Summer Research Projects for 2018

LIGO Livingston (Louisiana)

Scattered Light Investigations

Light scattered from the main beam path in the Advanced LIGO interferometer can re-enter the beam path after bouncing off objects that are moving. This light picks up phase from the moving object and thus couples the motion of these objects to the interferometer output; creating a source of noise. This project will involve hands on investigations of this noise source with the aim of improving the Advanced LIGO sensitivity for observation run three.

Lab experience particularly with optics and some Matlab programming experience would be desirable.

Mirror Degradation Monitor / Modelling Stray Electric Field Noise

Anomalous absorption in LIGO mirror coatings was associated with a reduction in the Hanford detector sensitivity in observation run 2. In this project a real-time absorption monitor will be created. The monitor will use the test mass Eigenfrequencies to probe the test mass temperature. Then correcting for ambient temperature and several other factors the coating absorption will be estimated each time the instrument enters its operational configuration.

Stray time varying electric fields couple to force noise on LIGO test masses if there is residual charge on the test mass. This force noise can be manipulated by applying static fields to the test mass and has been shown to be a limiting source of noise in some configurations. In this project a model of the stray electric fields and charge distribution on the test mass will be created. This model will be verified against experiments on LIGO test masses. This project is dependent on new electric field meters being delivered in time.

For either of these projects experience with COMSOL, signal processing and basic programming in Python and Matlab would be desirable.

LIGO Hanford (Washington)

Studying Potential LIGO Noise Sources

Since instrumental noise limits the performance of LIGO instruments, identifying the noise sources and reducing their coupling to the LIGO gravitational wave signal channel is one of the most important tasks in LIGO. In this project, the student will work with the mentors to study potential noise sources in LIGO subsystems including but not limited to Radio Frequency (RF) modulation systems used for the control of LIGO instruments, and will study the potential improvement strategy.

Strong hands-on experience in lab environment and some practical knowledge about electronics is preferred.

Helping LIGO Detector Upgrades

Throughout 2018, we will be upgrading the LIGO detectors. The students will work with the mentors to help preparing for, and potentially implementing, the detector upgrades. This includes but not limited to investigating LIGO noise, testing and calibrating LIGO subsystem components.

Strong hands-on experience in lab environment and some practical knowledge about electronics are preferred.

Caltech Experimental Projects

An Optical Probe of Thermodynamics

A serious limit to the sensitivity of the LIGO interferometers is the thermodynamic fluctuations of the mirror material. To investigate this we have developed a pair of high finesse Fabry-Perot optical resonators targeted towards this noise source. This experiment is now quite close to the thermodynamic limit. This summer the students will develop a neural network based feedback/feedforward system for the cavity temperature control as well as acousto-optic devices to mitigate the excess phase noise from parasitic light scattering.

Strong hands-on experience in lab environment, some knowledge of modeling tools and some practical knowledge about electronics are preferred.

Modeling Quantum Noise in Gravitational Wave Detectors

Quantum noise is now the limiting noise source at high frequencies in interferometric gravitational wave detectors. The interaction between laser light and the mechanical motion of mirrors changes the quantum state of the light. It is thus possible in principle to use different optical topologies to put the light in an interferometer into a more favorable quantum state for gravitational wave detection. This project will simulate aspects of these proposed changes to the readout of an interferometer taking practical experimental difficulties into account in order to investigate their feasibility in practice.

The student should be familiar with the quantum harmonic oscillator and linear algebra. Proficiency with python is also preferred but not necessary.

Measuring the Frequency Noise of 2 um Lasers using Asymmetric Fiber Interferometers

Future generations of LIGO will embrace new materials and laser wavelengths to overcome limiting noise like Brownian and thermo-elastic noise. Presently the LIGO instruments utilize 1064 nm light and fused silica glass optics to make interferometric detections of the deformation of space from gravitational waves. Future designs will use silicon optics along with laser wavelengths as long as 2 um. Less is known about the design and performance of high power long wavelength lasers for these applications. This SURF project will investigate the frequency noise of one such laser using a compact fiber based experiment.

The experiment will involve performing an experiment using a pair of arm-length mismatched Mach-Zehnder interferometers as a frequency discriminator to make a measurement of fiber coupled 2 um diode laser. The student will then construct a fiber-based experiment using acousto-optic modulator to make a higher precision laser frequency noise measurement and attempt to stabilize the laser using a basic control loop. The experiment will also involve designing effective acoustic and thermal stabilization and dampening for fiber elements.

Strong hands-on experience in a lab environment, some practical knowledge about electronics and control theory are preferred but not essential.

Real-time universal transfer function synthesizer

LIGO uses a synchronized networked real-time computing system for data acquisition and interferometer controls. One of its most important features is the ability to implement minimally intrusive changes in the control loop landscape via and in-situ parameter redefinitions such as filter order and coefficients. However, many control loops require bandwidths that far exceed the capabilities of the global real-time system. Using programmable fast-clocked real-time hardware that can interface with the original configuration tools represents a compromise between the flexibility of digital logic with the speed of analog circuits. The goal of this project is to assemble a near-arbitrary transfer function synthesizer with noise-shaping that can be used in control loops and physically instantiate simulated plants for loop analysis.

This project will involve the graphical and text-based programming of real-time hardware in Verilog and Simulink, and a limited amount of analog electronics assembly for signal whitening filters. Familiarity with Python and a basic understanding of control loops is recommended.

Near-Infrared External-Cavity Diode Laser

Interferometric measurements for gravitational wave detection and many related table-top optics experiments require lasers with excellent frequency and intensity noise characteristics and capability for fast frequency tuning of the single-frequency output. The transition to cryogenically cooled silicon optics in next-generation interferometers requires longer wavelengths between 1.55 and 2 um. The combination of a free-space laser diode with a frequency-selective grating and a PZT-element for length actuation presents an affordable alternative to commercially available lasers, which are often limited either by a lack of output power, too high noise, or insufficient tunability. The objective of this project is to assemble an external cavity diode laser which can source the laser fields required for high-bandwidth cavity locking experiments and low-noise investigations of silicon optics for future detectors.

Previous strong hands-on lab experience is required and basic programming in Python and Matlab is recommended.

Cryogenic Zero-CTE Temperature Locking of Monolithic Silicon Cavities

Future cryogenically-operated gravitational wave detectors exploit the zero-crossings of the coefficient of thermal expansion of silicon or sapphire to minimize temperature-driven noise and stability issues, and various precursor experiments require their silicon parts stabilized to these particular temperatures. Modulating the intensity of a visible laser that is incident on the mirror of a fixed-spacer silicon optical cavity will deposit a time-dependent amount of heat into the monolithic optical assembly, driving temperature fluctuations. Since these in turn result in length fluctuations of the cavity - unless it is at the zero-crossing temperature - the control signal of a laser which is held on resonance with a feedback loop will show the same fluctuations as it tracks the frequency drift of the cavity. This project aims to use this effect to create a secondary control loop that holds the cavity at its zero-crossing point and enables precision measurements of other cavity noise sources.

Previous practical lab experience and working knowledge of Python is recommended.

Adaptive Optics for Next-Generation Interferometers

Squeezed light promises to boost the sensitivity of Advanced LIGO and future gravitational wave detectors, circumventing the standard quantum noise limit, but achieving those gains requires matching the laser modes inside different parts of the system to fine precision. This can be achieved with the use of adaptive optics whose radii of curvature can be actively tuned. This project will test prototype thermally-actuated optics and characterize their suitability for use as adaptive optics in future gravitational wave interferometers.

Hands-on experience in a lab environment and some practical knowledge about optics and Python programming are preferred but not essential.

Optical loss characterization for quantum-limited technology

Characterizing loss in various parts of the interferometer is an important step in quantifying its sensitivity. The goal of this project is to build up a loss budget for the various optical cavities in the 40m prototype interferometer, and investigate its implications on achievable levels of ponderomotive squeezing. A secondary goal is to set up the infrastructure, and develop a software library for the loss to be monitored over time, and to track any motion of point scatterers on the optic surface using GigE cameras and neural network based image processing.

Some hands-on lab experience and experience with programming in MATLAB and/or Python is preferred.

Mirror Mapping / Cavity spectroscopy

Developing a framework for in-situ analysis of the geometric properties of the mirrors making up the optical cavities in the LIGO interferometers will be an important tool in characterizing the instrument and understanding its response. For the arm cavities, this can be done by carrying out a mode scan using auxiliary lasers. The goal of this project is to extend this technique to interferometrically characterize properties of suspended cavities, using an auxiliary laser injected from the antisymmetric port of the interferometer.

Some hands-on experience with optics and electronics is preferred.

Double QPD Optical Lever

We will stabilize the mirrors using multiple quadrant photodetectors so as to eliminate spurious sources of beam jitter.

Extending the reach of gravitational-wave detectors with machine learning

With the advent of gravitational-wave astronomy, techniques to extend the reach of gravitational-wave detectors are desired. In addition to the stellar mass black hole and neutron star mergers already detected, many more are below the surface of the noise, available for detection if the noise is reduced enough. This project applies machine learning algorithms to gravitational-wave detector data and auxiliary channels on-site to reduce the noise in the time-series due to instrumental artifacts. This framework is generic enough to subtract both linear and non-linear coupling mechanisms, and teach us about the mechanisms which are not currently understood to be limiting detector sensitivities. Using realistic assumptions about coupling mechanisms, we seek to reduce the noise floor to lead to sensitivity improvements for binary systems. The expectation is that this work can be generalized to other time series regression analyses in all areas of science.

Interest and knowledge of Python, Machine Learning methods, and FFT / signal processing is recommended.

Phonon Decoherence Tomography for High-Q Mechanical Oscillators

Next generation LIGO detectors will be cooled to near 120K to take advantage of the low noise of silicon optics at this temperature. To achieve the lowest possible thermal noise in this configuration, low-loss coatings must also be developed. To characterize these coatings, one can measure the rate of decay of oscillations of a coated silicon wafer. However, the influence of other types of loss coupling to the wafer's suspension system, or imperfections in the wafer's surface can cause these oscillations to decay at a faster rate. To measure the loss due only to the coating's material properties, these other sources of loss must be subdominant.

This project will use finite element analysis and experimental tests to determine the frequency-dependence of different loss contributions for the wafer-coating-suspension system. The goal will be to create a model of Q (or loss) as a function of frequency that is parametrized by the strength of the various loss contributions. This model will then be used to determine the dominant sources of loss for any measurement of the frequency-dependent Q of a silicon wafer.

Experience with Matlab, COMSOL, FEA, and Monte Carlo methods would be useful.

Temperature Control by Tracking Oscillator Eigenfrequencies in a Frequency Stabilized Loop

Next generation LIGO detectors will be cooled to near 120K to take advantage of the low intrinsic loss of silicon optics at this temperature. To achieve the lowest possible thermal noise in this configuration, low-loss coatings must also be developed. To characterize these coatings, one can measure the rate of decay of oscillations of a coated silicon wafer. However, because the loss of the silicon wafer increases dramatically when its temperature varies from 120K, deviations in the temperature over the course of a single measurement will cause most of the oscillations' energy to decay through the internal friction of the silicon wafer, rather than through the coating. Therefore, to measure the loss of the coating the temperature must be precisely stabilized. Temperature stabilization in the wafer-coating-suspension system is challenging because any temperature probe or heat source or sink that directly contacts the disk will also provide a lossy channel for energy to dissipate, spoiling the measurement.

To achieve precise temperature control, we can take advantage of the temperature-dependence of the eigenmodes of the silicon wafer. This project will develop a control loop that tracks the eigenfrequency of several modes of the silicon wafer under study and controls a radiative heater that keeps these modes at a constant frequency by changing the disk's temperature. The project will involve work with liquid nitrogen, optics, the LIGO data acquisition system, and control theory.

Caltech LIGO Data Analysis / Astrophysics

LIGO data calibration

In the new era of gravitational wave astronomy, our primary goal is to measure source parameters and draw astrophysical inferences from observed signals. To do this effectively, we require an accurate calibrated estimate of the strain, or relative change in length, due to gravitational waves passing through our detectors. Students who work in LIGO calibration will combine precision controls engineering with computationally efficient signal processing to try to provide such data in real time.

Knowledge of signal processing and Python is recommended; students will also learn some techniques from controls engineering.

Understanding LIGO detector behavior

LIGO data is both non-Gaussian and non-stationary. Fourier transformed LIGO data contains strong features at particular frequencies which can pollute searches for gravitational waves from long-duration sources like spinning neutron stars and a stochastic gravitational wave background. LIGO data also contains short bursts of noise called 'glitches' that can confuse searches for transient gravitational waves including black hole and neutron star mergers. This project will investigate sources of detector noise, quantify their impact on the astrophysical searches, and explore methods for improving astrophysical search performance.

Experience with python and/or signal processing is recommended.

GWs from compact binary coalescences

To date, a technique called 'matched filtering' has identified every LIGO gravitational wave discovery. Matched filtering essentially works by scanning the data stream with a very precise model, looking for signals in the data that match this model. This technique is especially useful in searching for mergers of extraordinarily compact objects, such as neutron stars and black holes, for which we can use general relativity and numerical simulations to make very accurate waveform models. Matched filter searches on LIGO data use hundreds of thousands of waveforms models that span different object masses and spins. Students interested in searching for compact binaries can study the origin, evolution, and morphology of these signals to learn as much as possible about their implications for astrophysics and cosmology.

Interest in / knowledge of Python, signal processing, and statistics is recommended.

GWs from unmodeled bursts

Matched filtering is a powerful tool when we have an accurate model. Current modeled waveforms for the coalescence of neutron stars and black holes are difficult to generate if these objects have extreme spins or eccentric orbits. The Advanced LIGO detectors are also expected to be sensitive to less well-modeled gravitational wave sources such as galactic core-collapse supernovae. For such sources we use model-agnostic transient (or 'burst') gravitational wave searches. Burst searches are particularly useful to explore perhaps the most exciting potential gravitational wave signal of all: the unknown. As these searches are more susceptible to noise sources, current work explores methods to better differentiate astrophysical signals from detector noise.

Experience with programming in a terminal and/or via a remote connection is recommended.

GWs from continuous sources

This roughly amounts to something like a mountain sitting on the surface of a neutron star, the shape and height of which can teach us about how matter behaves at super-nuclear densities. Students will have the opportunity to look for potential LIGO signals that correlate with known pulsars in frequency and sky location, as well as sources corresponding to neutron stars not observed with light-based telescopes.

Experience with programming and Bayesian statistics is recommended.

GWs from stochastic sources

It is very likely that echoes of the Big Bang are currently reverberating around the Universe in the form of gravitational waves. We expect the superposition of these echoes with many overlapping, weak compact object merger sources form a detectable stochastic gravitational wave background. A key science goal for Advanced LIGO is to detect this background by searching for long-lasting coherent power between multiple gravitational wave detectors.

Experience with programming and statistics is recommended.

Measuring source properties from GW signals

Gravitational waves carry information about the astrophysical sources that create them, which can be measured with precision by comparing observed data to models and simulations. In particular, source masses, angular momenta, location on the sky, and distance from Earth (among other things) all affect the amplitude or phase evolution of an observed GW signal. Students who work on parameter estimation will be at the interface between theory and experiment, analyzing LIGO data and developing methods to improve our knowledge of the explosive sources of gravitational waves.

Interest in / knowledge of Python, signal processing, and Bayesian statistics is recommended.

Multi-messenger astronomy

Some of the GW signals that LIGO detects, such as the binary neutron star merger GW170817, will have gamma-ray, X-ray, optical/infrared, radio, or neutrino counterparts. In many ways this can be thought of as witnessing the same event with several different senses. But for most source types LIGO is the one to catch them first, so it's up to us to tell other astronomers where to look. Students who get involved in multi-messenger astronomy will analyze data and develop software to learn as much as possible from joint observations with other telescopes scattered across the world and in space.

Interest in / knowledge of Python, signal processing, image processing, and Bayesian statistics is recommended.

Black hole astrophysics

Numerical relativity is a powerful tool for simulating the gravitational wave signatures of binary black hole mergers, as well as the recoil response of the system after merger. One key direction in current research is using simulations, populations models, and observations of black holes to understand more about the evolution of black hole progenitor stars and binary black hole systems. Another direction is contributing to the body of waveforms that searches for modeled gravitational waves signals in LIGO data can draw on by improving the accuracy of phenomenological models and/or the efficiency of numerical simulations.

Experience with programming is recommended.

Theoretical astrophysics and general relativity

Breakthroughs in physics are often made at extremes, and the weakest of all interactions -- gravity -- is no exception. General relativity is the prevailing theory of gravity, which describes gravitation as curvature in space and time rather than as a force. Since the early 20th century, tests of general relativity were all done using measurements of Solar System objects where gravitation is relatively weak. However, with every LIGO observation of extremely compact sources such as neutron stars and black holes comes a unique opportunity to test general relativity using extreme spacetime curvature, pushing the theory to its limits. Students who work on such projects will test this foundational principle of modern physics using the cutting-edge LIGO experiment.

Knowledge of signal processing and Bayesian statistics are recommended; students will also learn a great deal about general relativity.