Calibration Uncertainty for Advanced LIGO's First Observation Run

The Advanced LIGO Calibration Team

On September 14th and December 26th of 2015, Advanced LIGO detected gravitational waves from a binary black hole coalescence during its first observation run. These detections required the accurate and precise calibration of the Advanced LIGO interferometers. Calibration is the characterization of each detector's response to gravitatational waves to produce strain data. Estimates of gravitational wave source parameters like total masses, distance, and sky location directly depend on the accuracy and precision of calibrated data. Tests of general relativity also rely on properly calibrated data, as miscalibrations could be degenerate with deviations from GR. Understanding the non-stationary, complex detector responses to gravitational waves and quantifying the response uncertainty is the role of the calibration group. We review the calibration process, quantify both time-dependent and frequency-dependent systematic errors, and produce the first observation run uncertainty budget.

I. INTRODUCTION

Twice during its first observation run, the Advanced LIGO detectors in Hanford, Washington and Livingston, Louisiana detected a gravitational wave (GW) signal [**?**] [**?**]. The September 14th and December 26th detections, known as GW151226 and GW151226, opened the era of gravitational wave astronomy when they were detected with significance $> 5.3\sigma$. Additionally, a LIGO-Virgo gravitational wave trigger occurring on October 12th known as LVT151012 was detected with significance 1.7σ. All three of these events are consistent with binary black hole coalesences [**?**].

The Advanced LIGO detectors are dual-recycled, Fabry-Perot laser interferometers with 4 highly reflective optics (called "test masses") arranged into 2 optical cavities (called "arms") 4 kilometers in length. When a GW is incident on the interferometer, it stretches and squeezes the space each arm occupies, simultaneously lengthening one arm of the interferometer and shortening the other. This type of motion is known as differential arm (DARM) motion:

$$\Delta L_{DARM} = L_x - L_y \tag{1}$$

where L_x and L_y are the lengths of the X and Y arms. DARM motion generates power fluctuations on the antisymmetric photodiode, making an interferometer highly sensitive to GWs.

The most powerful known source of GWs are binary black hole (BBH) coalescenses, where two orbiting black holes inspiral together, losing energy to GW emission, until at last they merge releasing an extremely powerful GW burst. As the GW propagates, the amplitude GW strain $h(t)$ falls as $1/r$ where r is distance from the source. BBH mergers are rare events, so in order to detect GWs from mergers the Advanced LIGO detectors must be extremely sensitive to increase the volume of space LIGO could potentially see a merger. The maximum amplitude strain $h(t)$ seen in any of the three detections was $h(t) \approx 1 \times 10^{-21}$ at the time of merger for GW150914. [**?**]

In order to be sensitive to GWs, the interferometer must be "locked" on resonance, meaning the optical cavities are aligned such that laser power builds up in the cavities. This occurs when the length of the cavity is an integer number of laser wavelengths apart so that constructive interference occurs. Feedback control systems hold the detector on resonance by actuating on the test masses to cancel optic motion. When a GW is incident on the detector, the DARM control loop error signal will contain the suppressed GW signal.

The Advanced LIGO calibration team is dedicated to converting the DARM error signal into GW strain data. This is done by characterizing the DARM control loop frequency response. The loop suppression is characterized by the open loop gain $G(f)$:

$$G(f) = A(f)\, D(f)\, C(f) \tag{2}$$

where $A(f)$ is the actuation function, $D(f)$ are the control loop digital filters, and $C(f)$ is the plant, or sensing function.

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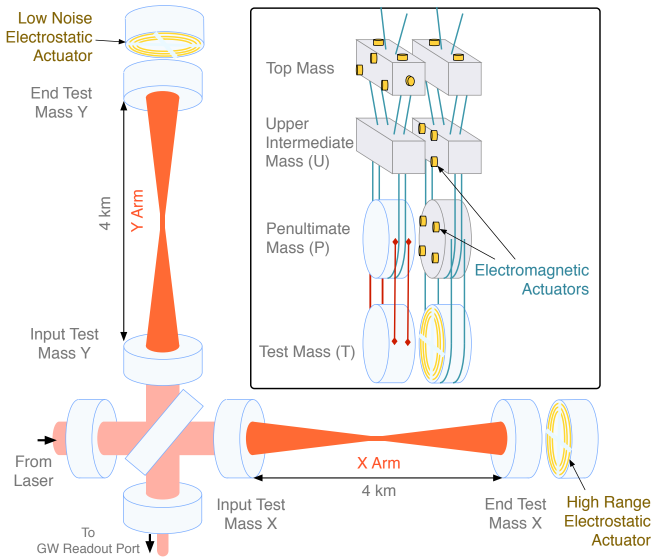

FIG. 1. Interferometer Optical Layout and Test Mass Suspension Diagram.

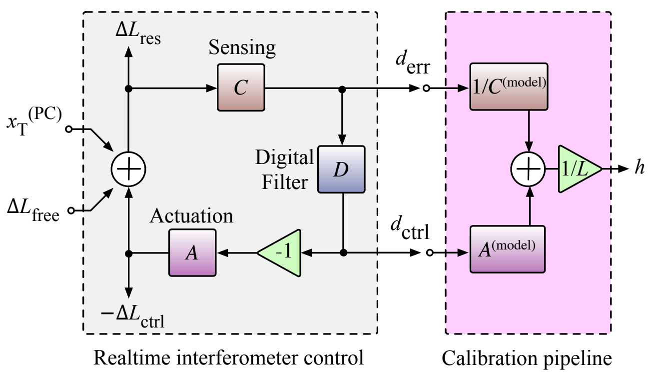

FIG. 2. DARM Control Loop and Strain Data Pipeline. The left box shows the DARM loop suppression, along with its output error signal d_{err} and control signal d_{ctrl}. The right box shows the calibrated data pipeline, which takes in d_{err} and d_{ctrl} and outputs strain data $h(t)$.