot noise level [3]

2 Arm Length Stabilization (ALS)

In order to operate such a sensitive interferometer, we must know and control the degrees of freedom of the Fabry-Perot arm cavities. In order to do so, we make use of a frequency doubled auxiliary laser (AUX) system, which operates at baseline 536 nm. The AUX frequency can vary, as it is locked to the arm cavity length by a Pound-Driver-Hall locking servo. Using this frequency as the measurement of the arm cavity length, it is then possible to bring the PSL into lock with AUX, and thereby, the arm cavity length. The length detection scheme is described below, v and δv referring to the baseline frequency, and change in frequency, and L and δL referring to the baseline length, and change in length.

$$\frac{\delta v_a(t)}{\overline{v}} = -\frac{\delta L(t)}{\overline{L}}$$ [2]

In this system, an AUX beam is injected through the Fabry-Perot arm cavity, then combined with the frequency doubled prestabilized laser (PSL) to beat with each other, and is fed into a photodiode which acts as an input to a delay-line frequency discriminator (DFD). The DFD functions to create a linear error signal, which is then used to correct the arm cavity length through servo controlled end test masses (ETM) [2].

3 Problem

The problem here lies within the offsetting system used to keep the AUX laser locked with the arm cavity length. The laser cavity actuators can only respond at $5\frac{MHz}{V}$ with a range of $\pm 10V$, while the arm cavity length can fluctuate on a length scale corresponding to a frequency range well beyond that of the laser cavity actuators [2]. It is clear that we are in need of another method of control, with a greater range.

When we sense a beat frequency >100MHz, we encounter difficulty, since we are outside the ALS system's effective working range. This is where the proposed new servo comes into play. Using a separate sample of each beam, (AUX and PSL) we will use their beat frequency to generate a digital error signal, which will be fed into a digital PID loop, and used to actuate the temperature control of AUX, in order to bring it back into within the working range of the ALS system.

We implement a temperature actuator, which will control the temperature of the crystal within the laser, yielding a controllable range of roughly $1\frac{GHz}{V}$. This servo will respond to signals below about 1 Hz.

4 Preliminary Design and Working Principles

In principle, the temperature actuator will modulate the temperature of the laser crystal when there is a signal of frequency below 1 Hz. Changing the temperature of the crystal changes its physical dimensions, and thereby modulates its frequency in proportion.

We will take beam samples of the AUX and PSL, and recombine them at the vertex of the detector. The combined beam will then enter a photodiode. This signal will enter a frequency counter, which will then give a remote readout of the beat frequency, and then go on to the digital PID loop, which will eventually go through the DAC to actuate the temperature control servo, and bring the AUX frequency back within a workable range.

This design is show in Figure 2.

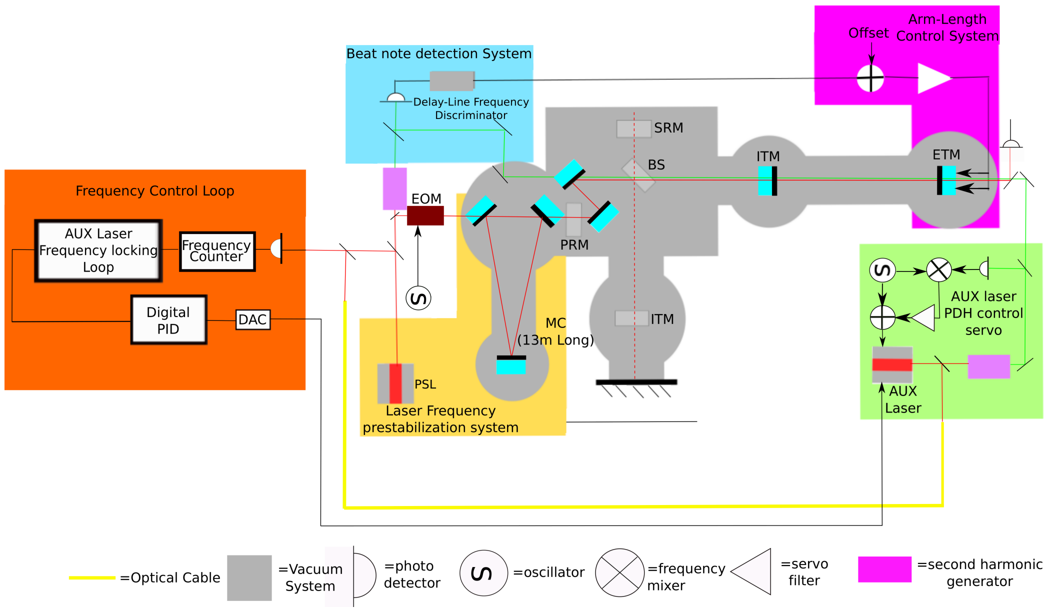

Figure 2: Schematic of interferometer with proposed AUX laser frequency locking loop

5 Current Progress

My current project is the setup of the optics that will eventually sample the AUX light, and transport it to the vertex, where we will beat the AUX and PSL. In order to do this, we must efficiently couple light into the fibers. In order to do this, we must understand the characteristics of the beam, that is to say, its waist. Measuring the beam waist has been my project since the beginning of my work, and I nearly there. Though my technique is sound, I have recently learned that I need to return to the instruments, in order to characterize my experimental error, and its propagation through my calculations.

6 Methods of Waist Measurement

In order to measure the beam waist, I have been using the "Knife-Blade" measurement technique. This technique involves shining the laser (1064nm NPRO) on a photodiode. The razor blade setup is pictured below in Figure 3

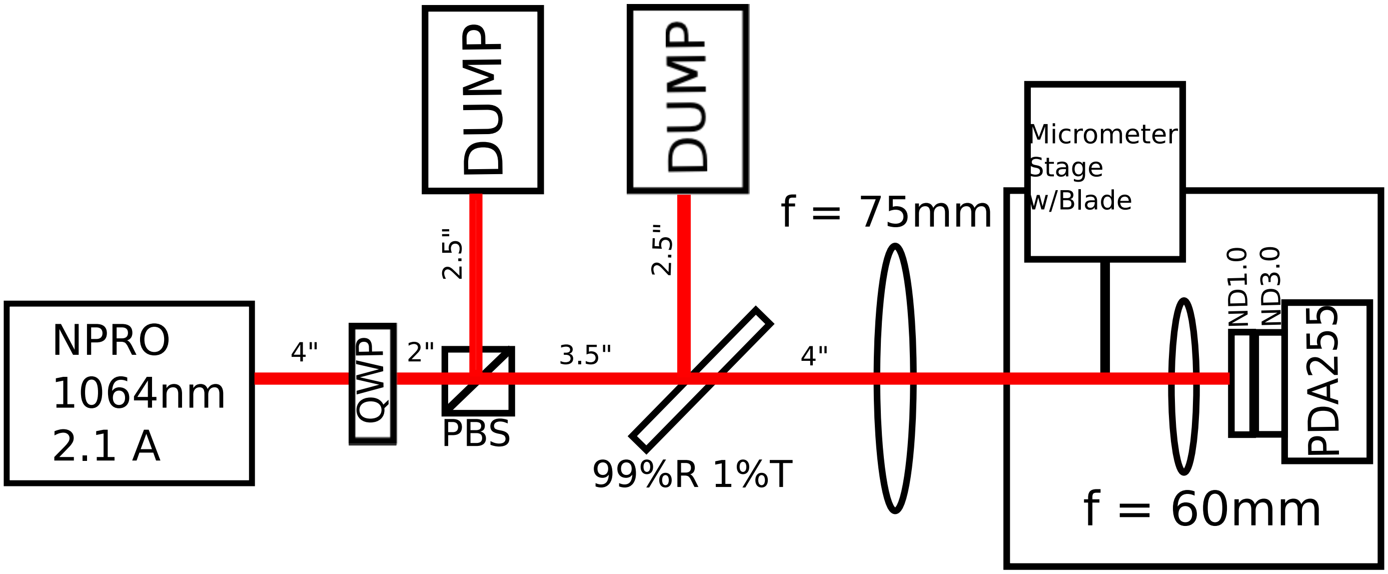

Figure 3: The razor blade setup used

Note: PBS stands for "Polarizing Beam Splitter" and 99%R 1%T is a 99% Reflective, 1% Transmissive mirror.

A razor blade is then translated orthogonally (both in the X and Y directions) to the beam via a micrometer stage, and measurements of the power on the photodiode are taken periodically in order to generate data that describe the fraction of total optical power contained in a given fraction of the beam's cross section at a specific point along the direction of propagation. These data are taken at multiple points along the optical axis. They are then fit to the following equation:

$$V_{measured} = \frac{V_{max}}{2}[1 \pm erf(\frac{\sqrt{2}(x-x_o)}{w_o})]$$

[5]

Where $V_{measured}$ is the measured voltage at x, x_o an offset from zero, w_o the spot size at that particular location along the optical axis, and plus or minus depending upon the direction the blade is translated, i.e. to occlude the beam, or to reveal the beam. An example fit is pictured below in Figure 4

The spot sizes determined by these fits can be seen below:

After extracting the parameters of these fits, we fit the spot sizes to the equation which describes how beam size propagates along the optical axis, as follows:

$$w_z = w_o\sqrt{1 + \frac{(z^2\lambda^2}{\pi^2 w_o^2}} \text{ [6]}$$

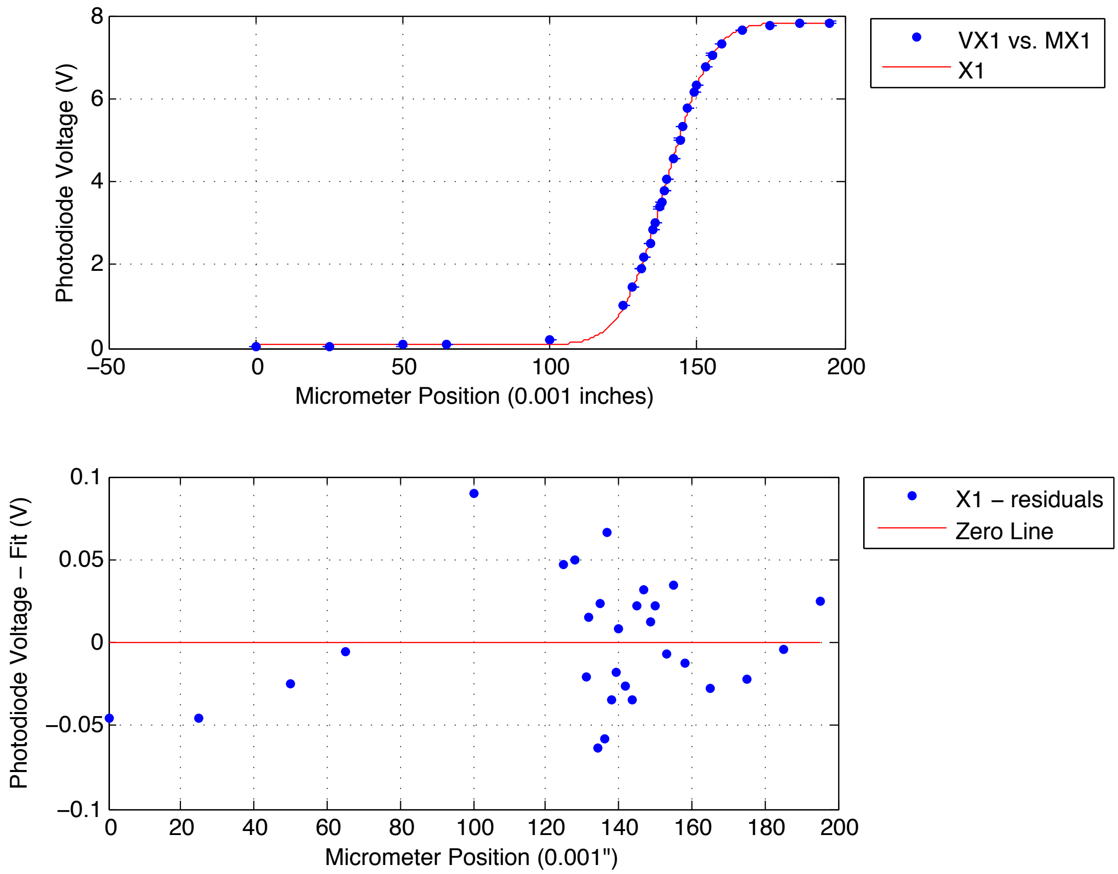

Figure 4: A sample plot of one cross section of the beam

Table 1: Spot Size Measurements

Z Pos. (m)	X Spot Size (μm)	Y Spot Size (μm)
0.0508	615.2 ± 10.67	574.0 ± 13.72
0.0762	272.8 ± 4.83	294.1 ± 10.16
0.1016	50.2 ± 2.64	32.6 ± 3.73
0.1270	293.4 ± 10.67	281.2 ± 9.14
0.1524	637.0 ± 15.49	548.1 ± 16.00
0.1778	926.3 ± 12.70	827.3 ± 17.53

Where w_z is the beam size at a particular value along the optical axis, w_o is the beam waist, z_r is the rayleigh range of the beam, and b and c are offsets in the w_z and z respectively. (We choose the optical axis to be the Z-Direction.) A sample of this fit is picture in Figure 5

This final fit yields the overall measurement of the beam waist, defined below.

Table 2: Beam Waists After Lens

X Waist (μm)	Y Waist (μm)
907.5 ± 4.5	840.5 ± 3.0

Unfortunately, since the waist of the actual NPRO was outside of the practical range afforded by the optical table the experiment was carried out on, a lens was used (as pictured in Figure 3) to focus the beam, so that we could take measurements near the waist, which affords a much better fit of the spot sizes vs Z Position. Once the waist after the lens can be determined, we can calculate the overall beam waist with the following equation:

$$w_f = \frac{\lambda f}{\pi w_o}$$

Where w_f is the waist after the lens, λ is the wavelength of the laser (1064nm), w_o is the beam waist before the lens, and f is the focal length of the lens ($75mm$) [4].

After this calculation is done, we arrive at the following final beam waists:

Table 3: Beam Waists of Laser

X Waist (μm)	Y Waist (μm)
135.4 ± 214.2	318.1 ± 316.7

7 Problems

Knife Edge measurement of the laser light has proven much more difficult than it seems in principle. For various reasons, e.g. too few data points, points too far from the waist of

Waist Fit.pdf

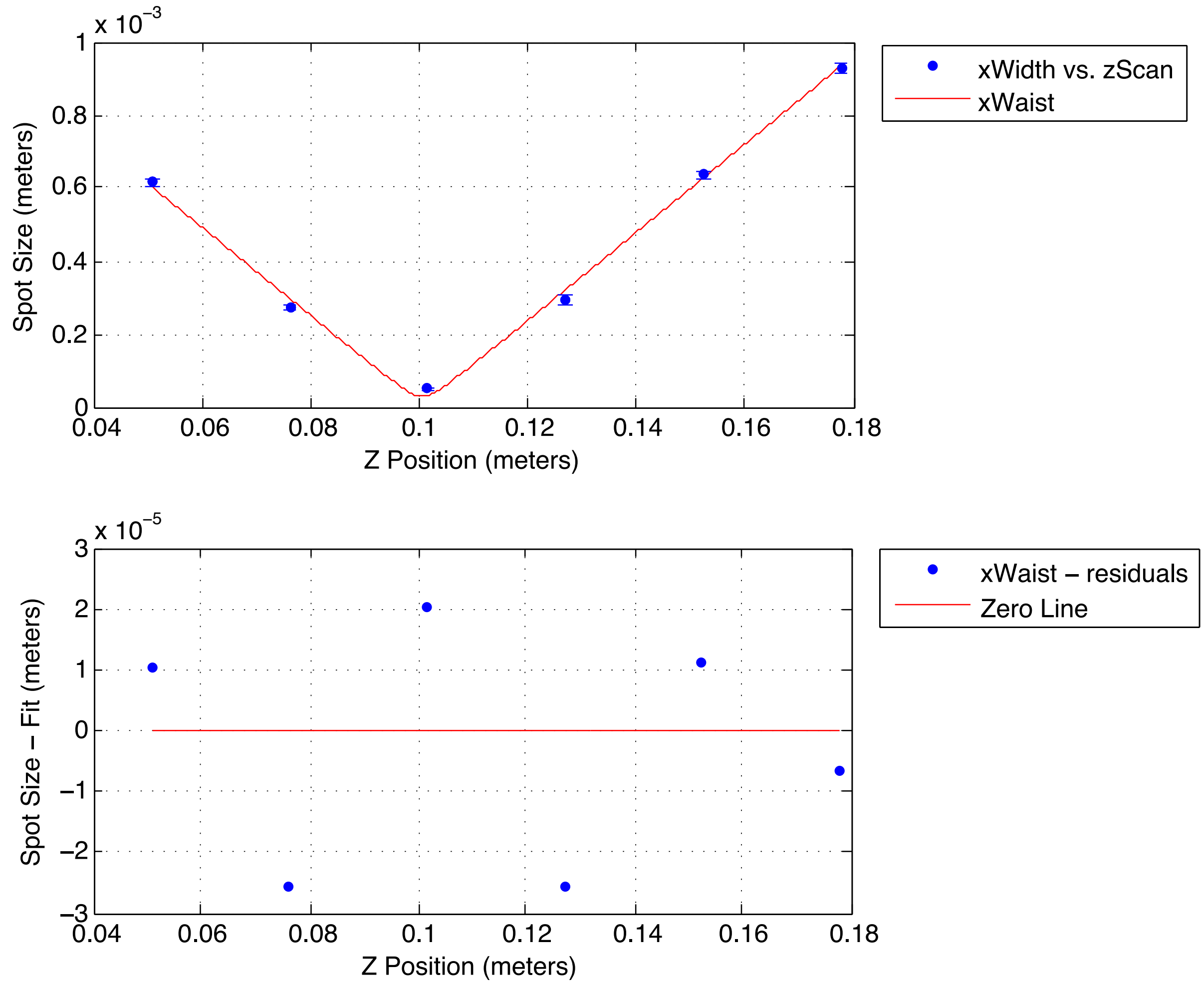

Figure 5: A sample waist measurement plot.

the beam, photodiode saturation, the fits haven't given very accurate results, until the most recent set of measurements. I don't envision other systematic difficulties for this section of the project, as I am now familiar with effective practices for beam waist measurement.

Additionally, I was previously unaware of theory behind error propagation, and am going to have to introduce it into my calculations of spot sizes, waists, etc.

8 Current State and Moving Forward

Currently, I have just been able to characterize the beam waist of the NPRO. In the next month, I hope to characterize the light coming out of the fibers, so as to be able to design and construct a telescope to appropriately focus and collimate the laser light into the fiber.

I plan to characterize the fiber light in much the same way that I did the NPRO light, though replacing the laser with an illuminated fiber. In order to accomplish this, I will need my razor blade setup used in the previous step, the fibers, and a fiber illuminator.

In order to construct the telescope, I will eventually need two lenses, and a means of mounting them, but further knowledge of those will require further knowledge of the characteristics of the light from the fibers.

References

[1] http://www.ligo-wa.caltech.edu/ligo_faq.html

[2] Kiwamu Izumi *Multi-Color Interferometry for Lock Acquisition of Laser Interferometric Gravitational-wave Detectors* Department of Astronomy, The University of Tokyo

[3] Masaki Ando *Power recycling for an interferometric gravitational wave detector* Department of Physics, Faculty of Science, niversity of Tokyo

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[5] http://pendientedemigracion.ucm.es/info/euoptica/org/pagper/jalda/docs/libr/laserandgaussian_eoe_03.pdf

[6] http://www.rp-photonics.com/focal_length.html