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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May 16, 2024

Introduction

Importance of Calibration for GW science

Calibration of gravitational wave detectors ensures that the signals detected accurately represent gravitational waves. Precise calibration aids in distinguishing that observed signals are indeed from cosmic events and not artifacts of instrument errors or noise and aids in extracting all astrophysical information that the wave carries about the source.

Displacement Calibration using photon calibrators

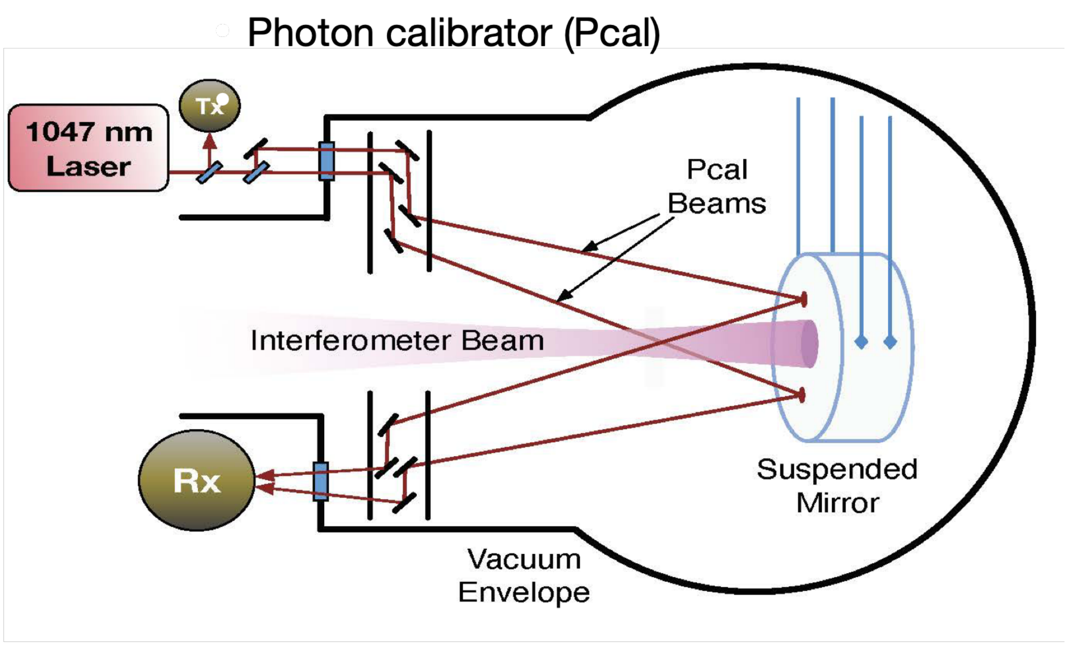

Figure 1: Photon Calibrator Schematic from LIGO-P2000113

All of the observatories in the current O4 run use photon calibrators as their primary calibration reference. The schematic diagram, Figure 1, shows the schematic diagram of the LIGO photon calibrator systems. Initially, a Gold Standard (GS) is calibrated to SI units via a NIST calibrated power sensor. This GS then calibrates Working Standards (WSs), one for each observatory, via responsivity ratio measurements. Finally, the WS's calibration is transferred to the power sensors (Tx and Rx) at each observatory's endstations. These sensors monitor the amplitudes of periodic displacements induced by power-modulated Pcal beams reflecting off the suspended mirror. Photon calibrators, or Pcals, are systems designed to generate periodic fiducial displacements using photon radiation pressure, as depicted in Figure 1. These systems employ power-modulated auxiliary laser beams that reflect off the interferometer mirrors, causing differential variations in the relative arm lengths. These variations mimic the effects induced by gravitational waves (GWs). The magnitude of the induced length variations is directly proportional to the amplitude of the modulated laser power reflecting from the mirror.

Photon calibrator X/Y comparison

Most gravitational-wave observatories like LIGO use Pcal systems calibrated with sub-0.5% accuracy at both end stations, which helps reduce overall uncertainty. These laser interferometers detect arm length variations caused by ETM movements, regardless of which End Test Mass, ETM, is moving, except for the movement's direction. Comparing Pcal fiducials from both ends in the interferometer signal measures the calibration ratio between the stations, further minimizing uncertainty in the displacements due to non-common factors. The X/Y calibration comparison between Pcal systems is achieved by modulating them at closely separated frequencies within the interferometer's sensitive band. By comparing the amplitudes of the peaks in the fast Fourier transforms (FFTs) of the interferometer output with those in the FFTs of the calibrated Pcal end station sensor outputs, the X/Y Pcal calibration comparison factor,χ_{xy}, is determined. Ideally, this factor would equal 1 if there were no uncertainties in the displacement calibration factors at both end stations. However, errors can arise from uncertainties in factors that are not common to both ends.

The differential arm length servo

The Advanced LIGO's differential arm (DARM) feedback control loop precisely manages arm length variations by converting residual displacement into a digital error signal, which is processed and used to actuate the test masses, thus maintaining resonance in the optical cavities. This sophisticated loop involves digital filtering, real-time control, and careful calibration using photon radiation pressure, ensuring the interferometer remains optimally sensitive for detecting gravitational waves. This control loop also calculates a response function.

The Grafana monitoring tool

The Grafana pages are a professional service that offers efficient Data Visualization techniques. We have used this tool to monitor the Pcal X/Y ratio as it changes over time during lock stretches. The signal through which the XY ratio is calculated is the GDS_CALIB_STRAIN signal. We plan to use these signals to derive the variation in the response function of the interferometer.

Objective

An investigation to quantify the impact of variations in the interferometer's sensing function on the Pcal X/Y comparison to better understand and reduce calibration uncertainty in LIGO detectors. This study will utilize the DARM_ERR channel, to calculate the X/Y comparison in Grafana, alongside the existing calculations using the GDS_CALIB_STRAIN channel. Assuming that the DARM loop is perfect, the comparison of these calculations should yield the inverse of the ratio of the suppressed DARM loop sensing function at the two Pcal frequencies. Monitoring this ratio during lock stretches will help identify any unintended or unexpected variations in the calculation of the GDS_CALIB_STRAIN channel. This investigation will provide valuable insights for both the Pcal and Calibration teams, enhancing their understanding of the observed variations in the calibration comparison and the stability of the suppressed sensing function of the DARM loop and the integrity of the GDS_CALIB_STRAIN data.

References

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