Characterization and Control of Coupled 5m and 50m Optical Cavities in CALVA

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Contents

1 Introduction

The detection of a gravitational wave is one of the great unachieved present day goals of experimental physics. The theoretical foundation for the existence of gravitational waves has been essentially well established since Albert Einstein's 1905 paper, "On the Electrodynamics of Moving Bodies." However, due to various bureaucratic and physical impediments, there has yet to be a detection of a gravitational wave.[?]

The current detection scheme for gravitational waves involves the use of large scale Michelson interferometers located in Europe and North America. The American project which is principally funded by the NSF is called LIGO for Laser Interferometer Gravitational-wave Obervatory, and has two installations; there is an interferomter in Livingston Louisiana, and one in Richland Washington. The European project is called VIRGO whose interferometer is located in Cascina, Italy just outside of Pisa.

The fundamentals of gravitational wave detection via laser interferometers will be covered in the following section, for now it is worthwhile to remark that the long delay between theoretical prediction and observation imply a tremendous technical challenge. The interferomters being used now have 'arms' with lengths of 3-4km and the signal that will ultimately lead to a detection will result from a change in that arm length of $10^{-18}m$. Concomitant with attempting to build a machine so sensitive are a host of physical and technical issues. The experiment I participated in this summer, CALVA, aims to solve one of the primary issues: locking the laser in the interferomter to the optical cavities formed by the arms.[?]

2 Background

To facilitate the process of describing both the CALVA project as well as the work accomplished this summer it will be beneficial to give theoretical review of some fundamental optical physics, as well as define a few terms and names that are specific to this experiment.

2.1 Gravitational Wave Interferometry

The Michelson interferometer was developed by Albert Abraham Michelson for use in the 1887 Michelson-Morley experiment attempting to show the effect of the aether on the speed of light. Although that experiment was a tremendously successful failure, his apparatus has found long life in optical physics.[?]

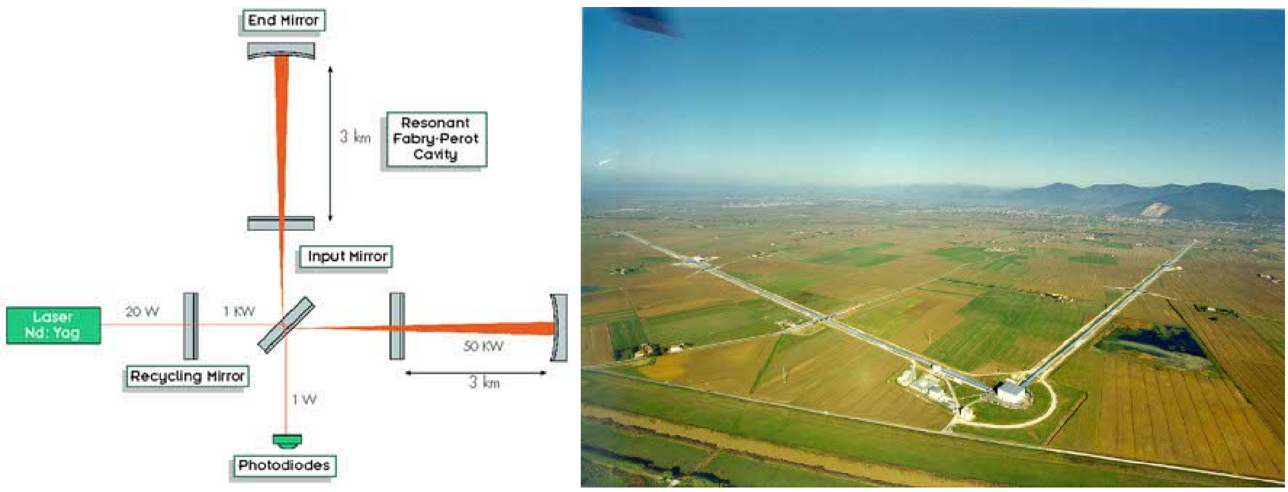


Figure 1: Left: A simplified diagram of the VIRGO interferometer showing the main laser and the most important optical cavities. Right: A bird's eye view of the interferometer, showing its scale and remote location.

An interferometer functions with a single, coherent source of light such as a laser producing a single wavelength. This light is collimated and sent to a half silvered mirror which, roughly speaking, directs two half intensity beams of light in orthogonal directions. After entering the optical cavities formed by the arms the light is eventually rejected back towards the half silvered mirror, which now superimposes the beams onto each other and focuses them into a photodiode.

Coherent light has an inherent phase because of its wavelike nature. If both of the beams of light after the half silvered mirror have the same path length, then they will impinge on the photodiode in phase, and simply increase the intensity of the signal. However if there is a difference in the path length of the two beams, then the beams will form an interference pattern on the photodiode; if the light is visible then you would see 'fringes', or light and dark patterns appear if you observed the beam at the photodiode. These fringes manifest as a modulated intensity of the signal on the photodiode.

For our purposes this is enough to understand the detection scheme; the interferometers are sensitive to physical changes that result in different path lengths for the two beams of light, and the measurable effect is a modulated intensity signal on the photodiode.

2.2 Gravitational Waves

It is now useful to address how a gravitational wave could result in precisely this sort of differential change in path length. Gravitational waves created by two massive objects such as stars orbiting around their center of mass will produce quadrupole waves in spacetime propagating outwards in all directions. General relativity describes the force of gravitation as a resultant effect due to geometric distortions in spacetime. This means that when a gravitational wave passes through and near an object, it will experience a change in the net force on itself, depending on the structure of the wave as well as the objects orientation relative to the source. The current breed of gravitational wave detectors have been designed to respond to and detect these types of waves.

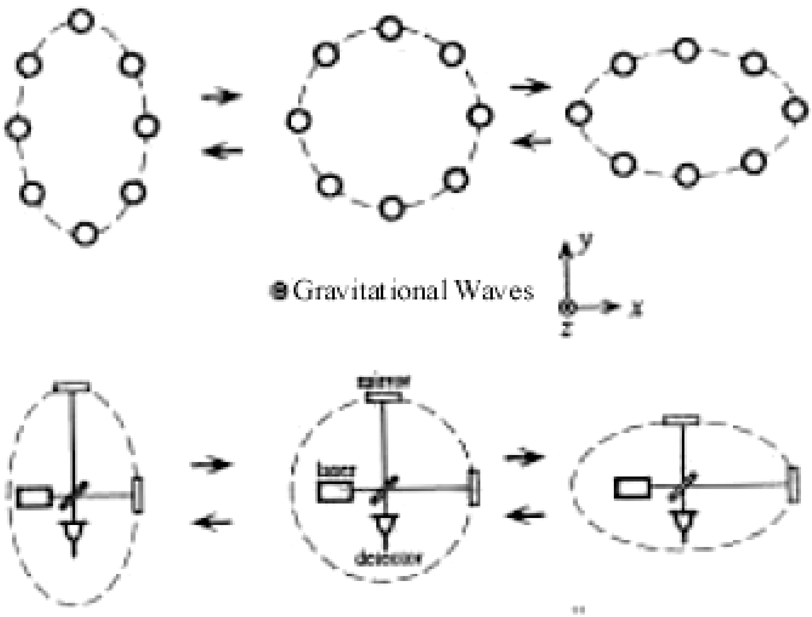


Figure 2: The top row shows how a circularly distributed group of particles would be displaced if a gravitational wave passed through them along the axis perpendicularly through the page. The bottom row illustrates how an interferometer would be affected. [?]

Fig. 2 illustrates how a passing gravitational wave would distort an interferometer in precisely the way necessary to measure its effect. Although this is greatly simplified, primarily because it assumes the wave is propagating along the axis perpendicular to both arms of the interferometer, this is sufficient to understand how an interferometer can detect a gravitational wave.

2.3 Fabry-Perot Cavity

As you can see in Fig. 1 on the left, the arms of the interferometer are formed by 2 parallel mirrors that form a Fabry-Perot cavity. A Fabry-Perot cavity is a standing wave optical resonator, formed by two parallel mirrors. In the case of gravitational wave interferometers and the CALVA experiment, the mirrors are reflective on only the side facing into the cavity to allow the beam to enter. The most critical aspect of a Fabry-Perot cavity relevant for this discussion is that only light whose wavelength divides the length of the cavity will resonate, i.e. the length of the cavity needs to be an integer multiple of the wavelength of the light.

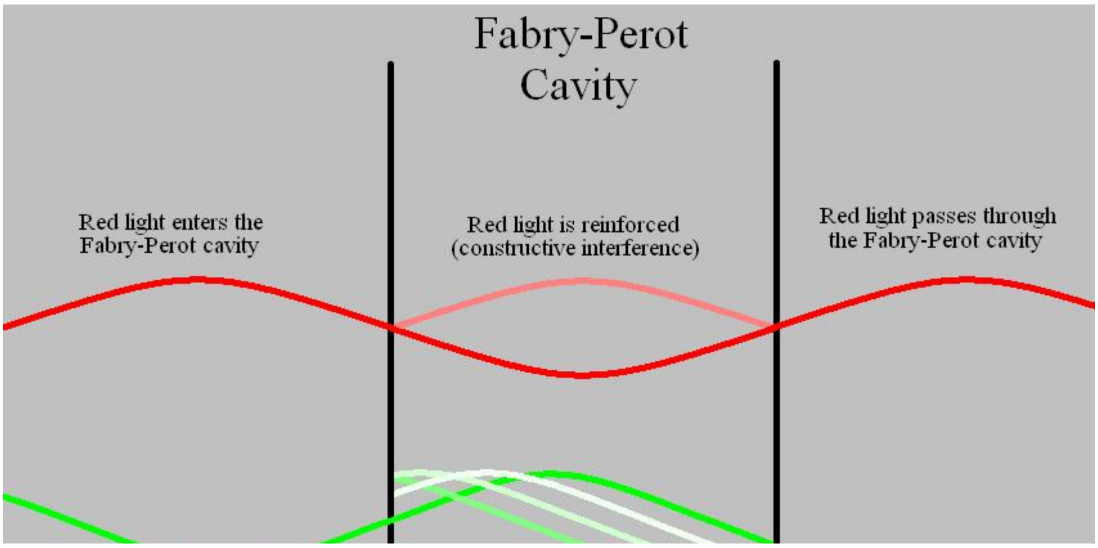


Figure 3: The red light resonates within the cavity and forms a standing wave, while the green light experiences destructive interference because of the difference in wavelength.

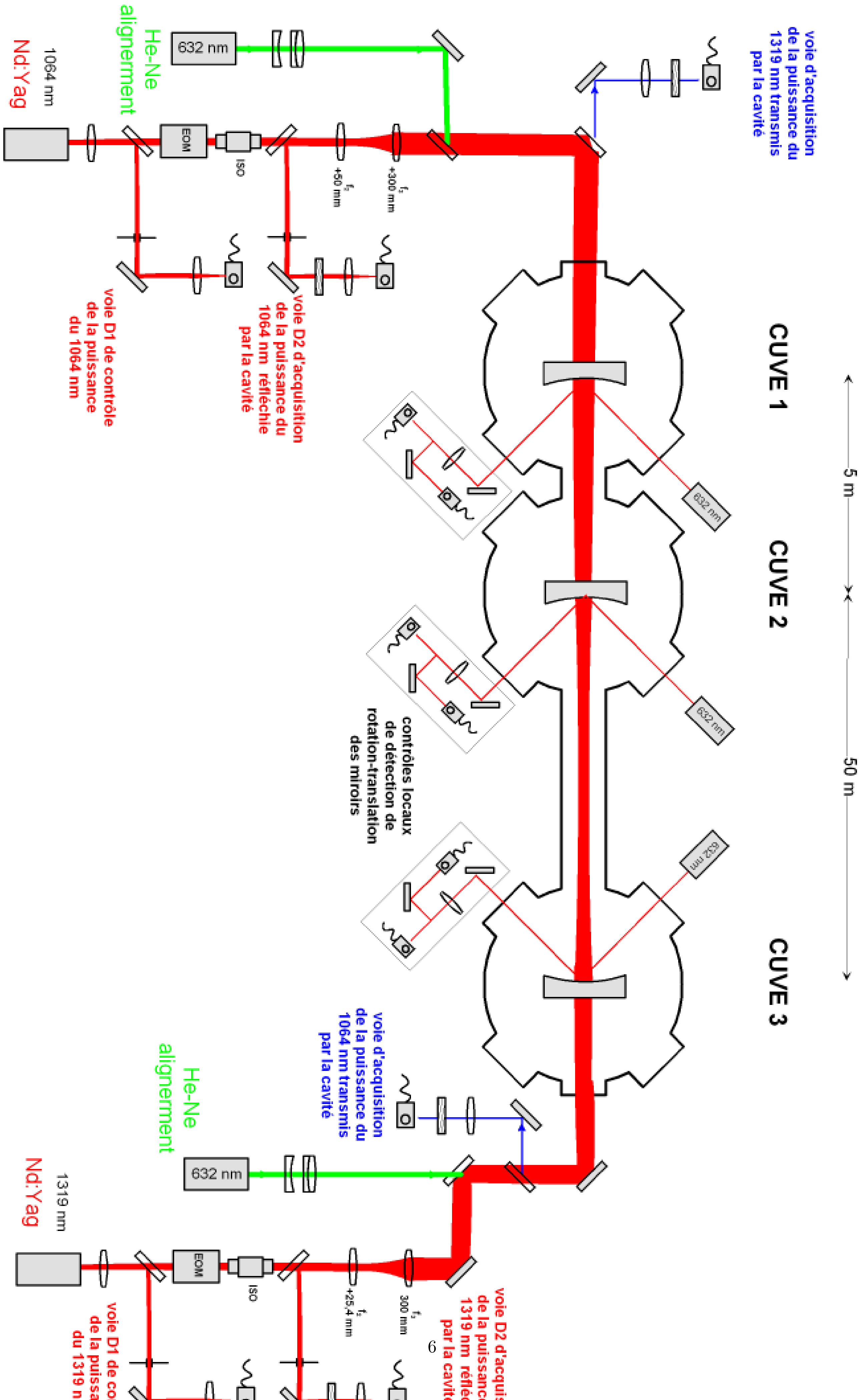
CALVA contains two such cavities, and the primary aim of the experiment is to develop a way to control the lengths of the activities to establish this resonant condition.

2.4 CALVA

CALVA (Cavité pour l'Acquisition du Lock de Virgo Avancé) is an experiment designed to test a lock acquisition scheme for the laser and optical cavities in Advanced Virgo. Advanced Virgo is the next generational upgrade to the gravitational wave detector Virgo. CALVA consists of a 5m optical cavity coupled to a 50m optical cavity. Both ends are contained in $100m^2$ clean rooms. These clean rooms contain the lasers as well as all optical and electrical components necessary for carrying out and managing the experiment. Figure 4 shows a diagram of the experiment, Fig. 5 contains a picture of Clean Room 1 containg the optical bench for the 1064 and the towers containg mirrors 1 and 2.[**?**]

2.5 Terms

M1 and M2 The diagram in Fig. 4 shows the mirrors which form the 5m and 50m optical cavities, contained inside CUVE 1, CUVE 2, and CUVE 3. The mirrors inside CUVE 1 and 2 will hereafter be referred to as M1 and M2 respectively. M3 was not installed during my time at CALVA. Inside the tanks, the mirrors are placed in a housing with four permanent 1T magnets, one at each corner. They are suspended and aligned in front of four inductive coils which are used to actuate the position of the mirrors. Figure 6 contains a diagram of the mirror assembly.


voie d'acquisition
de la puissance du
1319 nm transmis
par la cavité
632 nm
He-Ne
alignement
1064 nm
Nd:Yag
EOM
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f_2 +50 mm
f_1 +300 mm
voie D2 d'acquisition
de la puissance du
1064 nm réfléchie
par la cavité
voie D1 de contrôle
de la puissance
du 1064 nm
CUVE 1
CUVE 2
CUVE 3
5 m
50 m
632 nm
632 nm
632 nm
contrôles locaux
de détection de
rotation-translation
des miroirs
voie d'acquisition
de la puissance du
1064 nm transmis
par la cavité
He-Ne
alignement
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1319 nm
Nd:Yag
EOM
ISO
f_2 +25,4 mm
f_1 300 mm

Figure 5: The first clean room showing towers 1 and 2.

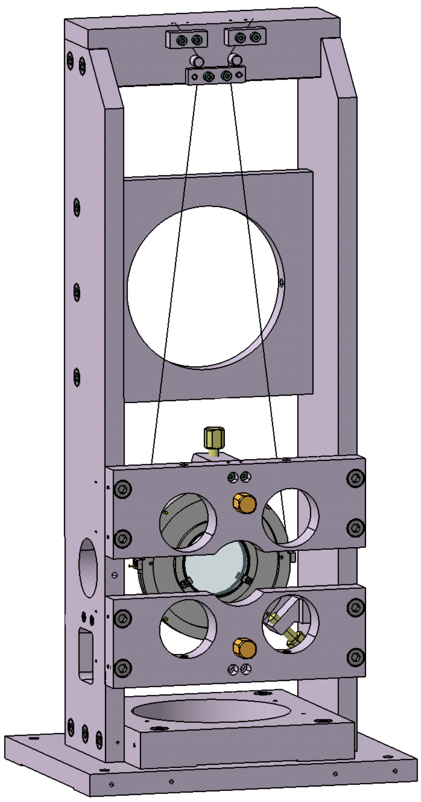

Figure 6: Diagram of the housing for the mirrors as well as the four coils used to control the mirrors.

Locking a laser/cavity As described in the 'Fabry-Perot Cavity' section, we know that optical cavities achieve resonance when the length of the cavity is an integer multiple of the wavelength of the laser. Locking a laser or cavity simply means controlling the length of the cavity as close as possible to this condition. In the context of the CALVA experiment locking a cavity will mean activating what we will call 'Global Controls' and attempting to achieve resonance in the 5m cavity with either a 1064nm laser or 1319nm laser.

Local Controls In Fig. 4 we see that each tank has a red HeNe laser and small optical assembly associated with it. These comprise the hardware component of the 'Local Controls' system, which are responsible for measuring the angular rotation and Z-axis displacement of their respective mirror. Each Local Control setup includes a 2mW red HeNe laser which impinges on the mirror whose reflection is captured and measured by two photodiodes. The photodiodes are placed at calculated distances[1] from the mirror, so that one of the photodiodes is sensitive to only angular rotation, while the other is sensitive only to Z-axis displacement of the mirrors. The Local Controls do not communicate with the other mirrors, they use only information from the adjacent mirror; this is what differentiates them from the Global Controls. To save ink, the local control systems will be referred to as LC.

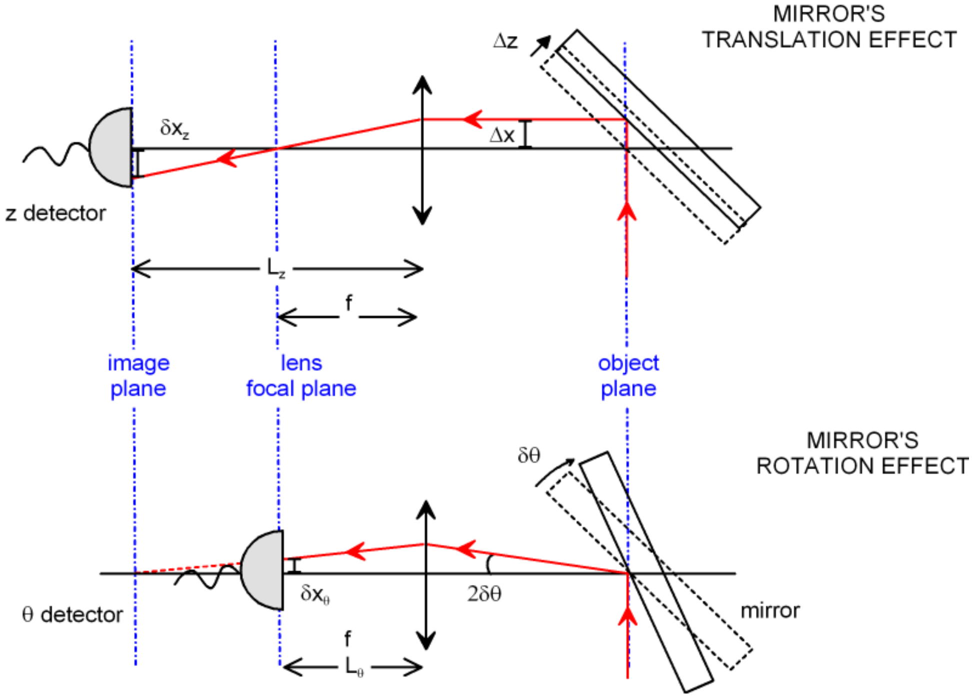

Figure 7: The photodiodes are placed at specific lengths to supress one or more degrees of freedom from affecting the measurement of that diode.

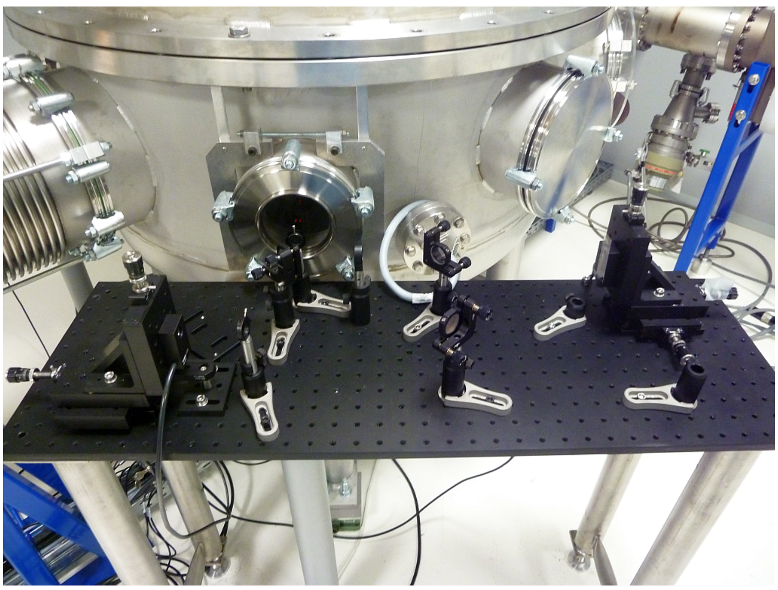

Figure 8: Local Control photodiode assembly from M2.

[1]As measured by path length of the laser

Global Controls The Global Controls are the component of the control system responsible for locking the cavities. Unlike the Local Controls, this control loop uses information from multiple mirrors and attempts to adjust the length of a cavity to achieve resonance. The Global Controls make use of photodiodes which are placed on the optical benches in both room 1 and room 2. They measure the reflected and transmitted signal from either the 1064 or 1319 laser and modify the signals sent to the actuation coils in response. The typical control scheme we employed during my time there involved releasing one of the mirrors from Z-axis control and allowing it to swing freely, and then forcing the other mirror to follow it.

The 1064 and 1319 Advanced Virgo will run with a main laser power of $P = 200W$ with a mirror mass of $m = 40kg$, the ratio P/m for Advanced Virgo then is 5. To emulate this ratio, CALVA runs a $1W$ main laser with a mirror mass of $200g$. Advanced Virgo will run a laser with wavelength $\lambda = 1064nm$ and so CALVA adopts that wavelength for the $1W$ laser.

A very important parameter for lock acquisition of an optical cavity is τ_{Res}, which is the mean time for crossing the resonance peak of a cavity. It is defined as

$$\tau_{Res} = \frac{\lambda}{2F\bar{v}} \tag{1}$$

Where λ is the wavelength of the laser, F is the finesse of the cavity that the laser sees, and $\bar{v}$ is the mean speed of the mirror. The finesse the Advanced Virgo is predicted to have is $F_{AdV} = 1200$ and so the mirror coatings were picked so that the 1064 would have the same finesse. It is easy to see that in equation 1, the higher the finesse, the smaller the time for crossing a resonance peak, which makes locking more difficult. The fundamental point of the CALVA experiment is to introduce a second, auxiliary laser, which will see a much lower finesse in the same cavity. Then the aim is to lock the cavity to that laser and then use the added control afforded by that to facilitate the locking process on the primary laser. The auxiliary laser is then chosen to have a $\lambda = 1319nm$, and it will experience a finesse of $F_{1319} = 15$. This is the cornerstone of the CALVA experiment.[?] [?]

3 Forward Progress

3.1 Diagonalizing the Actuations of the Mirrors and Testing the Local Controls

When I arrived CALVA was at an intermediate state of function. Although everything was installed and functioning, few things had been aligned or calibrated. The first step was to diagonalize the actuation for M1 and M2. As explained previously, the mirrors are held in a suspended rectangular housing with 4 permanent 1T magnets in each corner. When necessary, the mirror is actuated by running current through 4 adjacent coils which, thanks to Ampere's law, produce a consistent magnetic field.

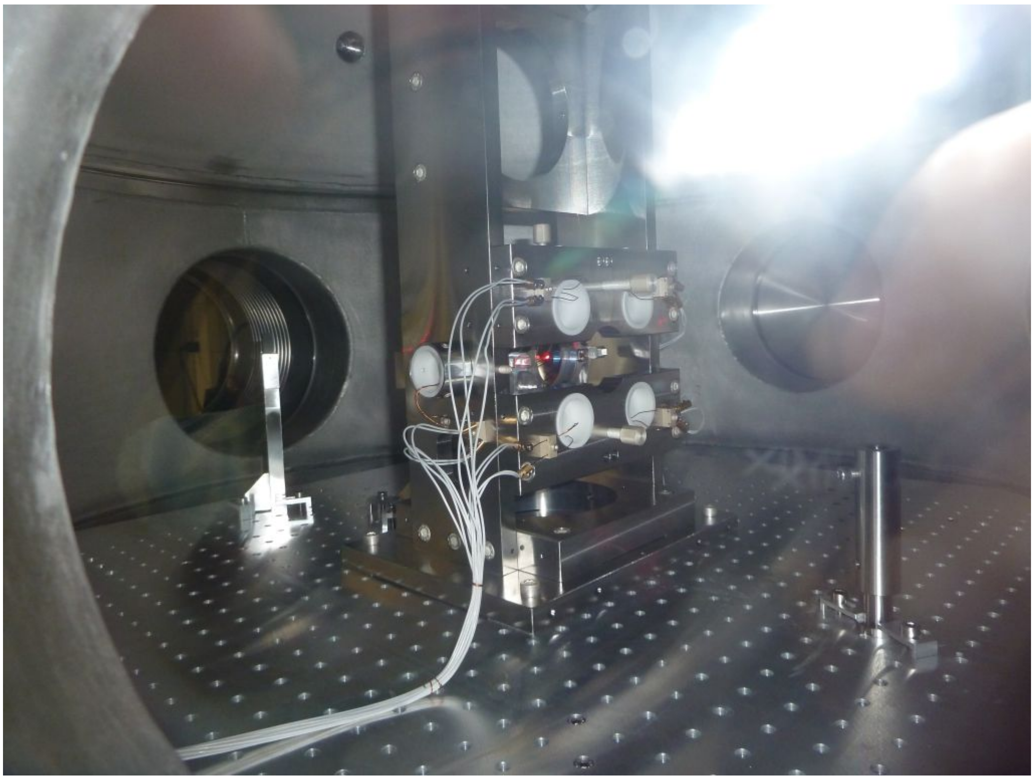

Figure 9: Tower 2, showing M2 suspended in front of the 4 coil rectangular assembly.

The mirrors are actuated continuously in the control loop to correct and maintain their position and orientation. The coils can be used to actuate rotations around the X and Y axes as well as displacements along the Z axis. However, since the coils, magnets, and mass distribution of the mirror housing are not perfectly consistent and uniform, the signals sent to the coils cannot be uniform. Otherwise while attempting to rotate around the Y axis you will excite the other two degrees of freedom. We correct this by injecting an $8.6Hz$ signal in one degree of freedom, θ_x for example, and then analyze the spectrum of the θ_x, θ_y, and z signals from the local controls. You then attempt to decouple the degrees of freedom from each other by adjusting the gains on each coil in the tower.

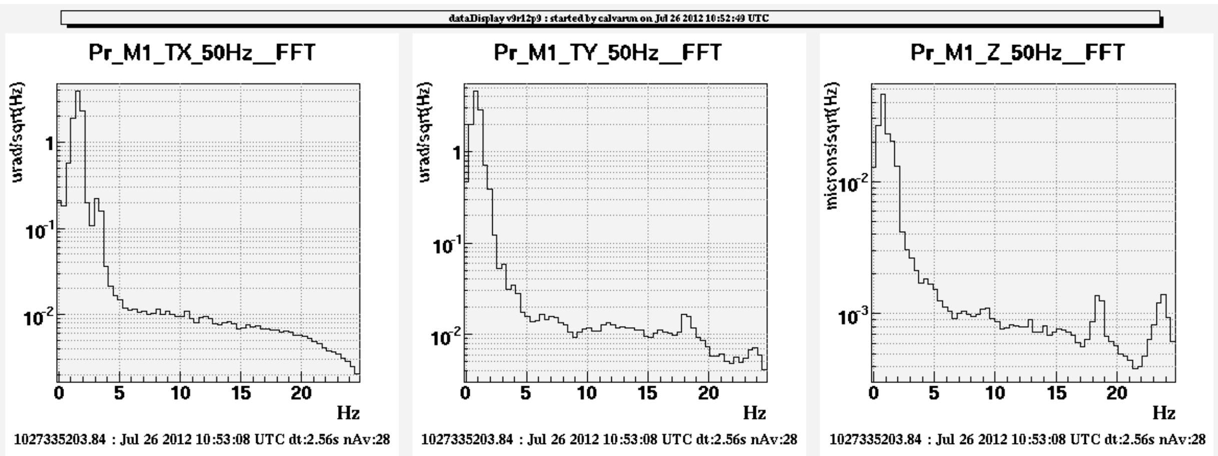

Figure 10: The spectrum of excitations on M1 when it is free E.G. not being controlled and no injected excitation.

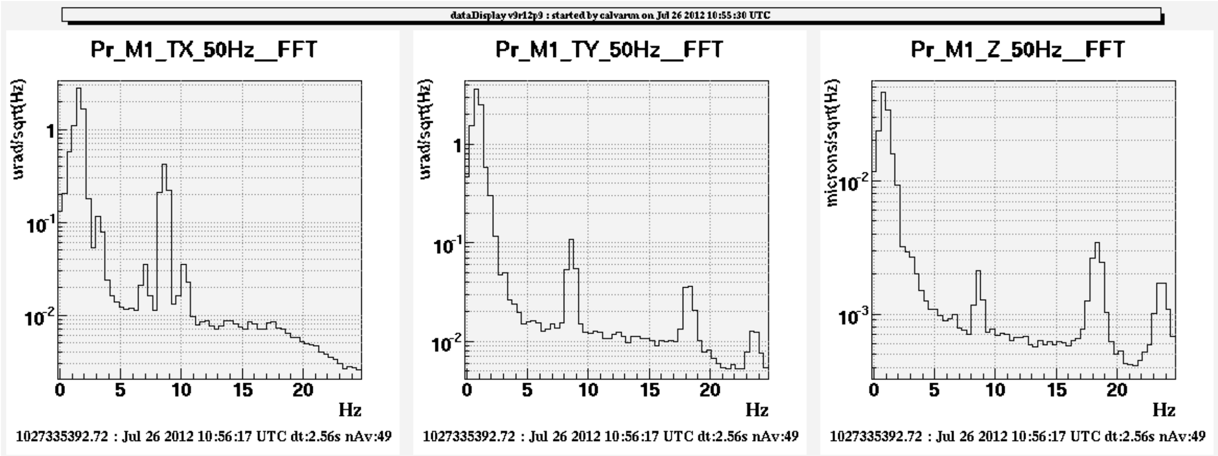

Figure 11: M1 spectrum after injecting an $8.6Hz$ signal on θ_x. Note the relatively large concomitant excitation inθ_y

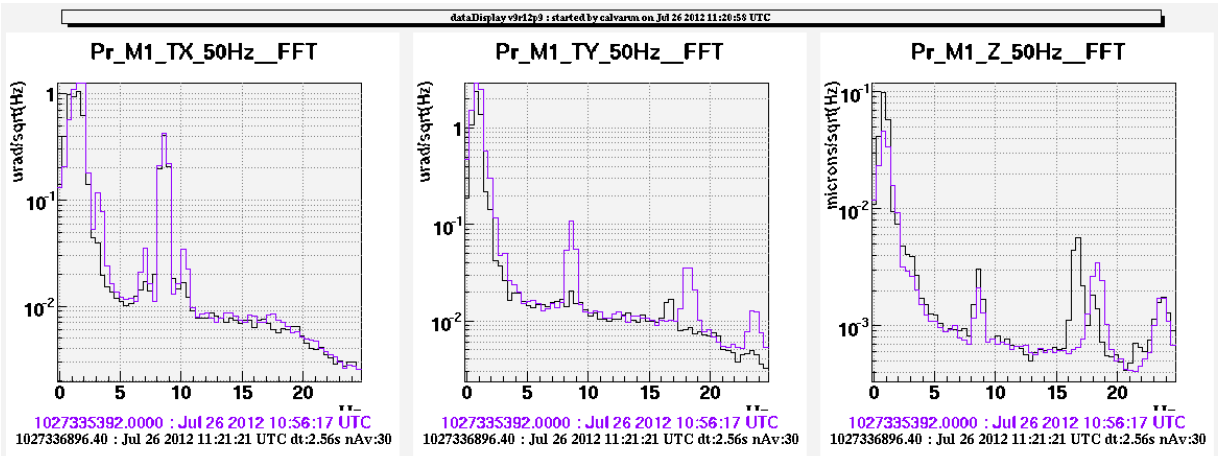

Figure 12: After adjusting the gains, there is now approximately a factor of 30 between the two excitations. Purple is the previous plot.

This process was repeated until all degrees of freedom were sufficiently decoupled on both M1 and M2. This was necessary because the control loop to stabilize the mirror would never work if while attempting to correct motion in one degree of freedom it excited another.[2]

After the actuation of the mirrors were successfully diagonalized, the Local Controls[3] needed to be aligned[4] to reach a well functioning state for the control systems. The software components of the control loop had already been created well before my arrival, so at this point the cavity was ready to be controlled. The following plots exemplify the effect that activating the LC has on the mirrors.

[2]This process of diagonalizing the actuation of mirrors will be significant again towards the end of the report.
[3]Hereafter referred to as LC
[4]This process is discussed in the Background section.

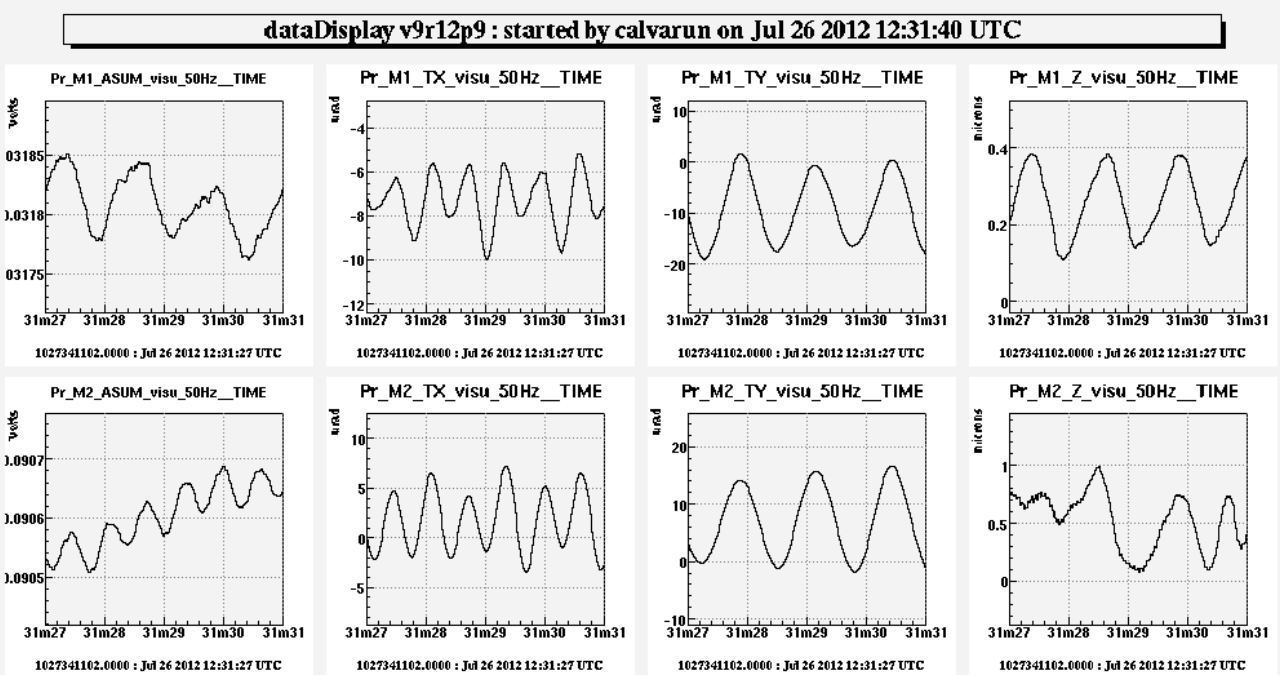

Figure 13: Angular and Z axis movement of M1 and M2 when the mirrors are free. This was taken after the mirrors had been allowd to dissipate energy for approximately two hours.

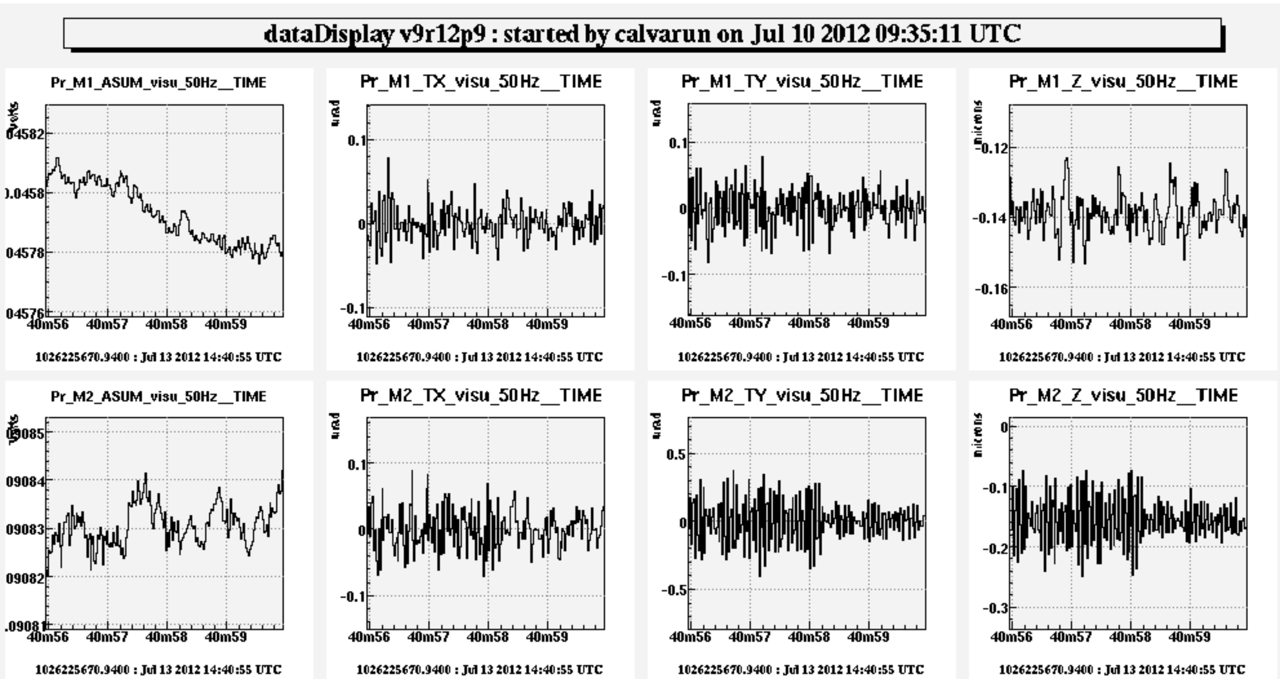

Figure 14: Angular and Z axis movement of M1 and M2 after the activation of LC. The movement of the mirrors has been reduced by two orders of magnitude.

3.2 Installation of Telescopes

With the control systems functioning, the next step was to prepare the beams and cavities for the injection of the 1064nm and 1319nm lasers. The InnoLight™ lasers produce by default beams with a waist inside the laser head, which produces a divergent beam. If one attempted to inject the default beam unchanged into the optical cavity you would not see a signal due to scattering of light within the cavity. [**?**]

To accommodate for this, both lasers require the installation of telescopes which serve to produce the correct beam size and shape for injection into the cavity. To determine the focal lengths and relative placement of the lenses in the telescope we first needed to verify the original beam waist position as well as see whether the mode of the laser was reall T_{00}. We did this by employing the razor blade technique. The beam from either the 1064 or 1319 was made to fall onto a photodiode, and a razor blade on a one dimensional test stage was placed in between the bath of the beam and the photodiode. We would move the razor blade incrementally and measure the change in the signal intensity.

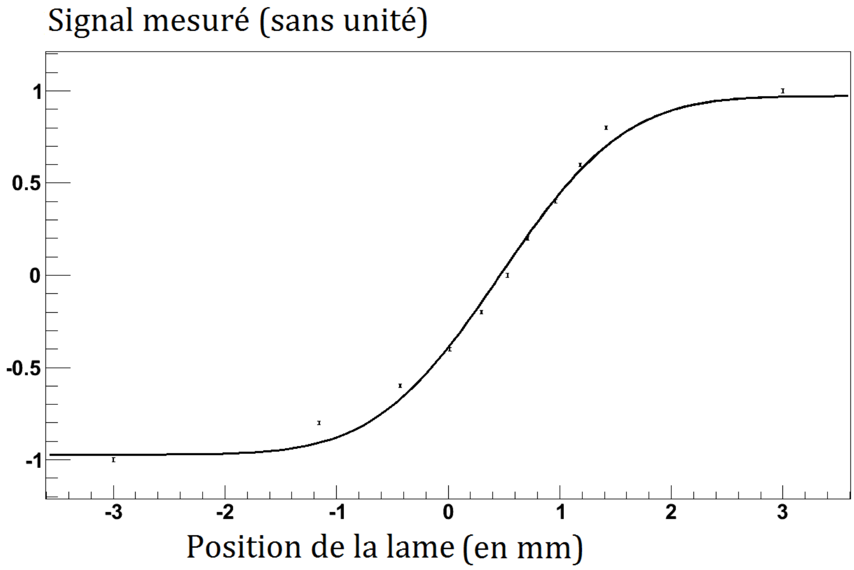

Figure 15: Measurements made for signal intensity as a function of position of the razor blade. Fit to theoretical prediction for a true gaussian beam. We can see that the beam is not perfectly gaussian.

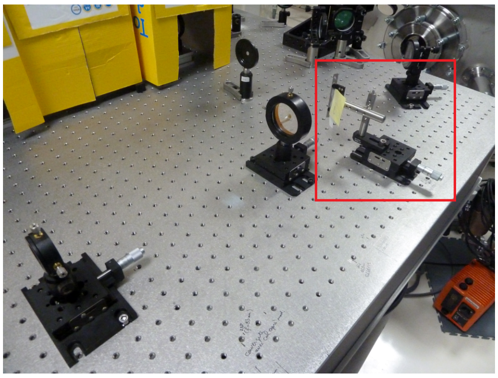

Figure 16: Typical setup used for razor blade measurement

After verifying the waist position and beam size measurements, one of the optics specialists in the group Dr. Loriette, would determine the lenses necessary to produce beams that would have a diameter of 2mm at M1 and M2.

3.3 Injecting 1319 and 1064

With both telescopes constructed to, in principle, match the beams to the cavities, the next step is to prepare them for injection. Even though the beams potentially have the correct dimensions, they may not be pointing the correct direction. Both beams are initially, and roughly, aligned with the cavity by first using a visible red HeNe laser to align the table lenses and mirrors so that the beam passes into and through the cavity. Then both the HeNe laser and the 1064 or 1319 are made to reflect back and forth across the room several times until they have the same path length as they would inside the cavity, E.G. if we're trying to center the 1319 on a mirror 50m away, we would first center the visible HeNe laser on that mirror, then bounce the HeNe around until it has traced out 50m and project it onto a surface or wall in the room. We then proceeded to align the 1319 with that spot on the wall by using either false color infared viewers or infared viewer cards.

Next we needed to verify that the telescopes we installed were producing the desired beam dimensionsto inject the laser into the cavity. An example of the techniques we used was to place two metal irises on the optical bench adjacent to each other. We then pointed the 1064 through the first iris, reflected it off of a mirror on the opposite side of the table and back through the second iris. These irises and mirrors were placed so that the first iris occured 2m after the end of the first telescope, and the second after 7m. This correspond to the positions of M1 and M2 that the 1064 would see after telescope. The irises were opened to slightly under 2mm diameter, which was the predicted beam size at those points. In principle at that point, if everything worked well we would see on each iris a small ring of infared light when observed with the infared viewer. In fact that is exactly what we saw and we were able to get a picture of it as well.

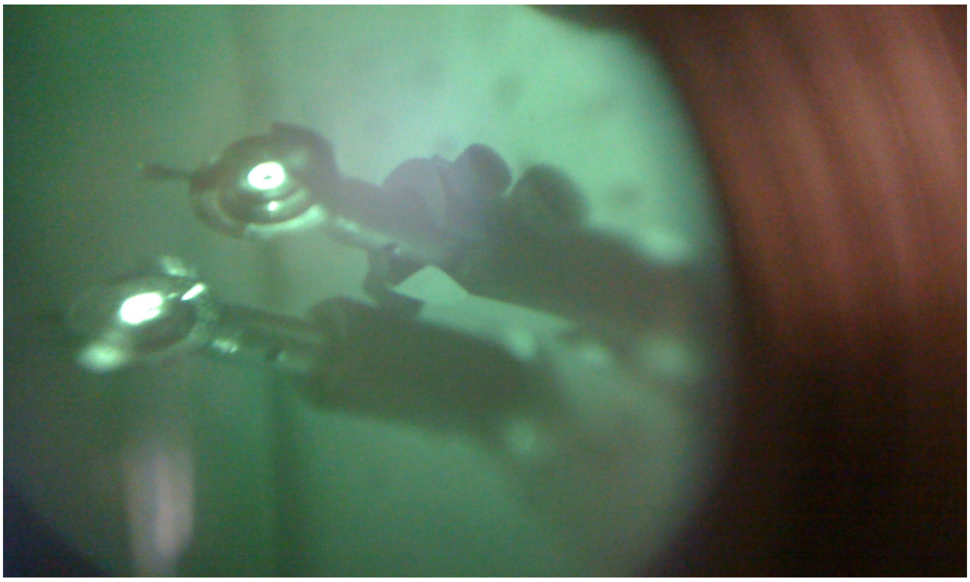

Figure 17: The two irises for verifying the effects of the telescope one the 1064nm laser. Camera pointed through the infared viewer.

3.4 Precision Alignment of Cavities and First Lock

After the cavities were roughly aligned ($10^{-2}m$ precision on position of the beams), the next step is to more precisely align cavities to the lasers. There does not seem to be a monotonic and deterministic way to do this in CALVA. The process employed by the group I worked with employed the age old scientific technique known as 'Guess and Check.' One can tell whether the cavity is well aligned by observing whether the transmitted or reflected beams exhibit fringing. Fringing of the beam indicitates the the cavity is resonant which is a sufficient condition for determining alignment. As described in the Background section, the Global Controls employ photodiodes specifically to measure the transmitted and reflected signals of each beam. Therefore the process to precisely align the cavity is as follows.

Fringes in the beam manifest as a time varying intensity of the signal impinging on the photodiode. If there are no fringes, the amplitude of the signal is more or less constant, where as if there are fringes the amplitude varies between inconsistent minimia and maxima. The value defined by $S_{max} - S_{min}$ we called the contrast. The process of aligning the cavity is to incrementally adjust the DC offsets set on the coils to move the mirrors. Simultaneously you watch the constrast of the signal you're interested in and attempt to maximize it, or more realistically we would proceed until the contrast reached a value you became comfortable with after experience. Typically we'd try and get a contrast of at least 50mV on the 1319 signal and 150mV on the 1064.

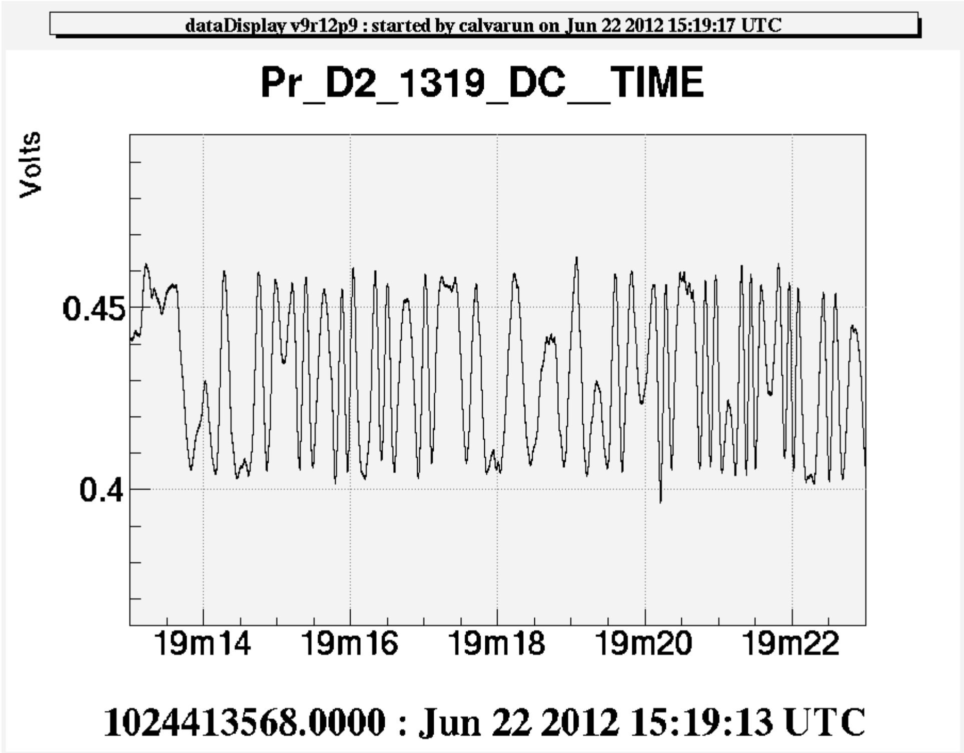

Figure 18: If there were a textbook about this, this would be a textbook example of contrast on the transmitted signal of the 1319nm laser.

In some sense all of the work is done at this point. If experimental physics worked like it was supposed to, everything at this point would be fully functional. The next step is to attempt to lock which simply means feeding in some simple parameters like S_{max}, S_{min}, and $\bar{S}$ into the software, and attempting to activate the GC. This is when one of the mirrors will be released and allowed to swing freely, and the other mirror will attempt to follow it to maintain the cavity length. What this looks like on the signal is the contrast is reduced dramatically because the fringes stop varying so dramatically with time. With GC off, the cavity length varies by $\pm 10^{-6}$m; with the cavity successfully locked the cavity length varies by $\pm 10^{-12}$m.

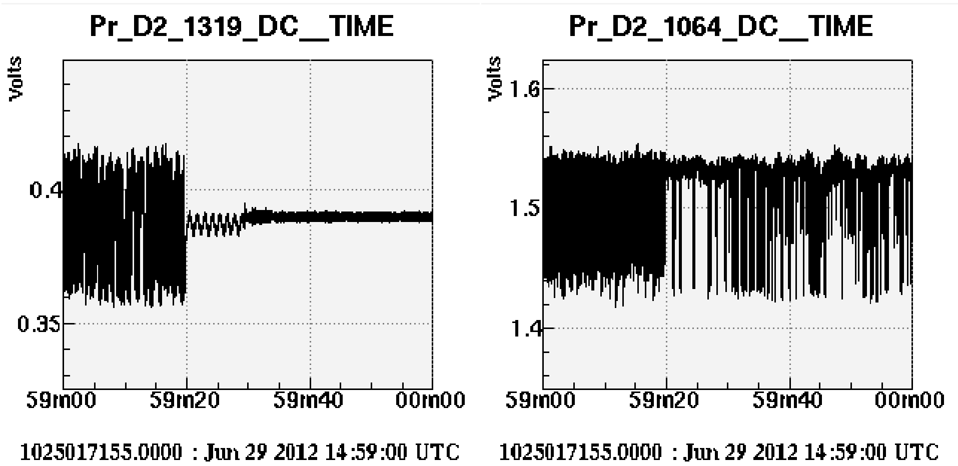

Figure 19: On the left is the same signal as the previous figure, as well as the commensurate signal for the other laser on the right. You can see that after locking the cavity the contrast is sharply reduced.

The signal on the right of Fig. 17 shows the reflected signal for the 1064 laser. Since the signal is the reflected one, when the cavity is resonant there is a minimum in the amplitude of the signal. The time spent in these minima is the τ_{Res} discussed earlier, which is affected by the finesse and mean speed of the mirrors. As you can see in Fig. 17, as soon as the 1319 is locked the minima in the 1064 signal become distinguishable. This is because $\bar{v}$ has been reduced significantly.

At this point we are approximately five weeks into the eight week project, and the next step would be to make fine adjustments to various parameters and lock the 1064, and proceed to investigate the initial problem we intended to, frequency noise in the 1064 laser. However, what follows is a tale of hardship, frustration, and possibly ghosts.

4 Stagnation

It's easy to imagine a scenario where one doesn't finish their work one day and goes home to try and complete it the next day. The first day we successfully locked the 1319 and achieved good contrast on the 1064 we weren't able to transfer lock of the cavity to the 1064, and thus we decided to call it quits for a day. When we returned the next morning, we noticed a peculiar problem: The contrasts for the two signals were not the same as the night before. There had been a gradual decrease in the amplitude and mean value of both signals over night. Moreover a problem that had been around consistently, that the LC signals would drift over night, became more troubling.

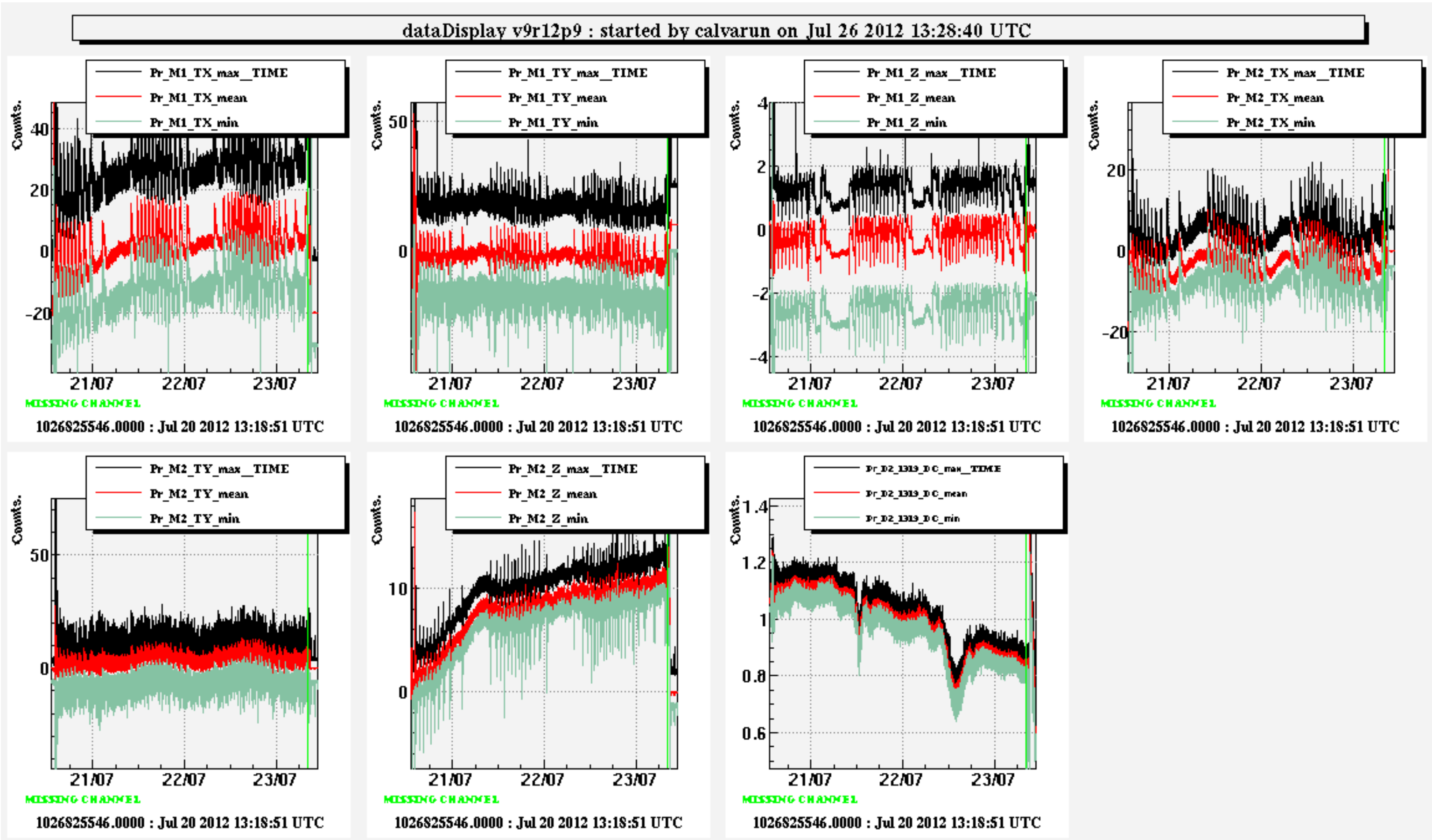

Figure 20: An example of the drift problem with the LC photodiodes. The X-axis is time and coveres approximately three days from July 20th to July 23rd. The Y-axis for all of them is DAC counts but can be treated as displacement. The red curves are the mean values. From the top left the graphs represent: θ_x rotation of M1, θ_y, Z-axis displacement, θ_x rotation of M2, θ_y, Z-axis displacement, and transmission for the 1319 laser.

Figure 18 shows what would happen over a typical weekend we were away. Several degrees of freedom would either oscillate wildly, slowly drift away from the value left on Friday, or both. We would come into the office and discover that somehow the cavities had come out of alignment, and we would spend either the whole morning or sometimes the whole day attempting to return the cavity to its previous day condition. On days that we were able to restore order relatively quickly, we would try and make progress on the principle task of locking the 1064 by making adjustments to things such as the damping algorithms. On days we were unable to restore alignment and order we would either discover or introduce more problems. Throughout the next three weeks we would do everything in the following list, most things more than once, some of them nearly every day.

- Realign LC photodiodes
- Add or remove diffusers to LC photodiodes

- Recalibrate LC photodiodes to accommodate diffusers or lack thereof
- Realign 1064 or 1319 laser with its HeNe laser to ensure it had not shifted
- Adjust telescopes of either laser to couple to the cavities better (at least that was the desired intention, not always the effect)
- Measure beam size and waist position to either verify previous measurements or correct them
- Inject noise into the mirrors to probe the damping algorithms in either the LC or GC
- Change the filter shape for the damping algorithms, sometimes with deterministic purpose and sometimes on a whim
- Adjust orientation of injection periscopes on both optical benches to improve alignment
- Investigated whether oscillatory effects were due to climatization system
- Constructed a fort made out of boxes for the optical bench of the 1319 along the entire path length of the laser to isolate it from climatization effects
- Cried

One of the worst consequences of problems of this nature is that whenever one of these systems failed due to some culprit, the control loop would lose control of mirrors and excite all of the degrees of freedom. It was essentially as if someone would come in and physically push the mirrors. Despite the fact that the tanks weren't under vacuum, the Q factor of the pendulum that the mirrors are in is still reasonably high, which means that allowing the mirrors dampen their motion by themselves would take between twenty and thirty minutes each time. This makes for agonizingly slow science.

Earlier a footnote addressed that the diagonalization of actuation coils of the mirrors would become significant again. In fact, here is that time. We discovered on one of the last days that I was at CALVA that adjusting the DC offsets, which is what you do when aligning the mirrors, affects the diagonalization of the mirrors. This is a telling example of the ignorance and futility that permeated the latter half of my time at CALVA. There was so much we didn't know, and not enough time to figure it all out and actualize solutions. As discussed earlier, if the actuation of the mirror is not well diagonalized then you will never be able to successfully damp and control the mirrors because trying to act on one degree of freedom will excite another.

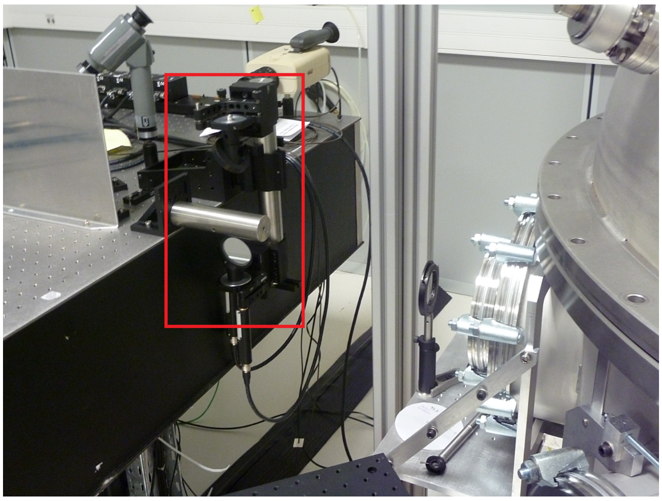

Figure 21: Periscope which adjusted height of the optical axis to match the cavity's height.

The most pernicious problem, in my humble opinion, is the mechanical drift in the periscopes which change the height of the beam to inject into the cavity. Towards the end of my time it became painfully obvious that they screws which controled the orientation of the persicopes would drift very quickly after being tightened. This is a particularly bad problem for the 1319 because its periscope is 55m away from the photodiode, and thus small angular changes have dramatic effects on the aligment of the laser. Ultimately we were unable to move past these road blocks, and the final three weeks on CALVA were spent dealing with a very dynamic and complicated problem.

5 Conclusion

5.1 Future of CALVA

Despite my departure from CALVA and France in general, the experiment will continue. In order to address the problems we encountered a few ideas were proposed. One of which is incorporating the alignment of the periscopes into the control system, to give active control of their orientation. This would be accomplished by installing stepper motors to control the rotation of the screws. Further, problems associated with the climatization system could be mitigated by placing the tanks and cavities under vacuum; that requires a tremendous amount of preparation which perhaps the experiment is not ready for. Finally an interesting idea proposed by Dr. Leroy is to install a fiber optic cable at the output of the 1319 laser, and run the cable across the 55m and inject from the opposite side. This could potentially remove the problems which are introduced by the 55m separation. This is however only a temporary solution since the lock acquisition scheme for AdV involves injecting the auxiliary laser from the opposite side.

5.2 Parting Thoughts

The lasting impression I would like to leave of my time in Orsay and at CALVA is one of supreme satisfaction. In truth I had a fantastic experience. The frustration associated with equipment or an experiment that won't work how it should is omnipresent in experimental physics. However the people and personalities in the Virgo group at Orsay, as well as the nature of the day to day work working at CALVA are not. The people were warm, and welcoming as friends, as well as invigorating and helpful as colleagues. The work was occasionally tedious towards the end but largely the grandiose scale of the experiment made me feel as if I was finally fulfilling my childhood picture of what being a scientist would be like. Especially things like getting to work in a clean room and run 50m between rooms to get to the other equipment. It was a fantastic experience and sometimes I can scarcely believe I was fortunate enough to be able to participate in it.

I'd like to thank Dr. Nicolas Leroy all of his instruction, patience, and personality, Dr. Florent Robinet for talking to me about movies and what it was like to be a data analyst, Dr. Vincent Loriette for always knowing which way to move the lens, Dr. Ivan Maksimovic for never knowing which way to move the lens, Dr. Patrice Hello for teaching us about food and wine at lunch, Dr. Fabien Cavalier for explaining to us why baseball is boring, and Samuel Franco for being the only other person without a Ph.D. I'd also like to extend a special thank you to all of them for always being willing to help me with french and entertaining my never ending supply of questions about their language.

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6 References