

Wave Front Detection for Virgo

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Abstract. The use of phase cameras in gravitational wave detectors allows imaging the spatial phase and amplitude distribution at the laser carrier and modulation sideband frequencies. Moreover, it allows mapping their dependence on the dynamics of the interferometer operating condition. The goal of this experiment is to build, test, and verify the performance of a new phase camera for the Advance Virgo gravitational wave detector. This report describes the background, the experimental set up, and the development of the data acquisition and signal processing for our phase camera.

1. Overview

1.1. Introduction

Gravitational wave detectors provide extremely sensitive measures of strain, capable of detecting fluctuations of $10^{-19}m$ over a distance of several km . In order to achieve this sensitivity, diagnostic sensors are crucial. A Phase camera allows for imaging the spatial distribution of the laser wave-front, providing both phase and amplitude information at DC and MHz type sideband frequencies. For gravitational wave interferometry, this information is extremely valuable, as the sensitivity of the interferometer depends on the interference between the laser carrier and a set of radio frequency phase modulated sidebands. The original phase camera developed by Goda et al.[1], utilized optical heterodyning, a pinhole photo diode, and galvanometer scanning mirrors to spatially image the phase and amplitude distribution of the laser. As a first step towards developing a new type of phase camera, the original wave-front sensor is reconstructed. Later in the course of this project different imaging methods will be explored, but these are beyond the scope of this report. During the course of the program, I investigated several aspects of this experiment. Each of these investigations will be addressed in the first section and contributions will be noted at the end of their individual description will be noted at the end of their individual descriptions.

2. Experimental Methods

2.1. Experiment Setup

Figure 1 gives an illustration of the experiment. Laser light is generated and passed through a Faraday isolator, reducing back-scattering. After the laser is properly

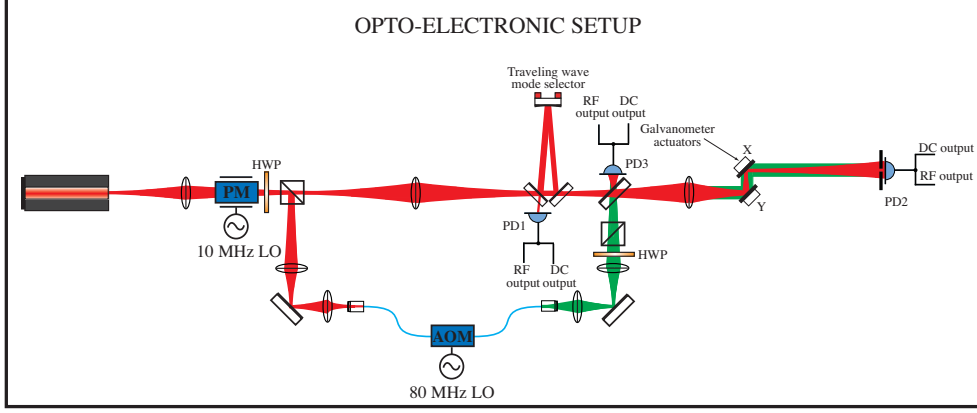


Fig.1 This figure illustrates a simplified setup of the experiment. PM is the phase modulator, AOM is the acousto-optical modulator, and HWP are half wave plates.

isolated, the laser then passes through a phase modulator, imposing phase modulated sidebands onto the carrier frequency. Light is then sent in two directions: one path is sent to the traveling mode selector, the other passes through a fiber coupled frequency shifter. After the cavity and frequency shifter light is interfered and co-propagated onto a second beam splitter. From which, the light is sent to a set of scanning mirrors which allow the wave front to be scanned a pinhole diode. The combined light is sampled over a pin-hole diode and stored for digital signal processing.

2.2. Pound-Drever-Hall Locking technique

Typically, light emitted from a laser propagates with a Gaussian profile. Deviations from the Gaussian profile can be expressed in terms of higher order transverse electromagnetic modes (TEM)[2]. In order to simulate non-perfect interferometer output in our experiment, containing the laser carrier frequency with non TEM00 mode sidebands, an optical ring cavity was employed. When laser is incident upon the cavity, the electric field is transmitted or reflected in accordance with the cavity free spectral range, electric field impedance, and cavity finesse (the optical equivalent of the quality factor in material science). Figure 2 demonstrates transmitted intensity as a function of cavity phase and is shown for several difference cavity finesse. When on resonance the transmitted and circulating cavity fields are maximized, while the reflected electric field is minimized. In order to ensure the cavity is on resonance with the laser frequency, the cavity length is controlled using the same technique used in gravitational wave detectors, called Pound-Drever-Hall locking (PDH) [3]. The PDH technique utilizes the phase modulated sidebands to read out the cavity resonance condition with respect to laser frequency and generates a correction signal that is used in a feedback loop to ensure the cavity remains on resonance with the incident laser frequency.

The signal generated to monitor the cavity's resonance condition in the feedback loop is known as PDH the error signal. About resonance, the error signal is linear, zero crossing and is directly proportional to the deviation from the resonance condition. Figure 3 shows the typical experimental setup for generating error signals using the Pound-Drever-Hall technique. As the phase modulated light is reflected off the cavity, the phase and amplitude response of the cavity affects the laser carrier and the radio

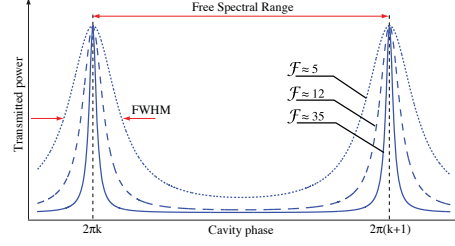


Fig.2 This figure demonstrates transmitted power as a function of the cavity phase for several different values of Finesse.

frequency phase modulated sidebands in a differential manner. This is the mechanism for generating the PDH error signal. The left plot in figure 4 shows the PDH error signals that I modeled. It shows the error signal where the phase modulation frequency is small compared to the cavity bandwidth. The right plot illustrates the shape of the error signals for phase frequencies that are greater than the cavity bandwidth.

2.3. Spatial Mode Selector

To test the phase camera, a cavity was designed to emulate the gravitational wave interferometer output, which contains a TEM00 carrier with a non TEM00 phase modulated sideband. The electric field for this non TEM00 sideband is generated by a broadband phase modulator which is driven at a frequency that coincides with a higher order mode frequency of the cavity. Imaging this well defined higher order modes allows proper testing of the phase camera. The frequency seperation of the cavity modes is solely determined by cavity geometry. Barringa *et. al.* [5] showed that for three mirror ring mode cleaner the frequency separation $\Delta\nu$ is given by

$$\Delta\nu_{mn} = \frac{c}{2L}(m+n)\frac{1}{\pi} \arccos\left(\sqrt{1 - \frac{L}{R}}\right) + \frac{\nu_0}{2} \frac{(1 - (-1)^m)}{2} \quad (1)$$

where, c is the speed of light, L is the cavity length, R is the radius of curvature of the primary mirror and m and n are the transverse mode numbers. The last term of this equation is an result of our three mirror cavity. For a cavity with an even mirror number of mirrors this term would vanish.

As part of the experiment and to gain better understanding of the system, I modeled the cavity reflected, transmitted and circulating electric fields with Matlab. Also, the phase and frequency response of the cavity were modeled, along with the PDH error signals as a function of cavity detuning. Using equation 1, we calculated the expected higher order mode frequency separation. Taking the imaging system bandwidths into account, we can expect to image TEM34 and TEM31 76Mhz and 43 Mhz respectively.

2.4. DC image acquisition set up

The image acquisition system consists of the two steerable mirrors galvanometer (Thor Labs Model GVS012/M) and a pinhole photo diode. A NI-PXIE 6363X series DAQ card was used to drive the galvanometer mirrors and readout the DC output of the photo diode. The Labview code was developed to scan the galvanometer mirrors over

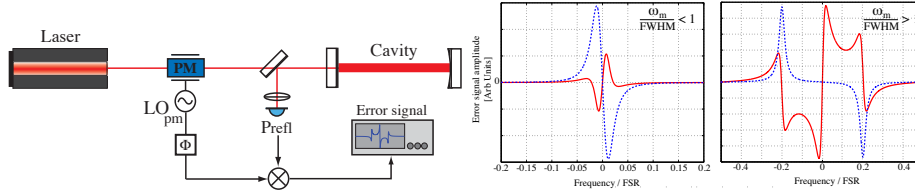


Fig.3, left This figure demonstrates a basic PDH experiment setup. Fig.4, right This figure shows the cavity error signal response for well within and well outside of the cavity linewidth

an Archimedes spiral to ensure a constant velocity scan. The Archimedes spiral is given by the parametric equation;

$$X(t) = p(t) \cos(\omega t); \quad (2)$$

$$Y(t) = p(t) \sin(\omega t)$$

Where ω is the spiraling frequency and $p(t)$ can represent any time varying periodic signal. The spiraling frequency ω will determine the density of spirals in the scan. The frequency and amplitude of $p(t)$ controls the image acquisition speed and the maximum amplitude of the spiral. For our experiment a sawtooth was determined to be the best function for $p(t)$. A ramp may also have been used, but the phase of the cosine and sine has to be taken into consideration when designing the spiralling pattern. Testing the steering mirror showed an image acquisition time of 50ms. Increasing the image acquisition speed any further causes the galvanometer system to respond in a non-linear manner.

The Labview image acquisition program was designed such that the maximum scan amplitude was set automatically, taking distances, galvanometer gains, and scanning frequency into account. As a standard, a scan amplitude was chosen of three times the Gaussian beam radius at the pinhole photodiode. Propagating from the waist, a Gaussian beam follows:

$$\omega(z) = \omega_0^2 \left[1 + \left(\frac{\lambda z}{\pi \omega_0^2} \right)^2 \right] \quad (3)$$

Where ω_0 is the initial waist size, z is the distance to the detector, and λ is the wavelength. The galvanometer driver board contains readout channels that allow monitoring of the mirror positions, which are stored and used for image reconstruction.

3. Experimental Results

3.1. Galvanometer Gain Measurements

In order to allow proper scanning of the Image Acquisition software it was important to measure the gain of the individual galvanometer mirrors. While injecting a slowly varying sinusoidal voltage into the galvanometer driver, the spot position was monitored on a position sensitive device. As the amplitude of the driving voltage varies, so does the position on the detector. Using trigonometric functions allows finding the angle per unit voltage. Plots of the angle per voltage gain are available in figure 5.

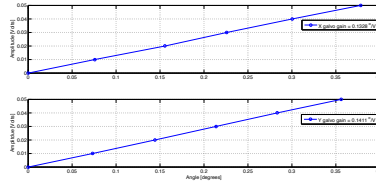


Fig.5 This figure shows angle per unit voltage galvanometer gain.

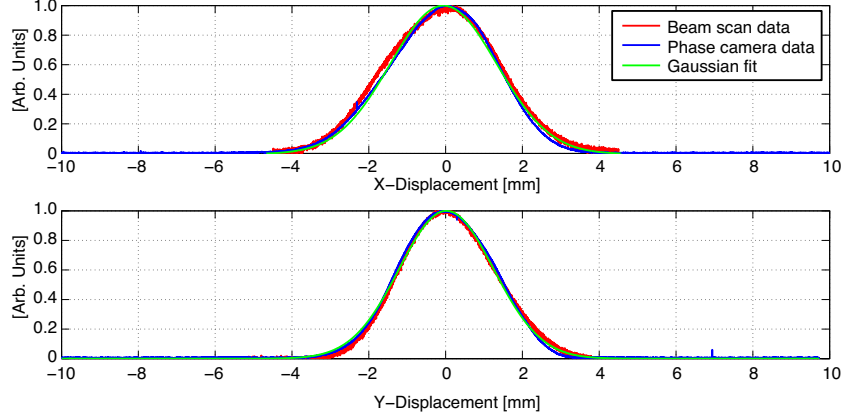


Fig.6 This figure shows the comparison of the commercial beam scan device with our image acquisition system. The both of which are compared to a Gaussian fit derived from the Least Square Method.

3.2. Image Acquisition verification

In order to verify the image acquisition software was working properly, the developed image acquisition system was compared to a commercial beam scan device from Thorlabs. The phase camera program was set to measure the DC photodiode output while scanning the galvanometer mirrors along one axis. Using the earlier measured galvanometer degrees/volt gains, the scanning voltage was converted to spatial distances and recorded on the hard drive together with the DC output of the pinhole photodiode. Figure 6 shows the experimental results next to the results of the commercial beam scanning device data, while scanning the x and y axis over about 10mm. The Image acquisition system of the phase camera also contained a Gaussian fitting tool which is also shows in the plot.

Finally, the scanning software was tested using the Archimedes spiral, reading out the DC output of the pinhole photodiode. Figure 7 shows the Labview code used for this measurement. On the left is shown how the driving voltages for the galvanometer mirrors are generated, while on the right the read functions are shown. First tests of the image acquisition system were successful. Minor deviations from the spiral pattern were successfully recorded and will therefore not affect the final phase map. Figure 8 shows the DC photo detector output after the image acquisition software was run. The right side of the figure shows the 16000 samples, spaced over the x and y axis. The left side shows the sampled pinhole photodiode output. The x and y axis show the spatial distance while on the z axis the normalised DC intensity is shown.

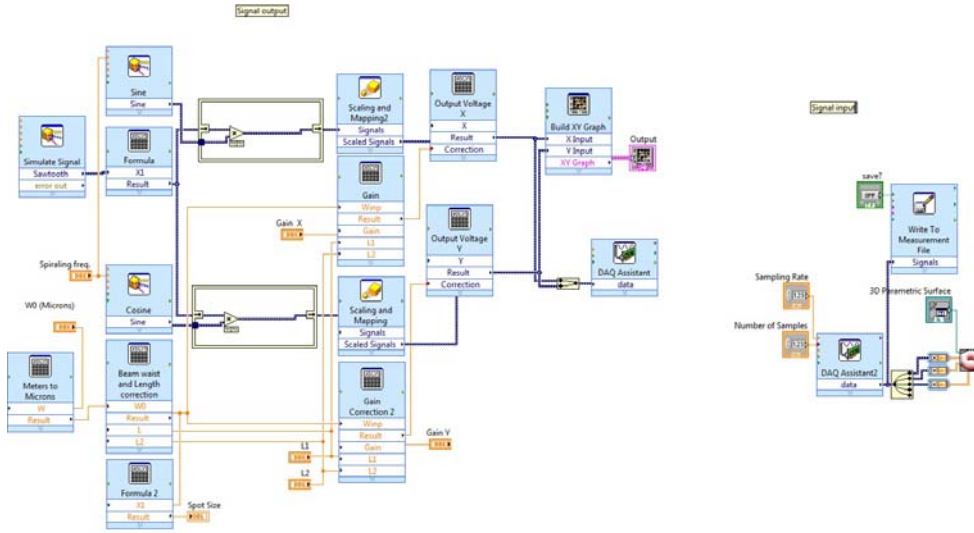


Fig.7 This figure shows the Labview code used in spiral scanning for image acquisition. The left component demonstrates calculations required for output and the right component is responsible for plotting and measurement recording.

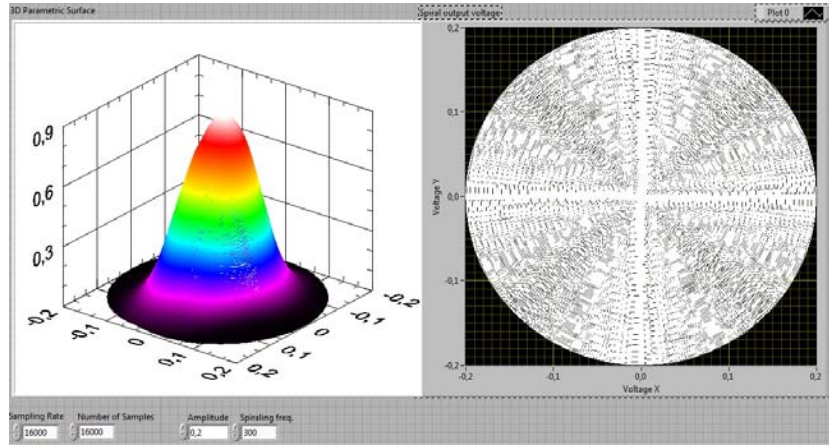


Fig.8 This figure shows the comparison of the commercial beam scan device with our image acquisition system. The both of which are compared to a Gaussian fit derived from the Least Square Method.

4. Conclusions and further work

We have successfully implemented the first steps towards building a phase camera for the advanced Virgo gravitational wave interferometer. The prototype allowed reconstruction of the Gaussian intensity distributions and a comparison between the phase camera measurements and a commercial beam scanning device.

Next, the demodulation stages will be implemented. This will allow imaging the phase and amplitude distribution of the laser carrier. After the cavity stabilisation scheme is implemented, generation and imaging of higher order modes will be possible.

5. acknowledgments

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