Investigation of the Impact of the Differential Arm Length Servo on the Photon Calibrator X/Y Comparison During the O4 Observing Run

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July 16, 2024

Abstract

The Laser Interferometer Gravitational-Wave Observatory uses the wave characteristics of light to detect gravitational waves. A beamsplitter divides the main interferometer beam into two perpendicular lasers, the X-arm and the Y-arm. Each laser travels a straight-line distance of 4 km before being reflected back towards the beamsplitter by a 40 kg suspended optic in a vacuum chamber, known as the end test mass. At this point the two lasers meet, interfere destructively, and are directed toward a photodetector. Both cosmic and earthly events can emit signals that cause the end test mass to experience displacements smaller than the width of a proton, altering the phase of the two lasers.
To accurately measure these minuscule displacements, gravitational-wave observatories use photon calibrator systems. They employ an external laser source that exerts photon radiation pressure on the end test mass, causing a displacement The laser is then directed towards a power sensor outside the vacuum chamber, which computes the power of the reflected laser, allowing for the calculation of the photon calibrator-induced displacement. To ensure precise and reliable calibration of the interferometer's response to infinitesimal displacements, gravitational wave observatories use two-photon calibrator systems, one for each end test mass. To reduce overall photon calibration uncertainty, a ratio known as the photon calibrator comparison factor, χ_{XY}, is calculated by using Fast Fourier Transforms of the time series of the photon calibrator and interferometer lasers-induced displacements on the end test masses [**?**]. This ratio is derived from two different interferometer signals: the calibration strain signal and the differential arm length error signal. The calibration strain signal uses the strain of the interferometer beam to calculate χ_{XY}, while the differential arm length error signal uses a control loop that manages arm length variations and converts residual displacement into a digital signal to actuate the test masses and maintain resonance in the interferometer beams. A ratio of χ_{XY} derived using the two signals will yield the interferometer's response function.

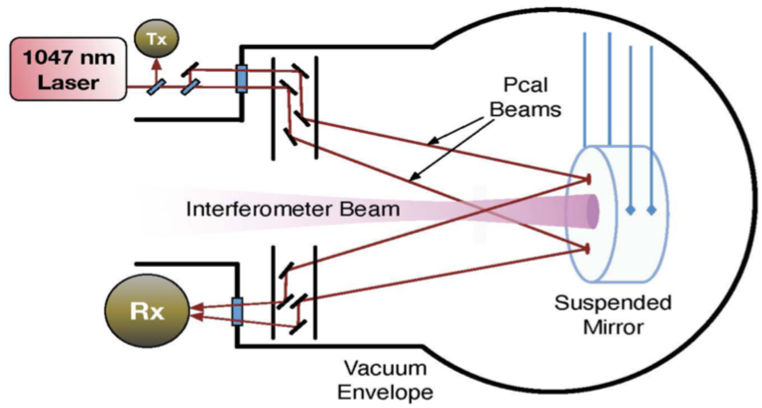

Figure 1: Schematic diagram of a typical photon calibration system from [1]. A small fraction of the power-modulated laser is sampled by a transmitter (Tx) module for optical efficiency purposes and directed toward the mirror surface. The reflected light is directed to a Pcal power sensor in the receiver (Rx) module that measures its power in counts per watt.

Introduction

Importance of Calibration for Gravitational Wave Science

Gravitational waves are ripples in spacetime caused by high-energy cosmic events. These waves distort spacetime by stretching and squeezing it, and the magnitude of this distortion can be detected on Earth at scales as small as 10^{-20} meters. Gravitational wave observatories, such as The Laser Interferometer Gravitational-Wave Observatory, LIGO, has the ability to detect these minute distortions. Precise calibration is needed to extract all astrophysical information about the sources of these gravitational waves. Photon Calibrator (Pcal) systems serve as the primary calibration reference for LIGO observatories. Figure 1 represents a schematic diagram of a Pcal system at the end station, where the end test masses reside. The system includes a laser beam, two power sensors, mirrors, and beam splitters. The laser beam, emitted at a wavelength of 1047 nm, has a small fraction of its power sampled by the transmitter power sensor module (Tx sensor) before entering the vacuum. This sampling is for optical efficiency purposes. The laser is then directed to strike the suspended mirror optic on the end test mass vertically above and below the center, where the main interferometer beam strikes. The laser beam is then reflected away at the same angle of incidence. Mirrors guide this reflected beam to the receiver transmitter module (Rx sensor), which measures laser power from the end test mass. The photon radiation pressure of the laser beam causes length variations in the relative arm lengths. Because the magnitude of these induced length variations is directly proportional to the power of the modulated laser power reflecting from the mirror, we can accurately calibrate these infinitesimally small length variations the end test masses experience.

Photon Calibrator X/Y Comparison

To reduce uncertainty in the overall pcal-induced displacement on the end test masses, we compare the frequencies of the pcal lasers normalized by the interferometer signal. Mathematically this is represented as:

$$\chi_{XY} = \frac{x(\omega_X)|_{PcalX}/x(\omega_X)|_{End-X}}{x(\omega_Y)|_{PcalY}/x(\omega_Y)|_{End-Y}} \tag{1}$$

where χ_{XY} is the X/Y comparison factor. $x(\omega_x)|_{pcal}$ is the pcal-induced displacement on the end test mass, with the subscript letting us know whether it is the X-end or the Y-end. $x(\omega)|_{End-X}$ is the interferometer-induced displacement on the end test mass, where is ETM at the X, and End-Y is the ETM at the Y endstation. We expect this ratio to be as close to one as possible, but because of differences between the X and Y end stations such as temperature, optical efficiencies, and laser instability, this ratio tends to deviate from one. To account for these differences, correction factors have been calculated and implemented as follows [2]:

$$x(\omega_X)|_{PcalX} = PcalX(\omega_X)C_X \tag{2}$$

$$x(\omega_Y)|_{PcalY} = PcalY(\omega_Y)/C_Y \tag{3}$$

C_X and C_Y are the respective X and Y correction factors.

Methodology: X/Y Comparison Using the DARM loop servo and the GDS_CALIB_STRAIN interferometer signals

Using the same formalism as in [2] the X/Y comparison factor,χ_{XY}, can be calculated as

$$\chi_{XY} = \frac{PcalX(\omega_X)C_Y}{PcalY(\omega_Y)/C_Y}\frac{D_{err}(\omega_X)/R(\omega_X)}{D_{err}(\omega_Y)/R(\omega_Y)} \tag{4}$$

this can be algebraically rearranged to:

$$\chi_{XY} = \frac{PcalX(\omega_X)}{PcalY(\omega_X)}\frac{D_{err}(\omega_X)}{D_{err}(\omega_Y)}C_XC_YR_{XY} = CC_{Derr}C_XC_YR_{XY} \tag{5}$$

where

$$CC_{D_{err}} = \frac{PcalX(\omega_X)}{PcalY(\omega_X)}\frac{D_{err}(\omega_X)}{D_{err}(\omega_Y)} \; and \; R_{XY} = \frac{R(\omega_X)}{R(\omega_Y)}, \tag{6}$$

R_{XY} is the overall response function quantifying the interferometer's response to pcal-induced displacements at both end stations. From this, using the formula we can algebraically deduce:

$$CC_{D_{err}} = \frac{\chi_{XY}}{C_XC_Y}\frac{1}{R_{XY}} \tag{7}$$

Ideally $\chi_{XY} = C_XC_Y$. Hence, the $CC_{D_{err}}$ is equal to the inverse of the response function. Note that $CC_{D_{err}}$ is the ratio of all four signal lines, i.e., the two pcal beams and the two interferometer beams. GDS_CALIB_STRAIN is another interferometer signal that can be used in place of the DARM loop signal to compute the X/Y comparison factor, χ_{XY}. The main difference between the two is how the interferometer signal is calculated as follows [3]:

$$x(\omega)|_{GDS} = \frac{d_{err}R(\omega)}{L} \tag{8}$$

Where d_{err} is the digital signal and L is the 4 km - the length of the interferometer arms.
Without much detail in the algebra, which can be done with similar steps as in the previous section, χ_{XY} is given by:

$$\chi_{XY} = \frac{PcalX(\omega_X)}{PcalY(\omega_X)}\frac{x(\omega_X)|_{GDS}}{x(\omega_Y)|_{GDS}}C_XC_Y \tag{9}$$

where CC_{GDS}, the ratio of the four lines calculated using the GDS_CALIB_STRAIN signal, is given by:

$$CC_{GDS} = \frac{PcalX(\omega_x)}{PcalY(\omega_X)}\frac{x(\omega_x)|_{GDS}}{x(\omega_y)|_{GDS}} \tag{10}$$

Hence:

$$CC_{GDS} = \frac{\chi_{XY}}{C_XC_Y} \tag{11}$$

The ratio of these two factors yields the response function as follows:

$$\frac{CC_{GDS}}{CC_{Derr}} = \frac{\frac{\chi_{XY}}{C_XC_Y}}{\frac{\chi_{XY}}{C_XC_YR_{XY}}} = \frac{\chi_{XY}}{C_XC_Y}\frac{C_XC_YR_{XY}}{\chi_{XY}} = R_{XY} \tag{12}$$

Objective

The Kenyon Line Monitoring (KLM) tool, which I designed using the framework of an already existing absolute calibration script in the summer of 2023 [4], processes real-time Pcal-induced displacement data by performing 240-second FFTs, with a 50% overlap to calculate a value of χ_{XY} for each data point, as well as compute running means and medians. The KLM tool uses Kafka to stream live data to the Grafana Pages[5], a data visualization service. That data is then stored in an InfluxDB database. This tool has been used since the start of the O4 observing run and we will use its stored data to compute the overall response function, $_{XY}$. Additionally, we plan to investigate the differences in the χ_{XY} when calculated using the DARM Servo and the GDS_CALIB_STRAIN signals.

Current Status

We utilized InfluxDB to extract darm error data and GDS calib strain data from the Grafana pages, from May 1, 2023, to June 1, 2023. We have accumulated a total of 3622 data points for each of the two signals. We identified an issue in the time series of the data. Although we anticipated total synchronization between the two time series of both datasets we encountered synchronization issues in 25% of the data, which was unexpected. Despite the differences in time steps, we continued with the derivation of R_{XY} because the values of χ_{XY} seemed logical, given that our datasets also maintained an equal number of data points. The disparity of the χ_{XY} values in the two signals supported our conclusion, as they compute χ_{XY} using distinct computational approaches. We calculated the ratio CC_{GDS}/CC_{derr} as outlined in Equation 12, to characterize the response function.

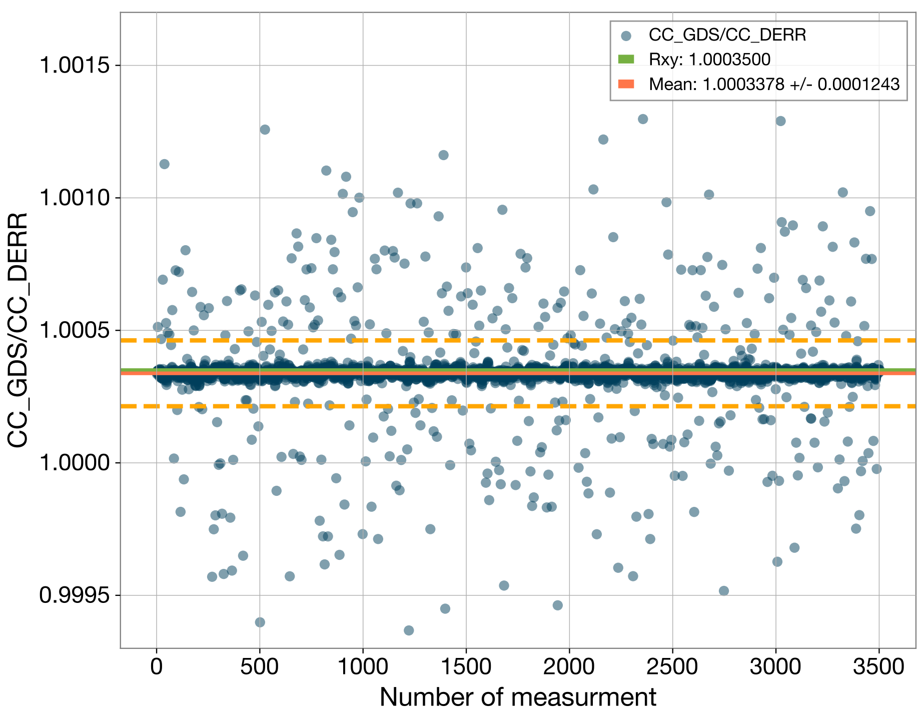

Figure 2: Each data point is the ratio of 240-second long FFTs, normalized by different interferometer signals, of the time series of the pcal-induced motion. The R_{XY} value, the mean, and the standard deviation are noted in the legend.

[2] reveals the value of R_{XY} for LIGO-Hanford as 1.00035. Figure 2 shows the mean of CC_{GDS}/CC_{derr} data is 1.0003378, which is less than one standard deviation from the cited value of R_{XY}. This gives us confidence to keep using data from influxDB for this project. Moving forward, we plan to obtain more data from influx DB to calculate the overall response function for the full O4 run. We also plan to dive deeper into the data and explore variations in the response function during different phases of lock stretches at both Hanford and Louisiana LIGO observatories.

References

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