LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
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(SURF Report)

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Calibration of the LIGO Interferometer Using the Recoil of Photons

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Abstract

Calibration of the LIGO interferometer is essential if we are to retrieve any meaningful or quantitative data from the interferometer's strain signal. For this reason, a photon calibrator has been developed to provide a physically independent means of evaluating systematic errors in order to calibrate the strain signal. Using the photon calibrator, an amplitude-modulated laser beam is bounced off one of the interferometer's end mirrors and then the displacement introduced by the radiation pressure is measured. This gives both amplitude and timing calibrations, since the reaction of the end mirror to a given force is well known. The first photon calibrator device has been built and tested. It consists of a 500mW Nd:YLF laser at 1047nm, an acoustic optical modulator and a photo receiver to monitor the modulated output power. The photon calibrator was installed on the 4k LIGO Hanford interferometer and preliminary tests were done to examine the response of the interferometer.

Introduction

A Michelson interferometer consists of a light source and two perpendicular paths of light, or "arms". In our case, a laser is used as a light source and a beam splitter directs half of the laser light into each arm. End mirrors send the light back toward the beam splitter where the two light paths interfere with each other. Using this interference, a difference in arm length can be measured at the anti-symmetric output port of the beam splitter with high accuracy. The LIGO interferometers are more complicated than a Michelson interferometer since they implement arm cavities to enhance the differential displacement signal by effectively bouncing the light multiple times in each arm. They also operate on a dark fringe and deploy a power-recycling mirror in the laser path to optimally use all the available light.

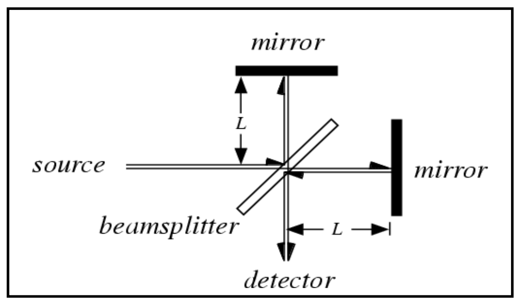

Figure 1: A Michelson interferometer is made of a light source that is split into two perpendicular paths of light which eventually recombine at a detector. [i]

Nevertheless, the principal of an interferometric gravitational-wave detector can be most easily understood by looking at the Michelson interferometer. When a gravitational wave passes by, space-time is stretched in one direction and contracted in the other, changing the length of the arms along with it. Since the arms are perpendicular, one will stretch while the other contracts, causing the differential change in length between them to be twice as much as the space-time distortion. LIGO uses suspended mirrors to measure this differential length change with an accuracy of 10^{-18} m in a 100Hz bandwidth centered around 150Hz. A calibration is needed in order to interpret the signal at the anti-symmetric port in terms of how much the lengths of the arms are changing. A calibration is also needed to know when the lengths of the arms changed as compared to when the signal was received. The expected distance that the mirrors move is on the order of the size of atomic nuclei or smaller, so calibrations are best done with very small displacement signals.

The LIGO Hanford interferometers currently use a calibration method based on the suspension actuators to determine the actual length change of the interferometer arms. Small permanent magnets are glued on the back of the suspended mirrors and a force can be applied through voice coils mounted on the suspension structure. At a given frequency, the motion is proportional to the current applied to the actuator, and is known quite precisely as: [ii]

$$\Delta l_{cal} = \beta \frac{V_{coil}}{\omega^2} \quad \text{for} \quad \omega >> 1 \text{ Hz} \tag{1}$$

where $\omega = 2\pi f$ is the sinusoidal calibration frequency and β depends on the mass of the mirror, the pendulum length and the strength of the actuator magnets. An amplitude calibration is made by injecting a sinusoidal current into the coils and then comparing the expected length change to the signal at the anti-symmetric port. This method can also give a timing calibration if the delays in the electronics are well understood.

Knowing the exact change in length and the time the length changes is absolutely essential to determining information about the sources of the gravitational waves. Errors in length or timing will propagate directly to errors in the distance to the source and the position of the source on the sky, respectively. To estimate possible systematic errors in the system, it is important to have another, independent calibration method to compare with. For this reason, the photon calibrator has been designed. Using the photon calibrator, a sinusoidal force is applied to the test mass by the radiation pressure of a laser beam. The recoil of the photons off the surface of the mirror pushes the mirror backwards by a small amount. If we consider the collision to be perfectly elastic and the incident angle of the photons on the mirror to be α, the force of the radiation pressure is: [iii]

$$F = 2\cos\alpha \frac{h\nu}{c} \dot{N}_\gamma \tag{2}$$

where $\dot{N}_\gamma = P / h\nu$ is the number of photons hitting the mirror per time. So we can also write:

$$F = 2\frac{P\cos\alpha}{c} \tag{3}$$

where P is the power of the laser beam. Then, if we treat the mirror as a simple damped oscillator, the light intensity can be written as:

$$P(t) = P_0 + P\cos\omega_c t \tag{4}$$

and the complex form of the displacement of the mirror due to this force is:

$$x_{cal}(\omega_c) = \frac{2P\cos\alpha}{cM} \frac{1}{{\omega_p}^2 - {\omega_c}^2 + i\omega_p\omega_c / Q} \tag{5}$$

where ω_c is the calibration angular frequency, ω_p is the pendulum's resonance angular frequency and Q is the quality factor of the pendulum. For the case that $\omega_c >> \omega_p$, as is true for LIGO's test mass, the amplitude of the displacement of the end mirror is:

$$A(\omega_c) = -2\frac{P\cos\alpha}{cM{\omega_c}^2} \tag{6}$$

The phase difference between the calibration force and the mirror's response is:

$$\phi(\omega_c) = \tan^{-1}\left[-\frac{\omega_c\omega_p / Q}{{\omega_p}^2 - {\omega_c}^2} \right] \tag{7}$$

As shown, the displacement $A(\omega_c)$ is dependent on the inverse square of the calibration frequency and proportional to the power of the incident laser beam. If we accurately know the power of the beam, then we can calculate the precise displacement and compare this known value to the anti-symmetric port signal giving us an amplitude calibration. Using equations 6 and 7, we also have a timing calibration. This type of calibration is well suited for low frequencies in the range of 50Hz < f < 1kHz where the displacement is well above the noise level, whereas at higher frequencies above a few kHz, the displacement is not large enough. Typically, frequencies from 50 to 1000 Hz can be calibrated without any problems.

Design

The first photon calibrator has been built and tested, and a diagram of it can be seen below. The photon calibrator uses a 500mW Nd:YLF laser at 1047 nm, which is pumped by a laser diode at 808 nm[1]. The laser has a horizontal plane of polarization with a polarization ratio greater than 100:1. The laser operates with a TEM_{00} transverse mode and a single longitudinal mode, has a 1/e^2.

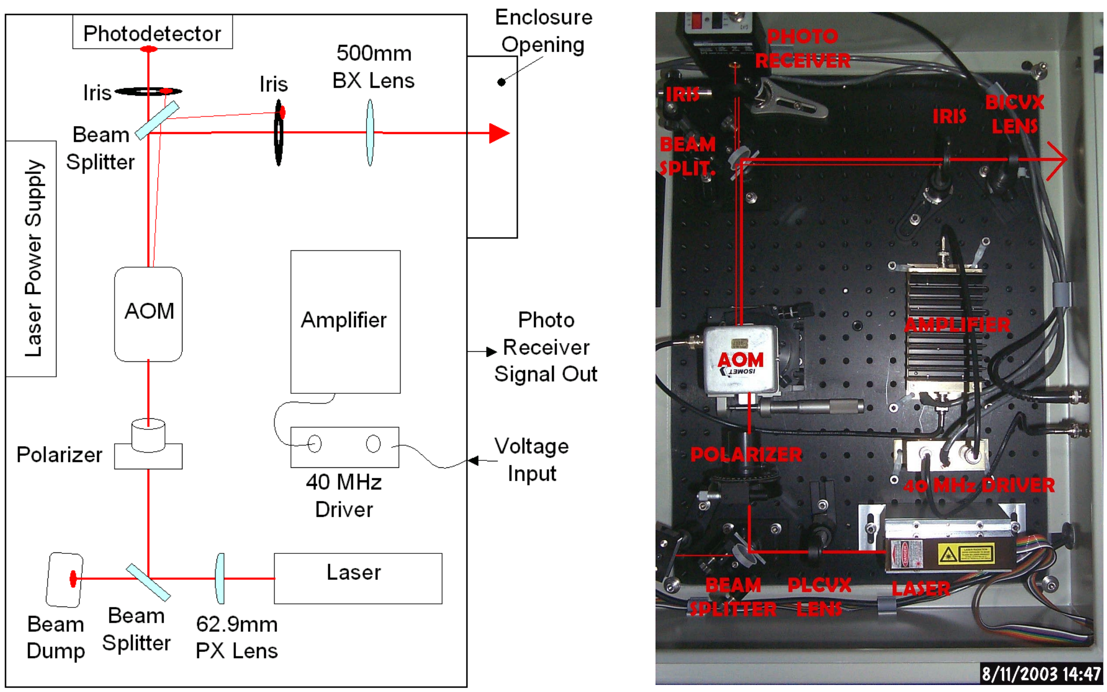

Figure 2: The figure on the left shows a top view diagram of the first photon calibrator design, while the picture on the right is an actual photo of the device. The key components of the photon calibrator are the laser, the AOM and the photodetector.

Since a sinusoidal force is needed for calibration, a source of modulation is required to vary the power of the laser beam. The photon calibrator uses an Acousto-Optic Modulator[2] (AOM) to achieve this modulation. The AOM deflects a portion of a beam that passes through it. The intensity of the deflected beam depends on the amplitude of an applied RF signal. By dumping the straight through beam and varying the intensity of the RF signal, the deflected beam will be an amplitude modulated laser beam that we can use for calibration. Looking at *Figure 2*, one can see two irises that block the straight through beam, and a voltage input that controls the intensity of the 40 MHz RF signal used to drive the AOM. Using this AOM, we currently achieve between 50% and 60% modulation. We also tried to modulate the beam power by modulating the current through the laser diode driver that pumps the laser. This method proved not to be useful, however, due to the instabilities it creates in laser temperature and the mode and shape of the beam. Furthermore, we observed a polarization shift as a function of current.

Other components of the photon calibrator include two lenses[3] for shaping the beam, a polarizer[4], two 99%, polarization-sensitive beam splitters[5] and a photodetector[6]. The first beam splitter lets through 1% of the laser light and approximately 99% of the 808 nm pump diode light. This effectively dumps all the excess pump diode light that exits the laser head. Since the beam splitters are polarization sensitive, a polarizer is placed before the second beam splitter to ensure that the 1% beam hitting the photodetector is a true representation of the beam exiting the enclosure. The photodetector puts out a voltage signal proportional to the power of the beam that strikes the detector. By placing power meters at the photodetector and also at the exit beam, a calibration can be made that will tell us the relationship between the voltage signal and the power of the beam that strikes the test mass. This relationship is linear, but the exact slope may depend on the precise alignment of the AOM and other optical components. For this reason, the internal photodetector should be calibrated once it is installed on the interferometer, and also periodically during use to ensure that it has remained the same. *Figure 3* shows the calibration for the initial installation onto the LIGO interferometer and also calibrations for different alignments of the components.

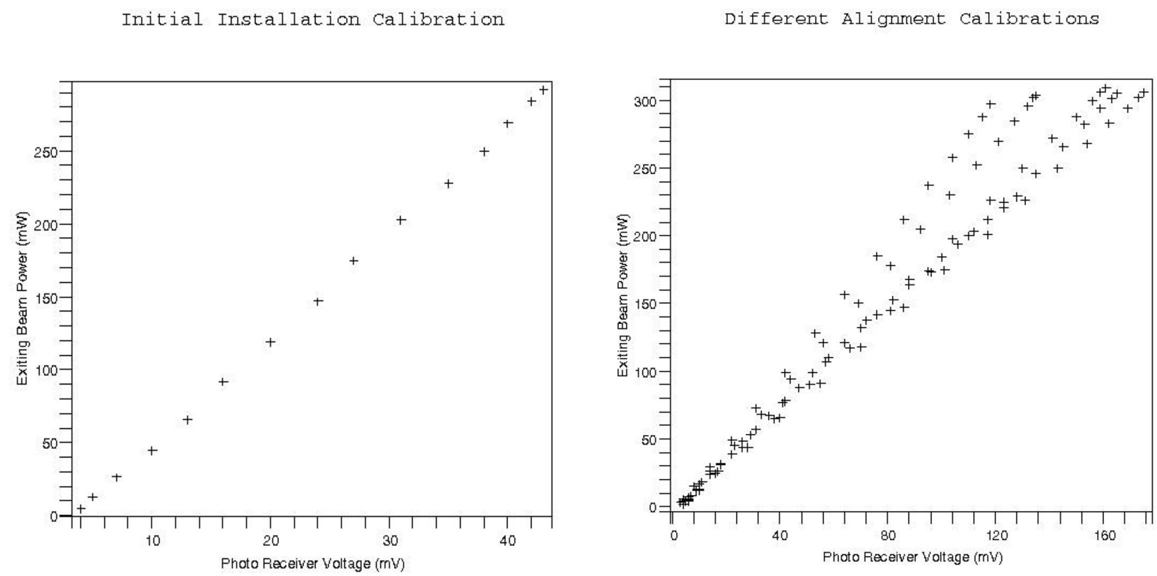

Figure 3: The graph on the left shows the calibration for the initial installation and the graph on the right shows different calibrations when the components of the photon calibrator are aligned in slightly different positions, notice the slopes vary slightly.

The beam is fairly gaussian and circular throughout the optics path in the photon calibrator enclosure. The average beam diameter while passing through the polarizer is 0.57mm, and then it enters the AOM opening with a diameter of 0.51mm. The full beam exits the AOM with a diameter of 0.81mm. The deflected beam through the AOM is distorted to a slightly elliptical shape, and *Figure 4* shows this in a CCD image of the beam that strikes the end mirror. The image was taken at a distance of 5.80 meters from the opening of the enclosure, which is accurate to the actual setup distance within 1%. Currently, the photon calibrator enclosure opening is approximately 5.75m from the end mirror, about 1m left of and 10cm above the main beam path. This yields incident angles of about 10° horizontally and 1° vertically. The beam is

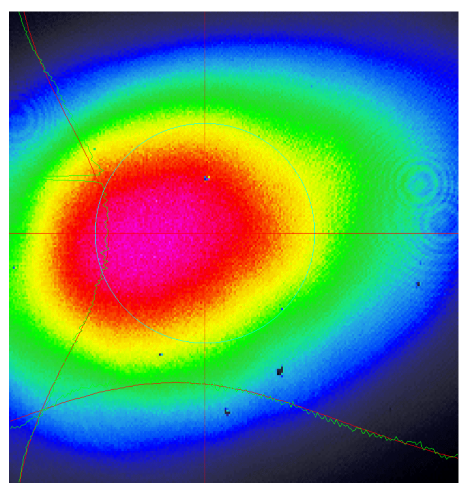

Figure 4: A CCD image of the beam that strikes the end mirror. The beam is fairly gaussian with an average diameter of about 7mm.

slightly elliptical with diameters of 8.5mm and 5.5mm. Still, the beam is fairly gaussian as can be seen in *Figure 4* (on the image, the green function shows the relation of the actual beam shape to the red gaussian fit).

Results

The photon calibrator is currently installed at the x end station of the LIGO Hanford interferometer. A data acquisition channel is connected to the photon calibrator in order to retrieve the photodetector voltage signal in real time. A function generator is temporarily connected to the input voltage until a channel of the Arbitrary Waveform Generator is ready, so that the calibration frequency can be set remotely. For the first tests, the internal photodetector was calibrated as shown above and the beam was aimed at the center of the front surface of the ETMX mirror. In the modulation range, the beam was found to vary from 13 mW to 284 mW, giving an rms power of about 96 mW. The input voltage was a sine wave at 113 Hz. Using equation 6, the theoretical displacement was calculated to be $1.2 \cdot 10^{-16}$ m. Looking at a power spectrum of the anti-symmetric port, a peak in the number of counts can be seen at 113 Hz, and from this we can calculate a meters-per-count calibration for 113 Hz. The first test revealed this calibration to be $2 \cdot 10^{-15}$ m/ct. *Figure 5* shows the peak and the scale is calibrated with the 113 Hz measurement, but the calibration does not hold for frequencies far from 113 Hz.

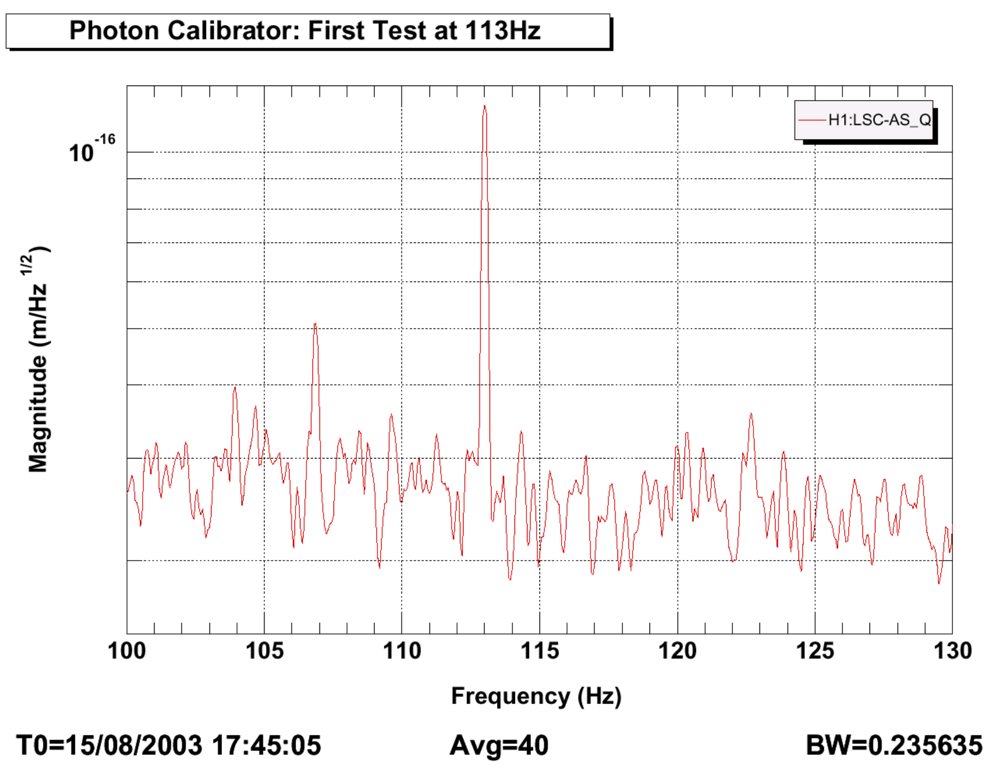

Figure 5: The line at 113 Hz was driven by the radiation pressure of the photon calibrator.

Comparisons with recent calibrated spectra graphs show the background noise and neighboring peaks to be of the same magnitude in both the LSC actuator calibrations and the photon actuator calibrations. A brief test was run with the laser aimed near the bottom edge of the ETMX mirror, and preliminary data seems to indicate that the mirror is displaced approximately 7% more if the beam strikes the center.

Future Work

More investigations should be made into the response of the mirror as a function of the position of the incident laser beam. Also, we would like to investigate different AOMs in order to achieve a deeper modulation, and therefore a higher rms beam power for better measurements. Most importantly, we have to implement swept sine measurements to calibrate the full range of frequencies, so a complete amplitude and phase calibration can be made.

Footnotes

[1] IFCL-500-1047, Diode Pumped Infrared CrystaLaser. Info at www.crystalaser.com.
[2] Isomet 1201 E-2 AOM, used in conjunction with an Isomet RFA-108 Amplifier and an Isomet 231 A-2 40 MHz Driver. Info at www.isomet.com or 5263 Port Royal Rd, Springfield, VA 22151.
[3] Newport lenses, part numbers: KPX085 and KBX082 with focal lengths of 62.9mm and 500mm respectively. More info at www.newport.com or 1791 Deere Ave., Irvine, CA 92606.
[4] The polarizer is a Thorlabs GL10-C26 Glan laser calcite polarizer, 1.06mm for high power applications. It is mounted on a Thorlabs PRM1GL10. More information at www.thorlabs.com or 435 Route 206 North, Newton, New Jersey 07860.
[5] Beam splitters are CVI models BS1-1047-99-1025-45-P. More info at www.cvilaser.com or 200 Dorado Place SE, Albuquerque, New Mexico 87123.
[6] A New Focus Model 2033, IR Photo Receiver. More info at www.newfocus.com or 2584 Junction Avenue, San Jose, CA 95134.

References

[i] http://scienceworld.wolfram.com/physics/MichelsonInterferometer.html
[ii] R. Spero "Calibration of 40m Interferometer Displacement Sensitivity", LIGO-T970232-R.
[iii] D. Sigg, "Strain Calibration in LIGO", LIGO-T970101-A-D.

Acknowledgements

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