LIGO SURF 2021 project abstracts
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Non-Linear Noise Subtraction for Low Frequency

The amplitude of the noise in laser interferometric data limits the astrophysical information that can be extracted from it. LIGO has a strong history in reducing the linear and stationary noise at different frequencies by monitoring auxiliary sensors and the correlation with the estimated strain at a given time. Recently, it was shown that nonlinear correlations could be used to reduce the noise even further for the case of the noise spectral density around 60 Hz in laser interferometers. The approach involved utilizing two types of auxiliary channels, each with different spectral content. In this project, a similar methodology will be investigated for the lower part of the LIGO spectrum (below 10 HZ) which has not been explored in any previous subtractions. The gravitational wave memory from Core Collapse Supernovae and pre-merger binary star signals are known to have low-frequency emission between 10−5 Hz and 50 Hz, which is the main motivation for this project.

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Reducing Early Warning Retractions to Facilitate Multi-Messenger Astronomy

Early warning gravitational wave detection pipelines are extremely important tools that could alert astronomers to a gravitational wave event before the event has occurred, facilitating a new frontier for multimessenger astronomy. The aims of this project were to study the early warning pipeline, specifically GstLAL, and run the pipeline using data from Advanced LIGO and Advanced Virgo’s third observing run colored to projected O4 sensitivities. This project involved varying the upper frequency bounds, which correspond to different early warning times, and using these different runs to test a new process of calculating the false alarm rate for events. The false alarm rate is a measure of how often we expect LIGO noise to produce a gravitational wave event. By decreasing the significance of noise events through this process, we are aiming to reduce the number of retractions for the next LIGO observing run.

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Ensemble Monte Carlo Markov Chain Methods for Testing General Relativity in Gravitational Wave Signals

The population of observed gravitational wave transients continues to grow, and with it, our ability to further constrain deviations from our current understanding of gravity. However, our current procedures for computing these constraints will not successfully scale with future transient catalogs. Thus, we will leverage modern statistical methods, like ensemble Monte Carlo Markov Chain sampling, to provide more efficient and more complete investigations of the parameter space of deviations from general relativity given gravitational wave observations of binary black hole mergers.

Optimal Settings for Fast Low-Latency Skymaps of Neutron Star Binaries

The detection of gravitational waves is instrumental to our understanding of astrophysical processes and the fate and evolution of the sources of such waves. One source of gravitational waves is compact binary coalescences (CBC's)–binary systems which consist of black holes, neutron stars, or both. Here, we examine neutron star binary systems and their intrinsic and extrinsic parameters and determine how to optimize data intake to improve the localization of such systems. We confirm that longer signal durations maximize relevant information we can extract from the signals but increase typical computing efforts. For analyses where prompt results are essential, such as for multi-messenger follow-up, we present the ideal conditions for fast and accurate analysis.

Studying the Detectability of High Mass Black Hole Binary Mergers with Future Gravitational Wave Detectors

In this work we will determine the distances to which gravitational waves from Intermediate Mass Black Hole Binary (IMBHB) mergers can be detected by ground based gravitational wave detector network in observing run four (O4), and beyond. Binary black hole mergers between 65 and 150 Msun are predicted to be rare as a result of pair instability in the final stages of their progenitor stars, so future observations of IMBHB mergers will help us to understand formation processes. Therefore, this study seeks to calculate the detectability of IMBHB mergers for future runs of the detector network. We aim to determine the sensitive luminosity distance of merger events within the IMBH mass range, averaged over other astrophysical parameters. Optimal sensitivity distances will be given for several detector network configurations, including predictions for future detectors. Additionally, we will present detection efficiency predictions as a function of red-shift, and distance horizon value for various high mass mergers. We will present the sensitive volume of the detector network and predict the number of IMBHB merger events we expect to observe in future runs.

Red Pitaya Digital Laser Controller

This report details using the Red Pitaya (125 MHz 14 bit) electronic board as a digital feedback controller for laser frequency stabilization. There is an exploration of various digital signal processing functionalities of a python interface to the onboard FPGA. Through a plant model approach, we attempt to validate the performance of Red Pitaya for feedback control. This is achieved by configuring the board to perform system identification and fitting frequency response data to a pole-residue model. The aim is to develop an automated device capable of determining the frequency response of some unknown plant and cancelling undesirable features (e.g. resonances) to produce a flat response.

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System Identification and Optimal Control of Mirror Suspensions

The Laser Interferometer Gravitational-Wave Observatory, abbreviated as LIGO, has successfully made advancements in the scientific community by detecting gravitational waves and a large number of black holes and neutron star mergers. Owing to the extreme sensitivity of the instrument, it becomes crucial to ensure that the activity of the suspended mirrors used for the reflection of the laser is controlled, especially in the presence of noise and seismic activity. Obtaining data regarding the system's behavior will give us information on the current state of the system. By optimizing the Fisher information about our system's parameters (e.g. poles and zeros) under the constraints that there are finite limits on the total excitation energy, the readout noise, and the measurement time, it is possible to improve the sensitivity of the system.

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Marginalizing Over Noise Properties in Parameter Estimation

The traditional gravitational wave parameter estimation process relies on sequential estimation of noise properties and binary parameters, which assumes the noise variance is perfectly known. Using new capabilities of the BayesWave algorithm and recent developments in noise uncertainty modeling, we simultaneously estimate the noise and compact binary parameters, marginalizing over uncertainty in the noise. We compare the sequential estimation method and the marginalized method on real GW events from GWTC-2 using both the wavelet-and template-based models in BayesWave. We find that the recovered signals and posterior parameter distributions agree in median and width. At current sensitivities, PSD uncertainty is a subdominant effect compared to other sources of uncertainty.

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Optimal State-Space Estimation of Interferometer Mode-Matching

LIGO's current detectors rely on a system of adaptive optics to carry out highly sensitive measurements, but they lack an optimal control system. In response, we have adopted the Kalman filter formalism to systematically derive a more optimal estimate of the state of the resonant spatial mode of each of the optical cavities by allowing this formalism to statistically weigh both measurement data and predicted state parameters. The filter is capable of accessing the plethora of information that is considered inaccessible by the current suboptimal control system, and then using that information to narrow down the location of the actual state in relation to the desired state. Python simulations are being run on a simple one arm cavity housing two mirrors being lazed by an input beam of an arbitrary mode. Our goal is to eventually be able to integrate this new control system within LIGO's current and future adaptive optics systems to calculate real time estimates of the state of the interferometer.

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Data Folding for the LIGO Stochastic Directional Analysis Pipeline

While a growing number of individual gravitational wave events have been observed, researchers are still searching for a stochastic gravitational-wave background. This superposition of weak, unresolved gravitational-wave signals could hold a wealth of both astrophysical and cosmological information. Studying both the isotropic and anisotropic components of the background at current detector sensitives could provide a measure of matter distributions and large-scale structure in the Universe. Eventually these searches may provide concrete evidence of inflation and act as a primordial analog to the Cosmic Microwave Background. This paper will detail the development of a data folding algorithm for the stochastic gravitational wave background analysis pipeline. Taking advantage of the fact that the detector response is periodic with the rotation of the Earth, long stretches of time series data can be condensed to the size of one sidereal day. We implement this algorithm in both simulated and real data and verify its efficacy through direct comparison to calculations with unfolded data. With the implementation of data folding, anisotropic directional searches can be carried out far more efficiently. Data folding only needs to be applied once, but brings orders of magnitude improvements in speed and data size, with negligible loss of information.

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Investigating data quality metrics for stochastic GW detection - StochCharMon

The detection of gravitational waves has created the opportunity for many new discoveries. One such potential discovery is the stochastic gravitational wave background. In order to detect it, stochastic data must be properly monitored and analysed. Stochmon, a low latency stochastic data monitoring pipeline, works to monitor the quality of stochastic data. Stochmon has not been recently updated and is not well integrated with current gravitational wave data analysis tools. The goal of this project is to identify potential improvements to make to Stochmon's analysis functions, implement said changes, and integrate the system with existing analysis tools so that it can be used during the next observing run. A new feature of Stochmon, the stochastic detector sensitivity (SDS) has been implemented which calculates the energy density at which a detector can detect a stochastic signal.

Refining the Search for Sub-threshold Lensed Gravitational Waves

Gravitational lensing of gravitational waves is predicted in terms of strong, weak, and micro lensing, but has not yet been observed in any of these lensing regimes. Efforts to detect strongly lensed gravitational waves using data from Advanced LIGO and Advanced Virgo include searching for sub-threshold lensed images, which have been de-magnified and are undetectable with usual signal analysis methods due to a high noise background. In this work, I describe efforts to make improvements to targeted sub-threshold lensed gravitational wave search pipeline, which included investigating the waveform family used in the pipeline, as well as imposing conditions on the sky location of the lensed images. Spin-aligned and precession included waveform families were compared, and it was found that while the spin parameter of the gravitational wave event is so unconstrained, it cannot be said that either waveform family would incur loss of candidate images. Furthermore, a constraint was implemented on the sky localisation of lensed gravitational wave images, which can be approximated to come from the same sky location. By imposing this condition, the rankings of lensed image candidates with a stronger overlap to a target event were boosted as expected. This now needs to be implemented into the search pipeline for sub-threshold lensed images.

Understanding the Physical Degrees of Freedom in a Parameterized Test of General Relativity

This paper provides a framework for understanding the physical degrees of freedom in a parameterized test of general relativity. In particular, we vary the post-Newtonian (PN) coefficients, the phenomenological coefficients, and the analytical black-hole perturbation theory waveform parameters and observe how this would affect the waveform and hence the physical parameters. The physical parameters include the energy radiated and the rate of angular momentum. Although it is possible to map the dephasing coefficients to physical quantities, the inverse mapping of the physical quantities to the dephasing coefficients is unknown. Therefore, this paper presents a method of obtaining this inverse mapping using the Gaussian Mixture Model (GMM).

Bayesian analysis of low latency LIGO alerts

LIGO (Laser Interferometer Gravitational wave Observatory) detectors are capable of detecting gravitational waves created by merging massive stellar remnants moving at high accelerations . Collisions of massive stellar remnants create electromagnetic waves that can reveal many aspects of the remnants that collided. The EM community is attempting to use data from the LIGO instruments to pinpoint the location of the sources and view the sources across all electromagnetic wavelengths as shown by observational campaigns conducted during LIGO's third observing run. Gravitational wave detectors are poor at localizing mergers, making the discovery of counterparts a challenging task. We will compare the Bayes factor and the Terrestrial probability of alerts as metrics of classifying sources as astrophysical in low latency. We will improve the low latency data products that are provided to EM observers in order to aid in the discovery more counterparts in the future.

Mitigating the effects of instrumental artifacts on source localizations

Instrumental artifacts which materialize as glitches in strain data can overlap with gravitational wave detections and significantly impair the accuracy of sky localizations of compact binary coalescence (CBC) signals. We present our Python package, PySLIDE (Python-based Skymap Localization with Inpainted Data Editor), which takes gravitational wave (GW) signals, removes a segment of the data, and corrects for the removal. To make this correction, we employ a method that applies a reweighting formula to the signal-to-noise ratio (SNR) of the signal. From tests on $\approx$500 simulated GW signals, we determined that reweighting the SNR timeseries is able to improve the accuracy over simply removing the bad data. When we repeated this process for raw data with a simulated glitch, the reweighting formula likewise improves upon removing the data alone. In this report we discuss the method we used to reweight the SNR, features of PySLIDE, and the results of our tests on simulated GW signals.

Low-noise Nonlinear Cavity for Cryogenic Interferometers

First detected by LIGO, gravitational waves (GW) offered valuable insights into astronomical phenomena that are crucial to our understanding of the universe. At its core, LIGO is modeled after the famous Michelson interferometer with arms of 4 kilometers and suspended mirrors to reflect a powerful laser beam. The passage of GW introduces changes in the arm length on the order of 10−21 meter. By analyzing the interference pattern taking place at the photodetector, the change in arm length due to GW can be detected. Due to the sensitive nature of its measurements, LIGO continually seeks to improve its sensitivity. Currently, scientists are aiming for a 100-times better sensitivity than the first-generation instruments. Achieving this improvement requires keeping the test masses at 123 K as well as changing the material that the mirrors are made of. The new material, crystalline silicon, absorbs the wavelength of the existing laser. Therefore, the change of the test masses material will necessitate a change in the laser's frequency from 1064 nm to 2128 nm, which will not be heavily absorbed by the new test masses. The change of wavelength is achieved through a Degenerate Optical Parametric Oscillator (DOPO). Due to many noise sources, the wavelength conversion process may not be perfect. In this project, we are investigating and quantifying the sources of frequency noise in DOPO as well as methods to detect it and mitigate it if necessary.

Back-action evasion for PT-symmetric interferometer

Future gravitational and astrophysical research calls for the broadband and high-frequency sensitivity of gravitational wave detectors. Conventional resonant detectors are subject to bandwidth-peak sensitivity trade-off. The idea to circumvent this limitation, i.e. to improve the bandwidth without sacrificing the peak sensitivity, is called White Light Cavity (WLC). The PT-symmetric interferometer with coherent quantum feedback is a stable realization of WLC (which is called sWLC for short), compared with the direct attachment of a filter cavity with anomalous dispersion (uWLC for short). However, the original proposal hasn't considered the back-action noise caused by the radiation pressure on the test mass. In this project, we work with the PT symmetric interferometer. We aim to explore a more complete PT-symmetric structure to improve the low-frequency noise spectrum by backaction evasion with an effective negative mass. The effective negative mass will be possibly achieved using parametric amplification and optical damping formed by multiple additional pumpings. and hence, have a larger bandwidth with sacrificing less of the sensitivity than we would for a conventional trade-off between the bandwidth and sensitivity.

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LIGO Laser Beam Tracking

When the GW passes through the interferometer its arm length increases and decreases consecutively which causes change in differential arm length during the event. The intensity of the recombined light at the detector readout which is a function of the differential arm length (DARM) of the interferometer, gives the infinitesimal gravitational wave strain as shown in Figure 1. The LIGO detector is highly susceptible to various kind of noises which are basically unwanted signal produced by interactions among detector subsystems or with the surrounding environment that gets added to the GW strain data. Here, we are interested in the Fabry-Perot cavity and test masses of the detector. In this project we are trying to detect the position of the laser beam spot on the test masses. The aLIGO is not free from scattered light noise. The scattering of light helps us to see the scattered beam spot from any angle on the mirror surfaces. Due to irregularities and point scatterers of the mirror, the light undergoes deflection from its path defined by specular reflection and hence scattering occurs. The angular motion of the mirrors causes oscillatory translational motion of the beam spot on the mirror. Thus, tracking the position of the beam has become one of the important task within LIGO community.

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Simulating Scattered Light For use in Training Beam Tracking Algorithm