Alignment feedback system for the interferometric optical cavity of CALVA (Advanced Virgo)

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Abstract: Advanced Virgo uses suspended Fabry-Perot cavities with a higher finesse than its initial stage, in which alignment of the laser beam within the interferometer arms becomes much more sensitive. We created an optical set-up which, unlike a local control system acting on the individual test mass mirrors, will center the laser light from the cavity onto a set of photodetectors providing information on the translational and rotational degrees of freedom of the cavity mirrors. The set-up consists of a laser source, two mirror galvonometers, a periscope, beam splitter and two photodetectors (one sensitive to beam rotations, and one sensitive to beam translations and rotations.) The beam position data acquired from the photodetectors, using a data acquisition board, is used to act through a proportional-integral-differential (PID) feedback system on the mirror galvonometers to center the beam on each photodetector. This system is first aimed for the CALVA platform and may then be installed in Advanced Virgo for the auxiliary laser system that will help in lock acquisition of the full interferometer.

I. Introduction

One hundred years ago, Albert Einstein formalized his theory of general relativity (GR). Deflection of light due to presence of mass, perihelion precession of Mercury, gravitational redshift, were just a few results GR predicted that withstood arduous experimentation. In recent years a major test for GR has been direct detection of gravitational waves; undulations in space-time due to the movement of mass propagating through the universe at the speed of light. These waves give astronomers a new tool to observe the universe; exotic celestial objects (binary black holes and neutron stars), as well as behavior in the very early universe would be accessible through a different perspective. Joseph Weber, in the 1960's, claimed to have detected gravitational waves, which was later discredited. Nonetheless, many still consider him the father of the field of gravitational wave detection. Kip Thorne, Ronald Drever, and Rainer Weiss in the 1980s brought the prospect of improved detection with the founding and development of Laser Interferometric Gravitational Observatory (LIGO); which primarily uses the laser interferometric method of detection.

On September 14, 2015 the first gravitational wave was detected by LIGO, originating from what was also the first observation of a binary black hole merger. A few months later on

December 26, 2015 a smaller black hole merger produced a signal detected as the second observation of gravitational waves. Only the LIGO sites were online at the time of these detections, but in the coming months the European Gravitational Observatory (EGO) will join the search with the improved Advanced Virgo interferometer (which has a sensitivity improved by a factor of 10 over its initial stage). The Japanese gravitational wave detector KAGRA (which uses cryogenics to reduce thermal noise in its test mass mirrors) will come online in 2018, and LIGO India (INDIGO) has been proposed to join the current detector network by about 2020.

Today's interferometric gravitational wave detectors are at their core a Michelson interferometer with Fabry-Perot (FP) cavity arms. The entire apparatus consists of a laser source from which the light passes to a beam splitter (BS); separating into two theoretically equal-amplitude beams passed into the orthogonal interferometer arms each composed of two test mass (TM) mirrors which constitute a FP cavity. After a decided number of round trips (corresponding to about a quarter of a gravitational wave period) in the FP cavities the laser light is recombined at the beam splitter. Most of the light is sent back towards the laser, and if a phase difference exists some light is passed to a photodetector (PD) operating on the dark fringe. A power recycling mirror (PRM) is placed between the laser source and the beam splitter, which when tuned properly will reflect the light from the cavities in phase with the incoming light from the laser source, thereby increasing the laser signal in the interferometer. (See Figure 1.)

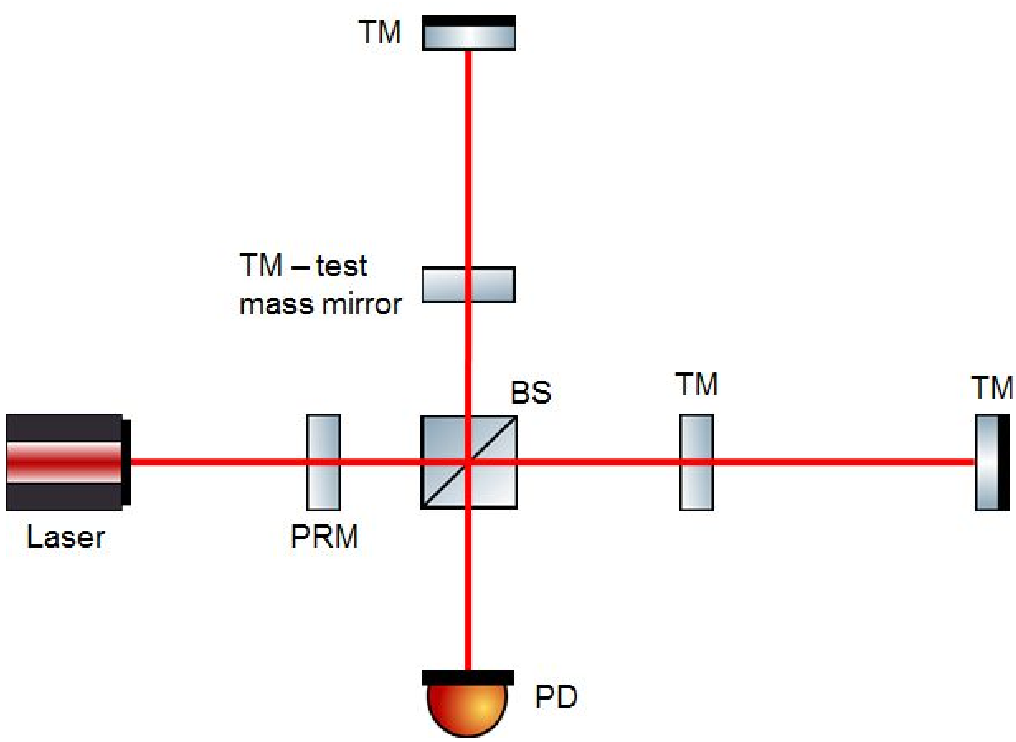

Figure 1. Basic interferometer setup for LIGO/Advanced Virgo. PD operating on the dark fringe will detect a phase difference between the light of each arm.

Advanced Virgo will be composed of suspended Fabry-Perot cavities of finesse almost 10 times higher than its initial stage, in which alignment of the laser beam in the optical cavities will become much more sensitive. CAvites pour le Lock de Virgo Avance, a group at Universite Paris-Sud in Orsay, France proposed a laser stabilization technique outside the interferometric arms is proposed which will provide information on the translational and rotational degrees of freedom of the laser light in the arm cavities. Instead of acting on the cavity mirrors through local controls (for which the noise level is mechanically limited), the laser light from the cavities will pass through an optical set-up consisting of two mirror galvonometers, a periscope, a beam splitter, a lens and two photodetectors. This apparatus is placed before the Fabry-Perot cavity of CALVA, after the site of signal input; (see Figure 2.) Beam position information from the photodetectors (which were position-sensing devices, PSDs) is passed to a proportional-integral-differential (PID) feedback system, which then outputs correction signals to the mirror galvonometers, centering the beam on the photodetectors. This system will provide information of the behavior of the entire optical cavity, unlike the local controls, which only give information on their respective cavity mirrors.

Figure 2. Model of CALVA's optical cavity; (essentially one interferometer arm, with a power-recycling mirror.) The alignment apparatus will be placed before the optical cavity, after input laser signal.

II. My project

Apparatus:

The final apparatus was assembled on an optical table. For my purposes, which was mostly creating and initially testing the optical feedback system, a red laser was used for its stability. (Initially a green laser source was used, but was abandoned due to its high instability. More on this to follow.) A neutral density filter (NDF) was placed in front of the laser source (which was left in place after use with the green laser, but not necessary with the red laser.) The beam passed to a set of two mirror galvonometers (which I will refer to as galvo mirrors, for short), (M1 and M2.) The beam was then passed to a periscope, consisting of two mirrors (used mostly to ensure the laser beam was not vertically deflected too much), after which towards a beam splitter (BS).

One beam passed directly to a photodetector (PD1) which was sensitive to beam translation and rotation, and the other beam passed through a lens to another photodetector (PD2) in its focal plane sensitive solely to beam rotation. (See Figure 3.) Both signals registered from each photodetector are used in the PID feedback, to act on each mirror galvonometer.

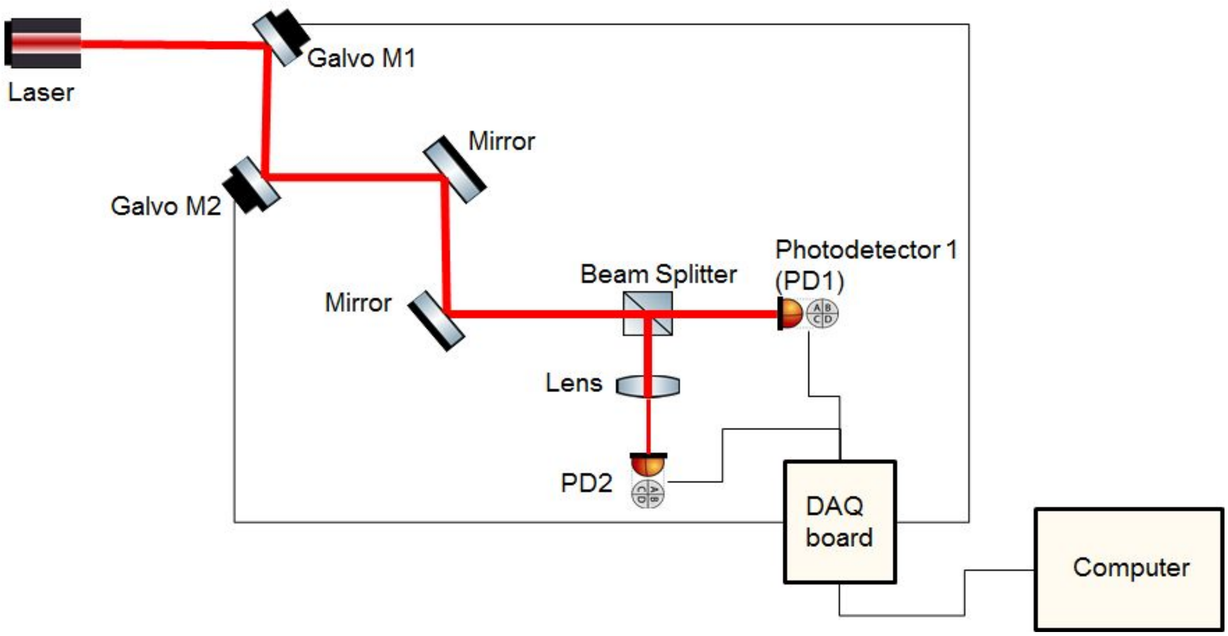

Figure 3. Optical alignment system for CALVA. PD1 is sensitive to beam translation and rotation, and PD2 is sensitive to solely beam rotation. A (PID) feedback loop will acquire beam position data from the PDs, and send correction signals to the galvo mirrors to center the beam.

During the assembly process I learned a few "tricks" from my advisors about properly assembling each component, and aligning the laser. For example, fixing the laser source (and therefore beam) height constant, and using the holes on the optical table as a guide for the laser beam. A technique he employed to get PD2 in the focal plane of the lens, was placing a piece of transparent glass between the periscope and beam splitter, then rotating it to simulate beam rotation. The photodetector's horizontal signal wire (which registered positive or negative voltage depending on which side of the central axis the beam was on) was attached to an oscilloscope. If the photodetector was in the focal plane of the lens, it would register little or no change in voltage when the glass piece was rotated.

Data acquisition testing:

We compared data acquisition and signal output capabilities between a National Instruments Data Acquisition (DAQ) board and an Arduino Uno board; and also used this opportunity to test some MATLAB command capabilities. MATLAB has Arduino and Data Acquisition tool boxes for download, so there was no need to program in the Arduino IDE or in C++. (In fact, MATLAB was the only language needed during the entire project.) Simple exercises to test Arduino function were performed, such as turning an LED on/off, changing its brightness, registering a signal when a button was pressed. Success of these tests gave way to testing digital inputs and outputs, and finally analog signals. The Arduino board however failed in two functions: it could not easily acquire a continuous signal (a complex code had to be written in the Arduino language), and the Arduino could not register a negative voltage (which was needed for the PSDs.)

One DAQ board was tested which, after initial signal testing using an oscilloscope and power generator, successfully controlled the galvo mirrors. This DAQ board was replaced by another (newer) DAQ board, due to ground connection problems in the previous one. Because the DAQ only accepted single wires for connection to its analog pins, a power supply box was used which converted signals from the photodetectors' Hirose connector cables to single wire connections after some electrical soldering. There were no other major issues in acquiring analog signals from the photodetectors, and sending analog signals to the galvo mirrors.

A little time was spent on creating a user interface (using MATLAB's App Designer program) which displayed signals from the photodetectors as well as allowed the user to send signals to the galvo mirrors. The side-project was abandoned as live signals could only be displayed graphically (not numerically), and one could not simultaneously (or even quickly) send signals to change the galvo mirror positions and read a resulting change on the photodetectors. This project and its results also proved time-consuming, but improvements can be made and this interface may be useful in the future.

<u>Photodetector calibration and noise</u>:

An initial measurement of the photodetectors' dark noise was taken. Dark noise for our purposes is defined for the state of the detector when the laser is off, and covered (shielded from ambient light). This measurement was taken so as to compare how much of it affected calibration measurements and how well we would be able to center the beam on the photodetectors, to be described in the following section. Figures 4 and 5 displays the noise level of each PD.

After a fair amount of time spent testing laser signals and reducing power fluctuations, the photodetectors needed to be calibrated to the position of the laser beam across the PSDs. The first task was to calibrate the photodetectors to change in the beam position caused by changes in the galvo mirror positions. In other words, we needed to find a relation between the change in voltage registered on photodetectors when the voltage across the galvo mirrors were changed.

The procedure for the calibration was as follows: first zero (apply a zero voltage across) the galvo mirrors, then while keeping one galvo mirror position constant, change the voltage of the

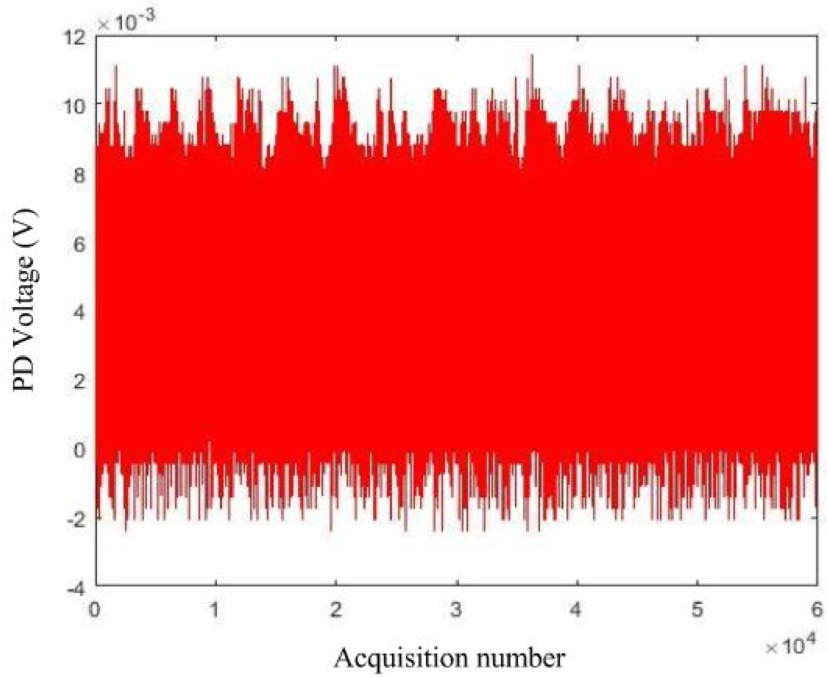

Figure 4. PD1 electronic dark noise, with calculated center at about 3 mV.

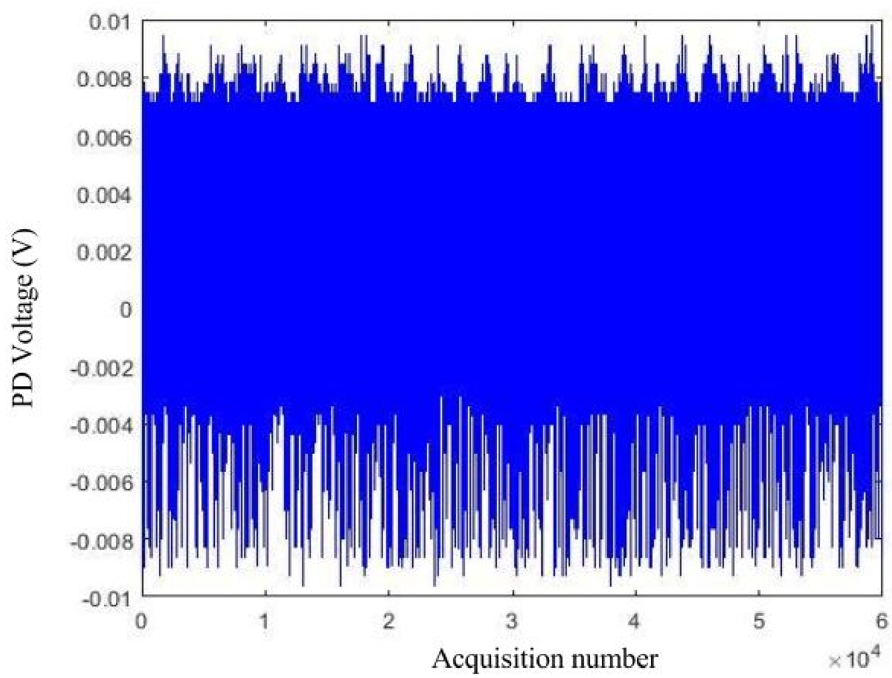

Figure 5. PD2 electronic dark noise with calculated center at about 0.7 mV

other and read the voltages across each photodetector. Once about 10 data points were acquired, perform the same acquisition using the other mirror. In the end we have four sets of data points (PD1 with M1, PD1 with M2, etc.) (Figures 6 and 7 show example calibration plots.)

Using a statistics software (Minitab), multiple regression analysis, and hypothesis testing was performed to find the best polynomial fit for the data. The linear coefficients arising from such analysis are to be used in a matrix of the PID feedback loop (more on this later.) The coefficients are listed below in Table I. for each set of data.

(A second calibration, between the registered voltage on the photodetectors and change in actual distance of the beam along the PSD was also performed, but may not be used until later. For the purposes of testing the PID loop, only the first calibration was required.)

An initial measurement of the photodetectors' dark noise was taken. Dark noise for our purposes is defined for the state of the detector when the laser is off, and covered (shielded from ambient light). This measurement was taken so as to compare how much of it affected calibration measurements and how well we would be able to center the beam on the photodetectors, to be described in the following section.

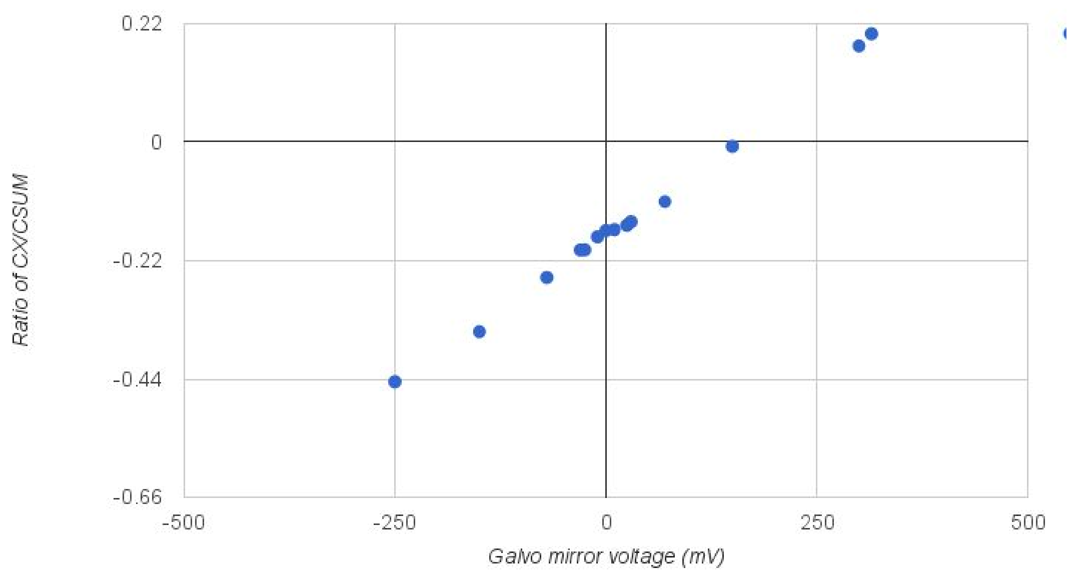

Figure 6. Calibration data. Ratio of registered X to SUM voltages across PD1 versus voltage applied on M1. (Note: The C's in "CX/CSUM", was for our personal labeling purposes.)

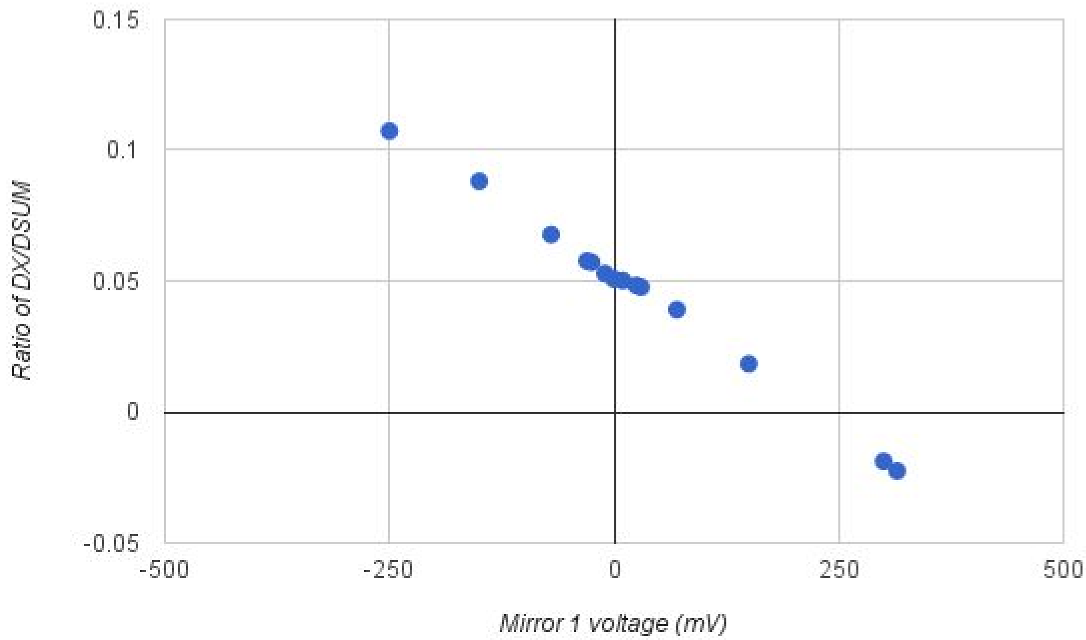

Figure 7. Calibration data. Ratio of registered X to SUM voltages across PD2 versus voltage applied on M1. (Note: The D's in "DX/DSUM", was for our personal labeling purposes.)

Table I. Linear coefficients of relation between X/SUM voltages on PDs to voltages across galvo mirror

	M1 (mV)	M2 (mV)
PD1 (ratio of X/SUM)	1.126×10^{-3}	-6.223×10^{-4}
PD2 (ratio of X/SUM)	-2.273×10^{-4}	1.503×10^{-4}

PID testing:

A PID loop is implemented to center a beam on the PSDs of the photodetectors. This control system was chosen for its reputation for wide use in industry due to its ease of use. As mentioned above, position data from the photodetectors is used to calculate a correction signal to be sent to the galvo mirrors to correct the position of the beam. Such feedback tries to minimize an error signal calculated from the difference of the beam's actual position to the desired position on the PSD.

Just to present a basic derivation of our PID, we start by defining two variables $V_{R,1}$ and $V_{R,2}$ as the ratio of the X voltage to the SUM voltage of PD1 and PD2, respectively.

$$V_{R,1} = \frac{V_{X,P1}}{V_{SUM,P1}} \qquad (1)$$

$$V_{R,2} = \frac{V_{X,P2}}{V_{SUM,P2}} \qquad (2)$$

These ratios each are further defined as a linear combination of V_{M1} and V_{M2} the voltages across galvo mirrors 1 and 2, respectively.

$$V_{R,1} = \alpha V_{M1} + \beta V_{M2} \qquad (3)$$

$$V_{R,2} = \gamma V_{M1} + \kappa V_{M2} \qquad (4)$$

Re-writing (3) and (4) as a matrix-vector equation, we have

$$\begin{bmatrix} V_{R,1} \\ V_{R,2} \end{bmatrix} = \begin{bmatrix} \alpha & \beta \\ \gamma & \kappa \end{bmatrix} \begin{bmatrix} V_{M1} \\ V_{M2} \end{bmatrix} \qquad (5)$$

or

$$\vec{V}_R = \mathbf{L}\vec{V}_M \qquad (6)$$

Multiplying each side of (6) by $\mathbf{L}^{-1}$ on the left, we have our definition for the error signal vector to be used in the PID. That is

$$\mathbf{L}^{-1}\vec{V}_R = \vec{V}_M = \vec{\varepsilon} \qquad (7)$$

Numerically the values in Table 1, will (in their current order) correspond to the values of **L** (matrix of linear coefficients.)

$$\mathbf{L} = \begin{bmatrix} \alpha & \beta \\ \gamma & \kappa \end{bmatrix} = \begin{bmatrix} 11.26 & -6.223 \\ -2.273 & 1.503 \end{bmatrix} * 10^{-4} \qquad (8)$$

Three terms in a PID loop determine the correction signal to be sent to the galvo mirrors; the proportional term is based on the current error values, the integral term takes past values into consideration, and the differential term for possible future values. Figure 8 gives a visualization of the workings of a PID. Each term contains its own coefficient, called gains, which are manually tuned to achieve a desired result (in our case, zeroing the beam position.)

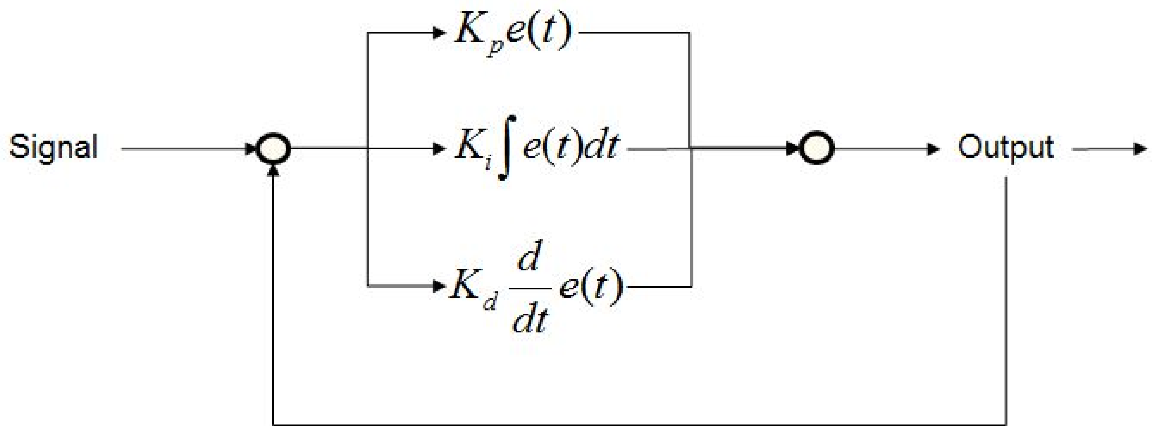

Figure 8. Visual representation of the workings of a PID. *e(t)* represents the error signal calculated by the PID (as the difference of the desired point to the actual point.) Each *K* is the gain of each PID term. Our PID does not explicitly use functions of time, but still is very effective as we shall see.

Example code is presented below to show how we applied our PID. Note this code goes inside the code for the loop. Each iteration minimizes the error signal and ultimately centers the beam on the photodetectors.

```
-   Aqvoltc; % Acquire PD1 sig
-   Aqvoltd; % Acquire PD2 sig
-
-   % Li is inverted linear coefficient matrix
-   ersg = Li*[cx_mean/csum_mean ; dx_mean/dsum_mean]; % error
-
-   % Kp, Kd, Ki are gains to be tuned.
-   E=(Kp*Ep+Kd*De+Ki*In);      % signal vector to be output
-   In=In+ersg;                 % integral
-   De=ersg-Ep;                 % differential
-   Ep=ersg;                    % proportional
-
-   outputSingleScan(m1,E(1));       % m1 signal out
-   outputSingleScan(m2,E(2));       % m2 signal out
```

There does not seem to be any formal methodology of tuning the gains, except based on intuition. For example, one should probably begin with the integral term, because its primary job is to force the error to its lowest value (i.e. attain the desired signal.) Tuning progress is shown in Figures 9, 10, 11.

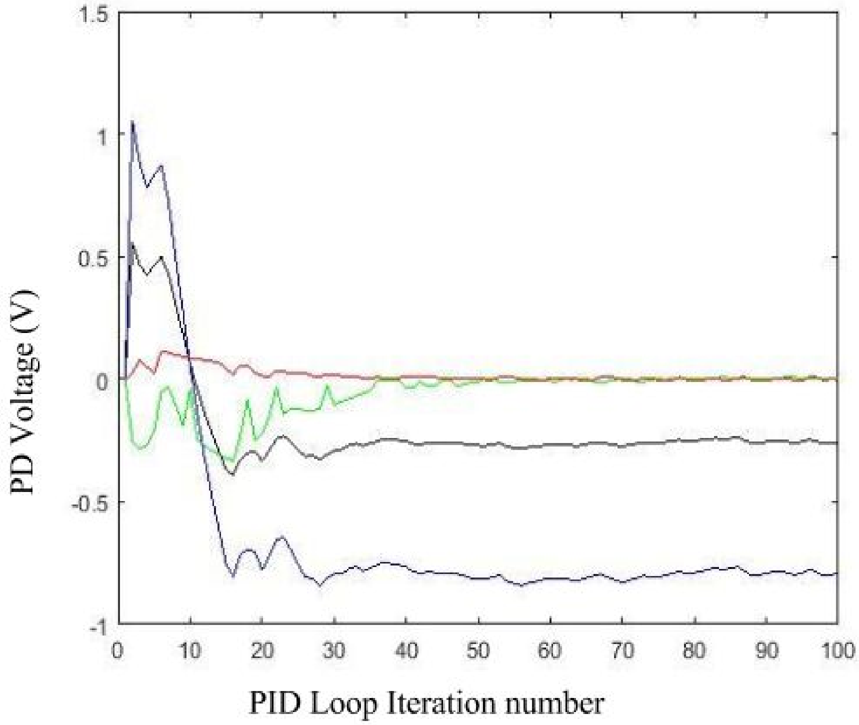

Figure 9. PID tuning using only the integral term.

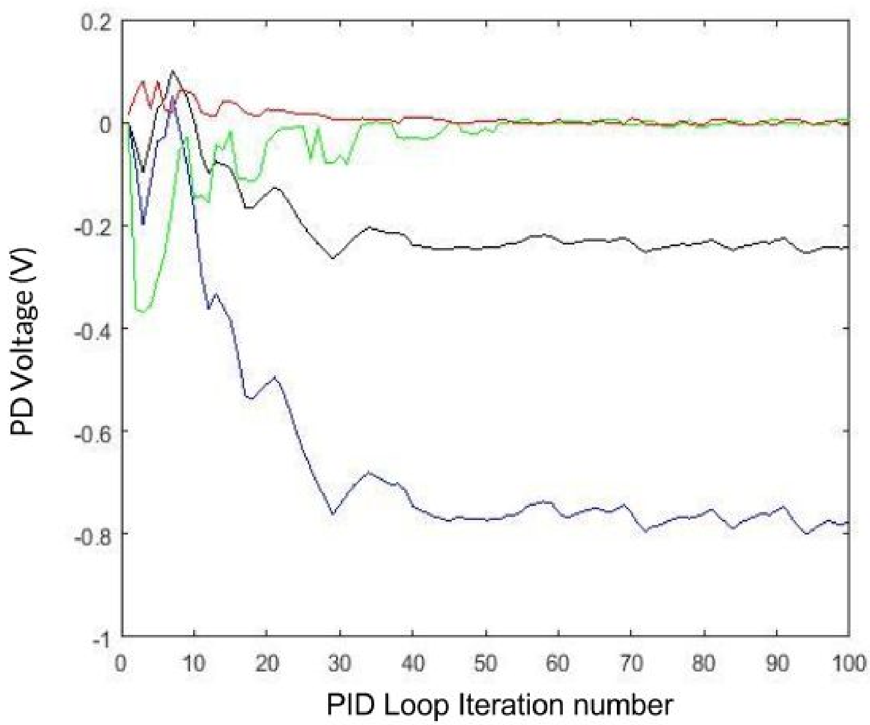

Figure 10. PID tuning results using proportional and integral terms.

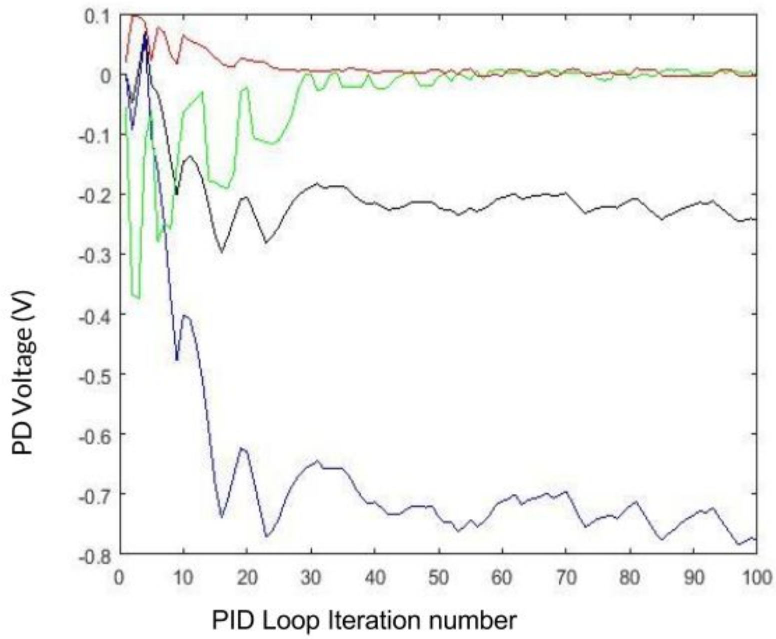

Figure 11. Full PID implementation; proportional, integral, and differential terms.

During the course of the tuning process, only the integral term was actually needed. That is to say the proportional and differential terms did not affect the centering of the beam. Contrarily, they seemed detrimental to the PID, slowing the centering process or causing divergence in the error signal. (Divergence would really be caused by the integral term, but a large proportional value maybe taken into account in future iterations, thereby causing divergence of integral term, and therefore the error signal. The integral gain may be adjusted to a lower value so its impact is less, but when optimizing it for use with the proportional and differential gains, there was a limit past which the error signal would take too long to minimize.

Testing was continued with solely the integral term. For reference, a zero voltage registered on the PSD meant the beam was perfectly centered. However accounting for electrical noise of the photodetector a "zeroed" beam would be at about 3 mV for the PD1 and 0.6 mV for PD2. To test the PID, a voltage was applied to displace the mirrors (and therefore the beam across the PSD). When the loop was run the voltages registered were about 8 mV on PD1 and PD2, which was close to the noise levels, but not so much as to be drowned out by them. Also note the noise level of PD1 was much higher, because though it was a Gaussian beam, it was not focused by a lens like the beam incident on PD2. Also as far as the time interval over which the PID ran, the beams were centered within about 3 seconds, after which the signals oscillated within 8 mV of zero. The PID loop duration was changed to last three minutes, but no change in the laser beam signal was noticed (as in, it remained within the 8 mV limit about zero.)

Notes on problems faced:

Flooding: Initially my project was delayed by about a week due to flooding at the University Paris-Sud campus during the first week of my stay in Paris. We also had to switch to another room for work during the first week and a half of work, due to power shut down in the CALVA building. Eventually, the entire apparatus was shifted back to the CALVA building where my project continued for the rest of my stay.

Laser stability: As mentioned above, initially a green laser source was used which was composed of the laser LED and a temperature control. For the purposes of aligning each optical component a low power was used, but when it came time to measuring exact signals, specific parameters for the laser power needed to be chosen or otherwise cause large power fluctuations. (Figure 12 shows laser power fluctuation comparisons between the red laser and green laser without proper parameters.) However, even with proper parameters, the green laser which was more stable, still displayed power fluctuations higher than the red laser which was chosen for the rest of the development process. The red laser was already known to be stable, but we tested to confirm nonetheless. The fluctuations seemed to have dropped to about 10-12 % from the initial 30-60 %. To note, after a series of different types of acquisitions (continuous and discrete using different acquisition rates and times) the actual fluctuations were determined to be on the order of 0.01 %. Sunlight played a role in causing fluctuations, which was remedied by covering the system.

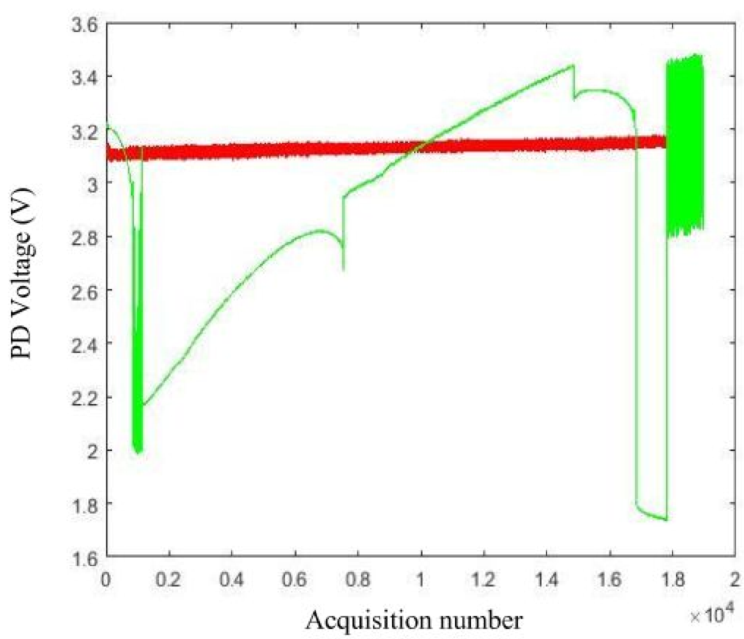

Figure 12. Laser stability comparison, green versus red laser. Green laser parameters (LED power, and temperature control were not optimal.) Not shown, but even with optimal parameters, the power fluctuations of the green laser were 2-3 times that of the red laser; leading us to choose the red laser for the duration of the research.

Limitations and future work:

We have done limited testing of the PID with artificial noise, using a simple optical chopper. The chopping rate however at its lowest value was too high for the acquisition rate of the PID. We did not have time to find an alternative method for testing the PID with artificial noise during my time there, so future work will include this test. Other limitations to consider in the system is obviously the photodetector electrical noise, reducing this and then working to tune the PID for finer centering, would be the next step. Cutting down on laser power fluctuations, and would be the next key to even finer control.

Ultimately, we would like to conduct tests of this optical feedback system using the infrared laser of CALVA, taking into consideration the higher finesse optics. Naturally, due to dependence of refractive index of a material to the wavelength of light passing through the material PD2 (at the very least) would need to be adjusted to the correct focal plane of the lens before it. All other components are adjusted accordingly due to other physical constraints. After this, testing on even higher finesse cavities (those higher than CALVA's system), may begin.

III. Acknowledgements

I would like to thank Drs. Bernard Whiting, Guido Mueller, Carol Scarlett, Kristin Nichola, and Ryan Goetz of the University of Florida for the opportunity to take part in this REU, arranging travel and helping the program run as efficiently as it does. The National Science Foundation for the funding necessary for this program and continued support of programs like this which helps students like me realize how professional science is conducted. Dr. Michelle Caler, and Dr. Joseph Moser at West Chester University for feeding my curiosities of mathematics and physics during the past few years and especially the last semester while helping me understand General Relativity. I would like to thank the CALVA group, especially my advisors at Universite Paris-Sud: Nicolas Leroy, Vincent Loriette, and Ivan Maksimovic, whose support and knowledge encouraged my own curiosities. Finally, my friend Clement Walter in France with whom my conversations would enjoyably lift me from the mundane, and from whom I have learned my love of physics again.

IV. References

1. Åström, Karl J., and Richard M. Murray. *Feedback Systems: An Introduction for Scientists and Engineers.* Princeton: Princeton UP, 2008. Print.
2. B. P. Abbott *et al, Observation of Gravitational Waves from a Binary Black Hole Merger.* 2016 *Physical Review Letters* 116

3. B. P. Abbott *et al*, *GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence*, 2016 *Physical Review Letters* 116
4. Evans, Matthew. *Lock Acquisition in Resonant Optical Interferometers*. Thesis. Thesis (Ph. D.). PQ #304, 2002. Pasadena: California Institute of Technology, 2001. Print. Rakhmanov, Malik. *Dynamics of Laser Interferometric Gravitational Wave Detectors.* Thesis. Thesis (Ph. D.). UM #997, 2000. Pasadena, 2000. Print.

5. "Subsystem: Auxiliary Optics." Advanced LIGO. Massachusetts Institute of Technology, 20 Nov. 2015. Web. May 2016.