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Project Proposal for LIGO SURF 2022

GW strain calibration of LIGO detectors with high precision and low latency

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ABSTRACT

The detection of gravitational waves (GW) has opened a new era of astrophysical observation, allowing scientists to view and more deeply analyze previously unseen phenomena. This process hinges upon determining the strain $\Delta L/L$ of space over 4 km long baselines, which change by much less than the size of the nucleus of an atom (1). From this minuscule number, some of the most extreme gravitational wave-producing events in the universe can be more deeply understood. The Laser Interferometer Gravitational-Wave Observatory (LIGO), Virgo and KAGRA work together in this pursuit, in order to produce the most precise results possible. Precise reconstruction of the strain is incredibly important. The low latency pipeline *GstLal_calibration* is among the first steps of data analysis, and the strain it produces is crucial for all successive analyses of LIGO data (2). However, *GstLaL_calibration* does not produce an estimate for uncertainty. Instead, finding uncertainty takes minutes to complete, and requires multiple weeks to verify that it is accurate. In this project, we seek to produce estimates of systematic and statistical uncertainty in the calibrated strain, which are sufficiently accurate on time scales on the order of an hour. This promises to make the calibration pipeline more efficient, and allow LIGO data to be used more readily and with more confidence than ever before.

I. INTRODUCTION

The LIGO detector (Fig.1) is incredibly complex, and built at an incredible scale. In order to be sensitive to a strain $\Delta L/L$, corresponding to $/DeltaL$ on the order of 10^{-5} smaller than the size of a neutron, the interferometer must have arms which are 4 km long (1). The laser passes through resonant cavities in the arms, and upon returning to the beamsplitter, almost all of it is recycled in order to increase the sensitivity of the detector even further. The arms are housed within vacuum chambers to prevent laser frequency fluctuations, and the test masses are hung from multi-stage pendulums on glass rods less than a centimeter thick(5). Each stage is individually actuated through a second multi-stage pendulum, which produces a gentle current to counteract vibration. Keeping the mirrors stationary is imperative to maintaining complete destructive interference at the readout port of the interferometer. Gravitational wave strain is detected as a deviation from this condition due to changes in the differential arm length (DARM).

When a gravitational wave passes or the photon calibrators are used to induce strain, a change in arm length causes light to be detected by photodiodes at the readout port. This differential length is partially compensated by a control length, resulting in the residual displacement $\Delta L_{res}(t)$. (2). Once the light is detected by the photodiodes, the sensing function C converts the voltage to an error signal d_{err}. The digital filter D processes this to produce d_{ctrl}, which moves the mirrors back to their nominal positions. Both of these signals are used to construct strain $h(t)$. This is the calibration pipeline for LIGO in simple terms (Fig.2). In addition to this, the control signal is passed to A, the actuation function. This function produces forces which are allocated to each of the stages of the pendulum, for the purpose of keeping the test mass in its proper position. This keeps the laser resonant in the optical cavities in the arms.

Our goal is for the calibration uncertainty to be $< 2\%$ in magnitude and 2° in phase over the most sensitive frequency band (20-2000 Hz), in order for the strain to be accurate enough for further analysis (5). Currently, while we can obtain this level of precision with sub-second latency from the calibration pipeline, it still takes months to verify. Therefore, we would also like to determine early on if there will be errors to account for, in order to confidently obtain such a small level of uncertainty. Since LIGO's third observation run, several sources of error have been identified(5). The first of these concerns the sensing function. The laser power itself is stable, and due to constantly being tracked, does not present a significant problem. However, pitching or yawing of the test masses can affect the build up of laser power in the arm cavities, leading to uncertainty in the actual displacement that should have been produced by strain alone at the readout port (5). The second contributing factor to uncertainty is charge building up on the high range electrostatic actuators, shown in the inset in (Fig.1). While this process happens on the order of multiple hours, over time it affects how well the actuators can produce a stabilizing force on the test mass. LIGO's low latency calibration pipeline takes these sources of uncertainty into account by calculating time dependent correction factors (TDCFs) which are recorded at a rate of 16Hz and averaged each minute, then used to record the integrity of $\Delta L/L$ (2).

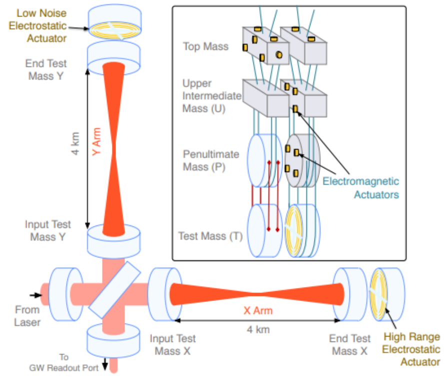

Figure 1. A simplified figure of the LIGO detector. Laser light enters from the left and splits down both of the arms. The laser cycles hundreds of times, building in power. If a GW passes, the length of the arms will change. This differential length is detected from the readout port as a phase change.

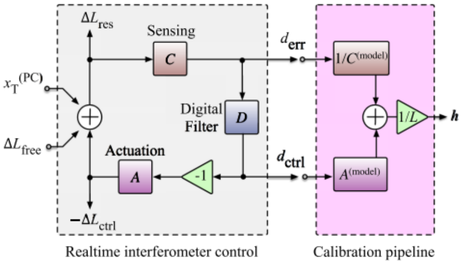

Figure 2. The LIGO calibration pipeline (on the right) and the LIGO control pipeline (on the left). The calibration pipeline passes the signals d_{err} and d_{ctrl} through filters to reconstruct the strain. The control pipeline uses these same signals to actuate the test masses. This ensures that the mirrors remain in their nominal positions.

One of the crucial reasons to rapidly produce a precise uncertainty estimate for strain is multi-messenger astronomy (5). The transient sources which LIGO observes, such as binary neutron stars (BNS) and neutron star black hole binaries (NSBH) are called standardizable sirens. They are light-emitting GW sources from which, should their signal be consistent with templates produced by General Relativity, a luminosity distance can be found. There are also Binary Black Hole (BBH) Mergers which don't emit light; while these are not candidates for multi-messenger astronomy, they can still be used to determine luminosity distance. Strain is a key value in this calculation for all sources, and for the many template pipelines which follow calibration. However, our signals have fairly low SNR, which makes them susceptible to statistical uncertainty. Additionally, a significant uncertainty in strain may cause the wrong template to be matched to a waveform, leading to incorrect extrinsic parameters. Rather than passing flawed data to telescopes only to hear it wasn't reliable later on, it would be ideal to receive the strain and uncertainty estimate at the same time, and only send out parameters we are confident in. Understanding the uncertainty in our strain measurement is also crucial in testing General Relativity in the strong regime, though this is not performed with low latency. GR describes how space distorts to create gravitational effects, and it is from the properties of this theory that templates can be constructed. If the detected strain signal is a poor match to GR-derived waveform templates, it may be evidence that General Relativity breaks down in the strong field, highly-dynamical regime of compact binary mergers. However, it may also be due to a poorly-understood uncertainty in the calibrated strain from the detectors. Producing the strain and uncertainty at the same time ensures that any true deviations with be noticed in low-latency, and that any apparent discrepancies between signal and GR waveform templates will be quickly understood as such.

II. OBJECTIVES

Our goal for this project is to understand, improve and rapidly generate estimates of calibrated strain uncertainty, with precision of $< 2\%$ in magnitude and 2° in phase, within 1σ limits. We will simulate low latency estimation with data collected during LIGO's third observing run (O3), which will be processed using the newly developed pyDARM code. We will also develop monitoring software which will process the uncertainty estimate, in order to determine whether it is in need of further investigation. For example, several problems with detector response during

O3 contributed to systematic uncertainty, yet they were only found months later (3). Ideally, our monitoring software will be able to detect these kinds of issues early on, although it cannot correct for them. A successful result of this project will be automated software which is able to read and process O3 data, and provide a warning if the recorded calibration uncertainty is too large within the band of 20-500 Hz. It must be ready for use by the start of the fourth observation run (O4), currently scheduled for December, 2022.

III. APPROACH

Our approach is to first study and understand the calibration pipeline and the generation of the uncertainty estimate under the conditions of O3. Following this, the relevant pipelines will be updated and run on simulated O4 data to validate the procedure and prepare them for O4. The third and fourth observation runs will store their data in a similar way, which permits us to base our updates off of the O3 calibration pipeline. Once the uncertainty estimation procedure is completed, it will be improved in several ways. These include Gaussian Process Regression, updating the uncertainty estimation for (and possibly the computation of) TDCFs, and running the pyDARM code as improved by Ethan Payne and collaborators. Finally, a monitoring software will be written to examine the output(s) of the improved uncertainty estimate procedure. It will alert us to any significant changes in the output, which will furthermore indicate changes in detector behavior. The majority, if not all of this will be written in Python, under the guidance of Graduate Student Ethan Payne and Advisor Dr. Alan Weinstein.

IV. TIMELINE

Along with the timeline listed below, there will be project reports due to the LIGO SURF program at dates to be announced at the end of the 3rd and 7th week.

1. Week One: An intense period of background education. I can expect to learn about how each part of the detector operates. I will also learn how LIGO's calibration pipeline and the current mathematical / digital process of uncertainty estimation works in great detail.

2. Week Two: Continuing education on important background concepts. Possibly beginning to engage with O3 data, in order to understand how to interpret our simulated data for O4; what are signs that our uncertainty is not accurate? What updates must be made to the calibration and uncertainty estimation pipelines for O4, and why?

3. Week Three: In this week, I will run the relevant pipelines on our simulated O4 data, and examine the results. I expect interpreting the results to take up a significant amount of time, as I apply my new background knowledge for the first time. We will discuss the methods of improvement as well (Gaussian Process Regression, Bayesian estimation, etc.) and why each is being undertaken.

4. Week Four: Continue learning about each method of improvement, likely creating an itinerary and breaking them up into steps. As I begin examining the code, I will likely spend some time refreshing myself on various astrophysics Python packages. I will also spend time learning about methods of curve fitting and statistical analysis. I expect more time will be spent learning how to complete the improvments than actually doing them, at first.

5. Week Five: As I get used to the software packages I will be working with, I can expect to spend more time working on the various uncertainy estimate improvements, and less going on tangents to learn crucial skills in the moment. There will be intermittent periods of writing code and testing it with simulated data, to determine if it is working correctly. An ideal milestone at this time would be to confirm that the improvements work as expected.

6. Week Six: Considering the output(s) of our updated uncertainty estimate pipeline, and what in each one may tell us about the quality of our estimate. Determining what a monitoring software would have to examine, and what would be the indicative signs of an estimate in need of further examination. Likely comparing it to the uncertainty from O3, and seeing what has changed with O4.

7. Week Seven: Start of writing the monitoring software. I can expect to be doing a lot of looking up how certain packages work, or other examples of learning on the fly. Lots of smaller tests to make sure each piece works

independently. Ideally, we should be able to have it read old data from fairly early on. This week I will also need to deal with automation, and making sure that the software writes to the correct files without providing errors.

8. Week Eight: Continued work on the monitoring software, similar to the previous week. Once it writes to the correct files, I can examine if the information being written is as expected.
9. Week Nine: Finishing up on the monitoring software, either completing it or creating a list of what works, and what must be done before the start of O4. I will also begin to put together my presentation for the final week of the REU.
10. Week Ten: Final presentation of research results at the LIGO SURF Seminar Day.
11. Post-Summer: Continuing work on this project, contributing to the ongoing work of my advisors. The software must be ready for use by O4. It is undetermined if I will produce a paper directly from my work this summer. However, this project will likely contribute to being listed as an author or contributor on a future paper published by the LIGO calibration team.

REFERENCES

[1]Sun, L., Goetz, E., Kissel, J. S., et al. 2020, Classical and Quantum Gravity, 37, 225008. doi:10.1088/1361-6382/abb14e

[2]Viets, A. D., Wade, M., Urban, A. L., et al. 2018, Classical and Quantum Gravity, 35, 095015. doi:10.1088/1361-6382/aab658

[3]Sun, L., Goetz, E., Kissel, J. S., et al. 2021, arXiv:2107.00129

[4]Abbott, E.P, Abbott R., et al. (2017), CaltechAUTHORS. doi:10.1103/PhysRevD.95.062003

[5]Email and Zoom correspondence with Advisor Dr. Alan Weinstein and Graduate Student Ethan Payne during the months of March, April and May 2022.