Implementing real-time calibration in Advanced LIGO control software

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1 Background

The concept of gravitational waves (GWs) comes from Einstein's General Theory of Relativity, published in the early 20th century: fluctuating gravitational fields produce disturbances that propagate through spacetime at the speed of light [5]. Physicists recognized that observing these waves would be a significant discovery, enabling them to gather data about the universe not possible through EM radiation. The potential to resolve fundamental problems in physics that deal with gravitation, including global aspects of the structure of the universe, remains encoded in GWs [2]. Experimentation to detect this radiation began around 1960 with Joseph Weber's resonant mass detectors [6], although his devices were not sensitive enough to measure the effect of GWs. Gradually, experimental methods in this field shifted from resonant mass detectors (bars) to the use of large interferometers. The Laser Interferometer Gravitational-Wave Observatory (LIGO) is one such project.

LIGO measures strain due to GWs by recording differential changes in the interferometer arm lengths. Because the goal of LIGO is to isolate a signal that is so weak (inducing a strain on the order of 1.0×10^{-21}) [3], great care must be taken to ensure that the optic, electronic, and mechanical systems of the detector are correctly calibrated. The differential arm length feedback loop ensures that the interferometer is sufficiently shielded from external and internal noise during operation. This feedback system is composed of a sensing function $C(f)$, a digital filter function $D(f)$, and an actuation function $A(f)$. A digitized error $d_{err}(f)$ resulting from residual displacements is generated by $C(f)$. A set of digital filters then transforms this error signal into a control signal $d_{ctrl}(f)$, which determines how the test mass actuators displace the mirrors at the end of the arms. For Advanced LIGO, the estimated strain is calculated by sampling both $d_{err}(f)$ and $d_{ctrl}(f)$,

$$h(t) = \frac{1}{L}\left[\mathcal{C}^{-1} * d_{err}(t) + \mathcal{A} * d_{ctrl}(t)\right], \tag{1}$$

where $\mathcal{C}^{-1}$ and $\mathcal{A}$ are time domain filters produced from frequency domain models of C and A, L is the average length of each detector's arms, and the * operator denotes convolution [4]. The functions described above are generated by taking measurements of the control loop parameters. Each parameter has an associated statistical and systematic uncertainty; uncertainty present in the calibration model parameters directly impacts the uncertainty in the reconstructed detector strain signal.

Advanced LIGO made direct observation of GWs on September 14, 2015 (event GW150914) [3]. During the ∼30 day window in which the event was observed, not a single calibration uncertainty limited the measurements of GW150914's astrophysical parameters [4]. It should not be assumed that this behavior will hold when improvements in Advanced LIGO's sensitivity are made in the coming years. Large effort needs to be made to ensure that the accuracy of the calibrated detector output remains a nonissue in characterizing GW sources from their observed signals.

2 Objective

Currently, Advanced LIGO calculates the external strain $h_{ext}(t)$ using the `gstlal` based pipeline [1]. Data from the front end of the interferometer ($d_{err}(t)$, $d_{ctrl}(t)$, excitation signals $x_{ctrl}(t)$, etc.) are broadcasted to the detector's Data Monitoring Tool. Within the DMT, the calibration pipeline writes the calibrated data into a shared memory partition before being sent to the clusters of the LIGO Data Grid: it is here that $h_{ext}(t)$ is produced.

We propose an improved version of this time domain calibration pipeline. We will implement a pipeline that runs in the front end of the interferometer and produces $h(t)$ in the raw frames. In the most recent engineering run at LLO, time domain calibration of $h(t)$ agreed to better than 1% in amplitude and 2 degrees in phase with the frequency domain calibration [1]. We will first generate front end code and import the full pipeline into the control systems of the interferometer, and then verify that its output is equivalent to the `gstlal` pipeline. This will yield $h(t)$ computation with extremely low latency, lending to prompt reporting of GW events that require further electromagnetic followup.

3 Approach

Before arriving at the program, I will look deeper into the literature on current calibration methods for the detector's control system. In the first weeks, I will work in MATLAB and C to produce the necessary digital filters that will be used in the importation of the current calibration pipeline. I will spend most time after that verifying that the front end pipeline is functioning correctly. Lastly, we will move to the interferometer and implement it there if time permits. An outline of the project appears below.

June 20 – July 4	Literature review, code digital filters to be used in front end pipeline
July 4 – July 18	Implement entire pipeline, troubleshoot errors, refine digital filter design
July 18 – Aug 4	Measure calibrated output and understand sources of uncertainty
Aug 4 – Aug 25	Move to interferometer; prepare abstract, final report, and presentation

Table 1: Project Timeline

References

[1] Advanced LIGO Calibration Team: LIGO Scientific Collaboration. Time Domain Calibration in Advanced LIGO, 30 Nov. 2015.

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