LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
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Implementing an Alignment Sensing and Control (ASC) System for the 40m Prototype Interferometer

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1 Introduction

Einstein's theory of general relativity has been successful in providing a satisfactory theoretical framework that is able to provide an explanation for several physical phenomena that Newtonian physics was incapable of doing. One of the predictions of the theory of general relativity is the gravitational wave. Measurement and characterisation of gravitational waves will be another empirical observation in support of this theory.

The physical manifestation of gravitational waves is a strain in space-time, which from a field-theory perspective can be modelled as a perturbation to the 4-dimensional Minkowski metric [1]. Measurement of this strain would then allow the characterisation of the gravitational wave. The primary difficulty in directly measuring a gravitational wave is the length-scale of the problem, set by the ratio of the universal gravitational constant, G and the fourth power of the speed of light, c [1].

$$h \sim G/c^4 \sim 8.23 \times 10^{-45} m^{-1} kg^{-1} s^2 \tag{1}$$

Thus, any attempt to measure the effects of a gravitational wave has to employ an instrument that is sensitive to extremely small strains. One such class of instruments, capable of measuring very small changes in length, are laser interferometers [2]. A schematic of how an interferometer is used to measure strain due to gravitational waves is depicted in Figure 1.

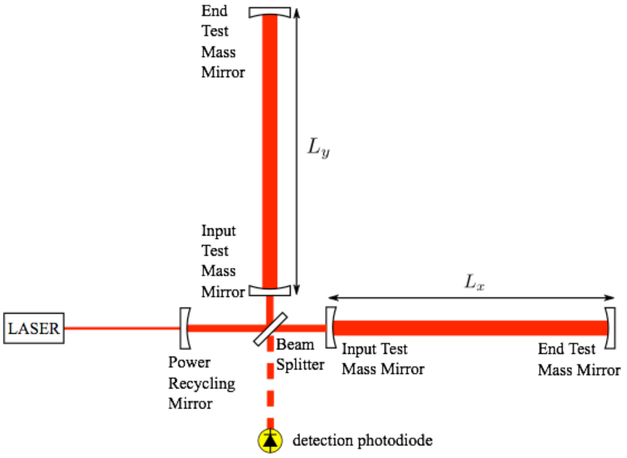

Figure 1: Diagram of a Michelson Interferometer (with Power Recycling and Fabry Perot (FP) Arm Cavities) for gravitational wave detection [3]

The end mirrors of the interferometer can be considered as free masses, which will be displaced by a passing gravitational wave. The fact that the two arms of the interferometer are orthogonal to each other means that an incident gravitational wave results in a phase difference $\Delta\phi$ (which is proportional to the differential arm length $L_x - L_y$) between the waves arriving at the Beam-Splitter from both arms.

Hence, the intensity of the recombined light is a function of the differential arm length (DARM) of the interferometer, and therefore, the intensity of the light at the detection port is proportional to the gravitational wave strain. While this scheme is simple enough in principle, there are a number of difficulties in a practical implementation of an interferometer to detect gravitational waves.

2 The Problem

There are a number of practical difficulties involved in building a gravitational wave detector. These may be broadly classified under two headings; those arising from the electronics used to track the intensities at the output ports and those arising from the interferometer parts themselves (mirrors, beam-splitters etc). I will be primarily concerned with the latter.

The difficulty is the following; if we are to indeed ascribe a change in the intensity at the output ports of the interferometer to a gravitational wave-induced strain, then it must be true that any change in the DARM must have been due to the gravitational wave alone. It is implicitly assumed that in the absence of a gravitational wave, the interferometer is perfectly still. Naturally, this assumption is not a valid one in a practical implementation of an interferometer, as there are various sources which corrupt the detector output.

Of the various degrees of freedom of the interferometer, the angular ones are particularly important. Not only do they couple to the DARM, but angular misalignment also affects the ability of the the coupled cavities of the dual power-recycled michelson interferometer to remain resonant to the main laser beam. Maintaining the angular positions of the mirrors is critical if this is to be attained. Thus, reducing unwanted angular motion is an important milestone in increasing the sensitivity of the LIGO detectors.

A number of control loops are common in interferometers. These loops sense undesirable movements of the mirrors in the interferometer (from various sources), process this information and appropriately actuate on the mirrors to counteract the movement such that the interferometer as a whole remains stationary.

3 Project Objectives and Approach

Alignment Sensing and Control (ASC) systems have been successfully commissioned before, and their performance has been evaluated in detail [3]. In designing an ASC system, the important steps are the following:

- Identify points from which the error signal is to be sensed.
- Digitize the error signal and filter it appropriately.
- Derive a feedback signal.
- Actuate using this feedback signal.

Usually, the points of actuation are the various mirrors in the cavities themselves. Implementing an ASC in this manner, however, is a formidable task as there is a fairly complex, non-linear coupling between the various cavities in the interferometer that has to be taken into account.

3.1 The Approach

The approach to be taken in this project is as follows. Two auxiliary laser beams, each located at one end-station of the interferometer (near the "End Test Mass Mirrors" in Figure 1) output beams at 1064 nm. This light is then frequency doubled to create a 532 nm beam. A control loop (explained below) will make use of the 532 nm beam to ensure that the cavity is locked to the auxiliary laser beam. The 532 nm beam serves as a sensor for measuring the angular alignment for the Fabry-Perot arm cavity. The advantage of such an approach is that we are injecting the beam through the end-mirrors of the interferometer, avoiding the coupled cavities around the beam splitter, and so get information only about our arm cavity. Thus, we avoid the aforementioned non-linear coupling between the various cavities in the interferometer.

The other pertinent point about the proposed ASC is that there is no actuation on any of the interferometer mirrors. Rather, the proposed servo actuates on a set of steering mirrors that are used to guide the auxiliary laser beam into the cavity. Any misalignment in the cavity will mean that it is no longer perfectly resonant for the 532 nm auxiliary beam. Using the intensity of transmitted light at 532 nm as a measure of whether the cavity is ideally aligned to the auxilary laser or not, we are able to actuate on the mirrors that steer the auxiliary laser into the cavity such that it remains locked to the 532 nm beam.

The power of the transmitted light from a cavity is maximum when the cavity axis and the transmission axis of the laser beam coincide perfectly. When this alignment is distrubed, the transmitted power falls. A detailed mathematical treatment of this in terms of eigenfunctions of the cavity may be found in [4] or [5], but a qualitative picture can be derived from the sketches shown in Figure 2.

The inverted parabola in the top plot in Figure 2 is representative of the transmitted power as a function of the displacement of the centre of an interferometer mirror in (say) the x-direction with $x = 0$ corresponding to the cavity being perfectly aligned. A difficulty becomes immediately apparent-because the graph is symmetric about $x = 0$, we need a means of sampling the derivative of this function in order to actuate correctly on the steering mirrors. To help solve this problem, a modulation signal is introduced in the servo loop.

The actuators used to move the steering mirrors are essentially piezoelectric transducers, composed of Lead Zirconate Titanate (henceforth referred to as PZTs). PZTs respond to an applied voltage by a change in its physical dimensions, which is the mechanism by which they actuate the steering mirrors.

The signal applied to the PZTs on the steering mirrors is a combination of the feedback signal and a small amplitude modulation signal, at frequency ω_o. A photodiode measures the transmitted power of the 532 nm beam, and a band-pass filtering stage allows us to extract the error signal at the frequency of the modulation signal.

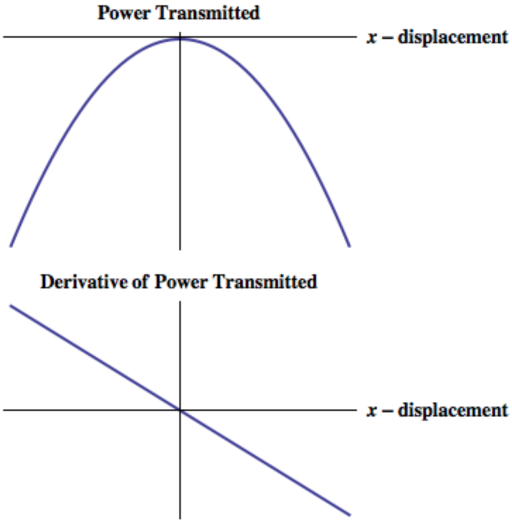

Figure 2: Transmitted Power of Auxiliary laser beam as a function of x-displacement of interferometer mirror (Top), and its derivative (Bottom)

By demodulating the error signal with the modulation signal, we get information about which side of the origin we are on.

Knowing the transfer function of the system, we can design a set of control filters, derive a feedback signal which will be fed to the PZTs. The feedback signal undergoes a low-pass filtering operation to ensure that only the first harmonic of the demodulated signal is sent to the PZTs.

A block diagram of the proposed servo, with all the elements explained above included, is shown in Figure 3.

4 Timeline

Given that I have a period of 10 weeks to work on this project, this is how I intend to use the time.

Table 1: Proposed Project Timeline

Week No.	Task
1	Installing steering mirrors on optical table
2-5	Calibration of PZTs, measurement of transfer function, and implementation of first version of servo (including software integration)
6-8	Testing, troubleshooting and modifications to servo
9-10	Implementation of a second version of servo

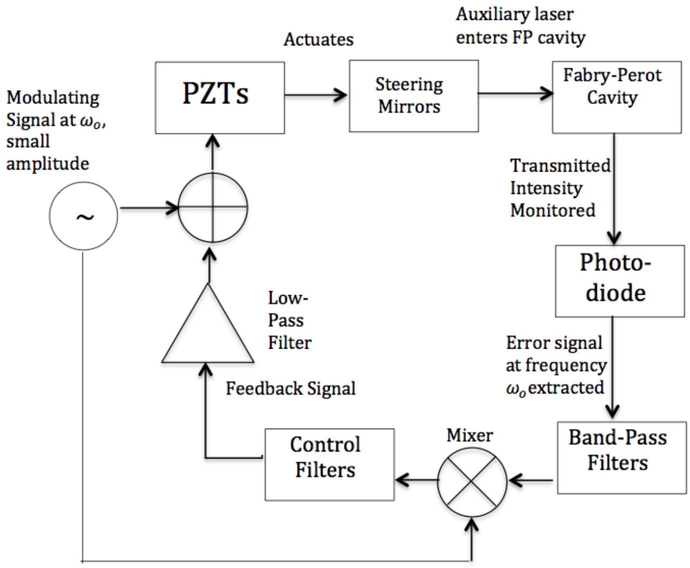

Figure 3: The Proposed Servo Design

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