LIGO SURF 2017 ABSTRACTS

Using Tidal Deformation Signatures for Gravitational Wave Cosmography With Third Generation Detectors
Shreya Anand
Mentor: Alex Urban

The past detections of Advanced LIGO have shown that current generation detectors have the capability to detect binary black holes at redshifts up to 0.2. Next generation detectors, however, with a factor of 10 increase in sensitivity compared to Advanced LIGO, are predicted to detect even binary neutron star (BNS) and neutron star-black hole (NSBH) sources to higher redshifts. We analyze a method of performing cosmography with third generation (3G) detectors using gravitational waves from BNS and NSBH inspirals alone. One can relate the distance to a source obtained from the amplitude of the gravitational waves emitted to its redshift by breaking the mass-redshift degeneracy in the signal waveform, using the frequency at which tidal disruption and tidal deformability signatures are visible. In the third generation detector era, we assume that the NS equation-of-state is known; we determine the measurability of these tidal signatures for different values of the tidal parameter, Λ, a proxy for the compactness of the star. Using waveform approximants that are valid in both inspiral and postmerger regimes to simulate NSBH and BNS waveforms with matter effects, we whiten the advanced LIGO data stream, inject the BNS and NSBH signals into the data stream, and attempt to recover tidal deformability signatures for both types of systems. Then, we recolor the current generation data stream using the modeled noise spectra for the next generation detectors Einstein Telescope and Cosmic Explorer. We determine how well tidal signatures can be recovered for systems of different mass, spin and tidal parameters, and use this to determine placement of calibr0ation lines in the sensitivity bands of current and next generation detectors. We aim to provide useful information for setting the calibration requirements for future 3G detector so that cosmography with gravitational waves alone will be possible.

Investigation of the Impact of Seismic Noise on LIGO Interferometer Performance
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Mentors: Thomas Massinger and Jessica McIver

The purpose of the LIGO (Laser Interferometer Gravitational-wave Observatory) Scientific Collaboration is to detect gravitational waves as predicted by Einstein's Theory of General Relativity. According to this theory, the acceleration of asymmetric matter results in small perturbations in space-time due to a changing gravitational field. These distortions, called gravitational waves, can be detected with a network of highly sensitive laser interferometers. However, due to this sensitivity the detectors are greatly affected by changes in the environment, such as ground motion, lightning strikes, storms, and other forms of inevitable seismic noise. Transient bursts of noise affect the ability of the detectors to recover signals. Using pyCBC software, we investigated the changing sensitivity of the detectors during periods of elevated seismic noise, ranging from 200nm/s to 700nm/s earthquake band ground motion. We found that changes in detector sensitivity to binary neutron star (BNS) waveforms differed from that to binary black hole (BBH) and black hole neutron star (NSBH) waveforms, and we analyzed types of detector noise which might be causing this decrease in sensitivity.

Towards a Fast Frequency-Domain Waveform Model for Kicked Black Hole Binaries
Katie Chamberlain
Mentors: Davide Gerosa and Rhondale Tso

Generic black hole binaries emit gravitational waves anisotropically due to mass and spin asymmetries. The gravitational waves carry linear momentum away from the binary in a preferential direction that causes the binary to recoil during the late inspiral and merger phases of evolution. The black hole recoil (or kick) results in emitted gravitational waves that are Doppler shifted during merger-ringdown as a function of the kick velocity. Gravitational wave observations of such a Doppler shift will allow for the first direct detections of black hole kicks from a binary coalescence. We extend existing phenomenological analytic frequency-domain gravitational waveform approximants to model gravitational waves from a kicked back hole binary. Our kicked frequency-domain model is quick to calculate and can be used to (i) explore kick detectability over large regions of parameter space, (ii) address degeneracies that are present between kicks and other binary parameters, and (iii) place projected constraints on black hole kick velocities with current and future detectors.

Electromagnetic Counterparts of Advanced LIGO Binary Black Hole Merger Events
Cierra Coughlin
Mentor: Alex Urban

The Advanced LIGO (Laser Interferometer Gravitational Wave Observatory) detectors have successfully detected gravitational wave signals from four binary black hole (BBH) mergers, GW150914, LVT151012, GW151226, and GW170104. These discoveries have prompted follow-up campaigns to search for any electromagnetic (EM) counterparts to the gravitational wave transients, which have yielded no strong candidates except for the detection of a weak gamma ray transient 0.4 seconds after GW150914 in the sky localization of this gravitational wave event. Our motivation for this project is therefore to study various models of binary black hole mergers to predict whether or not any EM emission should be expected, and if so, what kind, how much, and when. While we currently do not believe that BBH mergers produce EM counterparts, the results of this study will help assess the prospects of these campaigns given our current observing limitations and will ultimately be an important step forward for future work in multimessenger astronomy.

Computational Costs of Novel Parameter Estimation Methods
Zhanpei Fang
Mentor: Rory Smith

The aim of this project is to determine the computational cost of applying the Bayesian methods of source parameter estimation to gravitational-wave searches for LIGO. By implementing parallel-tempered Markov-chain Monte Carlo (PTMCMC) with the Message Passing Interface (MPI) protocol, which distributes computational tasks across a cluster of parallel CPUs, one might in theory be able to complete data analysis in near real-time. The ability to complete parameter estimation analyses in near real-time would have important implications for searches, because parallel tempering also directly computes the evidence term and thus the Bayes factor, which allows us to select between models describing the data as either noise of noise plus signal. The Bayes factor is proposed as an alternative detection statistic that may be more robust than the signal-to-noise ratio (SNR), as using Bayesian evidences may result in fewer false dismissals of real signals. The SNR is cheap to compute, while the computational cost of calculating the Bayes factor is currently unclear. This project quantifies the cost of a search algorithm that uses the Bayesian methods of parameter estimation, with implications for the ways in which LIGO conducts data analysis.

Squeezing Quantum Noise With Waveguides
Dhruva Ganapathy
Mentor: Andrew Wade

The LIGO gravitational wave detectors use a modified version of the Michelson Interferometer designed to detect strain signals in the order of a few parts in 10^-24. The vacuum fluctuations entering interferometer through the antisymmetric port are the origin of shot noise in the gravitational wave channel that limits the design sensitivity over most of the detection band. Squeezing entails preparing a special quantum state of light where for a pair of non-commuting observables, such as phase and amplitude of a light state, most of the uncertainty is reduced in only one of the variables (phase or amplitude) at the expense of the other. The aims is to convert vacuum to squeezed vacuum, which has phase fluctuations smaller than normal vacuum. Currently, free space optical parametric oscillator squeezers are being integrated into Advanced LIGO, with a goal of a 6 dB reduction in quantum noise. Squeezing is reduced by losses caused imperfections in optical surfaces, substrates and polarizing optics, and, by imperfect spatial overlap with the interferometer fields. In this project, we attempt to make an alternative type of squeezer in a waveguide rather than free space cavity enhanced non-linear devices and that offer to simplify operation and eliminate some sources of noise that affect free space squeezing. We will be using a rubidium infused PPTKP waveguide as our source of squeezed light. By the end of this project, we hope to demonstrate its operation as a source of continuous wave squeezed states and evaluate its viability as an alternative technology for enhancing the quantum noise performance of future gravitational wave detectors

Characterizing Bulk Scatter in Crystalline Silicon
Amani M. Garvin
Mentor: Andrew Wade

In current gravitational wave detectors, coating and substrate Brownian noise dominate around 10Hz. This noise depends on the material's temperature, so in order to decrease this noise cryogenic temperatures are projected to be used. However, fused silica, which is currently used as the mirror's substrate and test masses, has high mechanical losses at cryogenic temperatures. In order to decrease the detector's Brownian noise efficiently, we must change the substrate material. Crystalline Silicon is a great proponent due to its low mechanical loss at low temperature, however its optical properties have to be investigated. The scope of this work is to characterize the scatter in Magnetic field-grown Michael Czochralski silicon. Scatter from the materials in the detector can add phase noise, contribute to cavity loss, and disrupt squeeze states. In order to analyze scatter from silicon, a motorized scatterometer was built to measure the scattered field. Since Rayleigh scattering is expected, that is explored here in order to be compared to the results.

cWB Optimization for GW Signal Waveform Reconstruction Stage
Yanqi Gu
Mentor: Sharon Brunet

GW signal Wave Reconstruction has been profiled as a highly CPU intensive and time-consuming step in the cWB pipeline. The aim of this project is to give deeper profile of the time costs of cWB pipeline, understand and address cause(s) for the likelihood WP section of CWB which is most time consuming, and find a probable candidate for porting to execution on a GPU and Many Integrated Core (MIC) architecture, using a specified collection of parameters (input configuration) specified by the code developers. The optimization focuses on: 1) use a many core system to run the likelihood WP in parallel 2) port the time-consuming code to GPU for specific parallelization 3) optimize the data structure of reconstruction for parallel access.

Deep Learning for Gravitational Wave Searches
Sarah Hale
Mentor: Rory Smith

Currently gravitational wave signals are detected by matched filtering using data from the main astrophysical data channels. Unfortunately, there are transient sources of noise which limit the effectiveness of this method, so many signals of moderate SNR cannot be classified for sure as true signals or not using just the astrophysical channels. We expect to be able to improve upon this by incorporating other auxiliary data channels which inform us about environmental noise, which could correlate with transient noise in the astrophysical channel. These noise sources are coupled to the detector nonlinearly, so modeling their effect on the detector's noise from fundamentals is difficult and not practical. Instead, we propose to use deep learning. A well trained neural network could potentially learn how environmental noise affects the detector without a priori knowledge of how the noise couples with the detector. This project will investigate how deep learning can help differentiate signals from transient noise using well chosen auxiliary channels, potentially outperforming current matched filter searches.

Temperature Control and Coupled Oscillator Modelling for LIGO Voyager
Jordan T. Kemp
Mentor: Brittany Kamai

In 2022, the Laser Interferometer Gravitational-Wave Observatory (LIGO) project will undergo its transition from its third iteration, A+, to its fourth iteration, Voyager. LIGO Voyager intends to reduce coating thermal noise by operating LIGO at cryogenic temperatures and replacing fused silica optics with silicon. My summer research with the Voyager group addressed the cooling of the planned thermal shields surrounding the LIGO optics using copper straps, the parameter optimization of a ringdown experiment to determine the loss of optics coatings, and determining the temperature dependence of the eigenfrequencies of bulk silicon to develop a method of decoupled temperature determination. Our findings suggest that the F designated copper straps cool more efficiently than S and L straps with a thermal conductivity constant of $.06721 \pm .0009$W/K. We have produced an approximation of the error budget for the ringdown measurement which suggests that the uncertainty in the loss angle of the disk and coupled system most strongly influences the error in our loss measurement, and precise measurement of these parameters will result in the most precise results. We have also produced an apparatus for calibrating the temperature dependence of the eigenfrequencies of silicon disks.

Searching for Echoes of Gravitational Waves from the Coalescence of Exotic Compact Objects: A Bayesian Approach
Ka-Lok (Rico) Lo
Mentor: Alan Weinstein

The ringdown part of the gravitational wave from the merger of two black holes was suggested as a probe of the internal structure of the remnant compact object, which may be more exotic than a black hole. Cardoso et al. pointed out that there would be a train of echoes in the late-time ringdown phase for different types of exotic compact objects (ECOs). Abedi et al. claimed that they have found evidence of echoes in binary black hole mergers detected by LIGO. In this project, we aim to search for echoes of gravitational waves in the three detections LIGO had, and verify their results using their phenomenological model with Bayesian analysis instead. We perform a Bayesian parameter estimation on the parameters related to echoes and Bayesian model selection of presence of echoes versus their absence, to provide stronger evidence for the presence or absence of echoes in these detections. The analysis technique developed in this project could be repeated with different models to provide even more robust evidence of the existence of echoes from ECOs.

Development of Remote Controls for the Motorized Polarization Controller in LIGO's Arm Length Stabilization System
Caroline Martin
Mentor: Daniel Sigg

The arm length stabilization (ALS) system allows the arms of the interferometer to be locked separately, decoupling these two degrees of freedom from the Fabry-Perot and recycling cavities; this system faces issues with polarization drift along fiber optic cables, however, due to factors such as thermal stress, mechanical stress, and irregularities in the shape of the core. If this drift is not corrected, the mismatch in polarization can prevent the interferometer from observing. Currently, this drift is corrected by a motorized polarization controller (MPC) that must be adjusted manually on a regular basis. This project aims to develop comprehensive, user-friendly, and robust remote controls for the polarization controller to streamline the drift correction. The controller was connected through a serial port to TwinCAT Programmable Logic Controller software, on which the controls were written in IEC-1131 structured text. User input through a graphic interface is interpreted and written to this code, allowing the user to remotely control the polarization. In the future, this program could be used to automate the correction process.

Testing General Relativity With Binary Black Hole Mergers
Radha Mastandrea
Mentor: Alan Weinstein

The several recent detections of gravitational waves (GWs) by the Laser Interferometer Gravitational-Wave Observatory (LIGO) has provided researchers with the first opportunities to test general relativity (GR) in the strong-field and highly-dynamical limit. Qualitative tests of the agreement between LIGO's GW observations and classical GR have already been done; we aim to carry out more quantitative tests in terms of controlled, parameterized deviations from GR. In this project, we run a matched-filter analysis on LIGO's prior detections using templates with known amplitude and frequency deviations from those predicted by GR to a construct a probability function on the deviations. We then simulate a number of BBH merger waveforms with similar deviations from GR, use Bayesian analysis to recover the deviation, and provide an estimate of the number of GW detections from BBH mergers necessary to establish a given deviation from classical GR.

GeNS and Electrostatic Suspension Systems
Mariia Matiushechkina
Mentor: Brittany Kamai

The third generation of interferometric gravitational wave detectors will use silicon test masses and silicon suspension systems kept at low temperature (123K). For this reason it is important to find the appropriate high-emissivity coating to cool the detectors' test masses and the high-reflectivity dielectric coating so both introduce the lowest additional thermal noise. The project includes the characterization of the Gentle Nodal suspension (GeNS) experimental set-up for measuring mechanical loss angle of the thin film coatings on silicon at cryogenic temperature and developing for future precision experiments a new low-loss suspension system that uses electrostatic field to levitate a disk without mechanical contacts. The second part consists of designing the Printed Circuit Board of the electrode pattern, assembling the set-up and optimizing its parameters with finite element modeling (FEM) software like COMSOL Multiphysics. The aim is to compare noise that appears due to GeNS and electrostatic suspension systems. This project will help to conduct higher-precision loss measurements of test masses for future development of gravitational wave detectors.

Determining Remnant Parameters From Black-Hole Binary Systems
Nicholas Meyer
Mentor: Mark Scheel

Computing the remnant mass, spin, and recoil of a black hole binary in principle requires numerical relativity (NR) simulations. Unfortunately, NR simulations cannot be performed quickly enough for some waveform models and LIGO data analysis routines that require remnant parameters. We develop phenomenological formulae for the remnant mass, spin, and recoil of binary systems given arbitrary initial spins and mass ratios. We do this by constructing fits to NR simulations in the SXS catalog. In particular, we explore the use of Gaussian Process Regression. We use the SXS catalog to compare the accuracy of our remnant mass and spin fits with that of the remnant mass and spin formulae in the Effective One Body (EOB) waveform model in the LSC Algorithm Library (LALSuite).

Characterization of Test Mass Scattering
Jigyasa Nigam
Mentors: Gautam Venugopalan and Johannes Eichholz

The scattering of light in LIGO has dual demerits, firstly this scattered light can reflect off other objects in the setup and couple back into the instrument, adding noise and secondly, the light power that is lost to scattering leads to a lower signal-to-noise ratio in the interferometer. Therefore, in order to increase aLIGO's sensitivity to gravitational waves, light scattering must be reduced. As a part of the laser beam scatters or deviates from the path governed by specular reflection, on account of roughness of the test mass surfaces and instead of yielding a coherent, collimated beam, the intensity pattern becomes angle dependent. This is modeled by the Bidirectional Reflection Distribution function (BRDF). The project aims to install, interface with and calibrate Gigabit Ethernet cameras to image the test masses, obtain the BRDF for light scattering at the test mass and identify point-scatterers in the images of test masses through the techniques of aperture photometry. These measurements could be used to quantify scatter loss and identify measures to minimize this loss.

Inferring the Astrophysical Population of Black Hole Binaries
Osase Omoruyi
Mentor: Alan Weinstein

LIGO's gravitational wave detections have not only proved the existence of black hole binaries but also confirmed the presence of stellar mass black holes larger than 20 solar masses. Our project aims to study these binaries and their mass distribution throughout space. Currently, LIGO has made 4 detections of binary black hole mergers. However, this sample is too small to draw significant conclusions about the mass distribution. To circumvent this problem, our project looks towards the future. Within the next 10 years, LIGO expects the number detections to rise significantly. With these future detections in mind, our project utilizes simulated data to generate a large population of black hole binaries. From our general astrophysical knowledge about black holes and nature, we expect the underlying population to fall like a power-law in the mass of the larger black hole, $M^{-\alpha}$, in which α is the power-law index. Using the large sample of events our simulations provide, we seek to constrain the value of the power-law index more precisely and accurately. This, in turn, will allow us to make inferences about how black hole binaries have formed and evolved over time.

Measuring Optical Scattering Off LIGO Test Masses
Christian Pluchar
Mentor: Keita Kawabe

The LIGO interferometers utilize precisely manufactured test masses made of silica glass in order to detect the small displacements due to gravitational waves. A number of optical techniques are used to increase the laser power circulating in the detector into the kilowatt range, including Fabry-Perot cavities and power recycling, increasing sensitivity. Optical scattering off the test masses introduce noise into the detector output and reduce the amount of light in the resonant cavities of the interferometer, reducing sensitivity. The power of the light scattered off the test mass by the main laser was measured using high resolution digital camera sensors, allowing for more detailed measurement of the LIGO Hanford test masses. Two DSLR cameras were calibrated to find the relationship between the power of light incident on the sensor and the digital output of the camera. While the interferometer was locked, a series of images were captured at different exposure times. Using the calibration of the camera and information on the placement of the Photon Calibrator (Pcal) cameras used, an estimate of the power scattered by the test masses was calculated. To further characterize the camera sensor performance, the photon absorption rate of the camera was measured.

Online Detector Characterization Using Neural Networks
Roxana Popescu
Mentors: Rana Adhikari, TJ Massinger, and Jess McIver

Data obtained from LIGO has noise that comes from many sources. To be able to better distinguish signals from the noise, it is important to characterize the type of noise observed. Machine learning algorithms can be used to look for patterns within the data and to classify the data into distinct categories. We are using clustering algorithms, such as kmeans, to identify earthquakes in seismic noise data. To test how well the clustering algorithms work, we compare the clusters to the times when earthquake waves reach the detector site. This comparison will be used to evaluate how well a neural network determines earthquakes compared to the clustering algorithms.

Optimization of the Coating Ringdown Measurement Laboratory Electrostatic Actuator With Finite Element Modeling
Zachary A. Rose
Mentor: Gabriele Vajente

In aLIGO one of the most substantial displacement noise sources is thermal noise, with the mirror coatings as the dominant source of this noise. The most viable option to limit this noise is producing mirror coatings with a smaller loss angle. The loss angle can be studied by exciting the resonant modes of a sample with an electrostatic drive (ESD) and then measuring their exponential decay time, or ringdown. For experimental ease, a 75 mm fused silica disk is used to simulate the LIGO test mass. To improve accuracy, it is important that the electrostatic actuator excites all of the fundamental modes of the sample as much as possible. The goal of my project was to determine the optimal shape of the actuator to drive all of the fundamental vibrational modes maximally. I accomplished this by modeling the current ESD in COMSOL, a finite element modeling software. Then I wrote scripts in MATLAB to iteratively sweep through various spatial parameters to determine the optimal geometry. Finally, I tried some non-standard geometries to determine the best design.

RF Leakage Studies and GPS Signal Jitter Analysis
John Schaefer
Mentors: Dick Gustafson and Keita Kawabe

RF signals are mainly responsible for putting the interferometer into lock, an important task that allows LIGO to be sensitive enough for gravitational events. However, RF signals can cause leakage that can interfere with other electronics. One culprit is DC ground isolation units. When performing a spectrum analysis using an RF analyzer and measuring cabling ground to cabling ground, it was found that there were significant signal leakages as high as ~80 mV when it should ideally be 1 mV. Upon investigation and testing, it was determined that the leakages were due to small or absent capacitance along the units' enclosures. After modifying the capacitance of the units and then testing for insertion loss and phase delay, an order of magnitude decrease in RF leakage was observed. Timing, from both GPS and a cesium clock, is another important aspect of LIGO which dictates much of how measurements are taken. When several atomic clocks are tuned to be in phase with each other and triggered on a 1 PPS GPS signal, the clock signals jitter on the order of nanoseconds. Given that this is tested against multiple clocks, GPS must be the source of the jitters. This may not have a large effect on short term measurements, but for long term integrations such as continuous wave searches, this error may become a problem. After long term data acquisition and analysis, it was found there were distinct periodicities in the jitter. Further analysis was also done to determine whether these jitters were random or deterministic.

Characterization of Angular Noise Coupling Into Differential Arm Length of the LIGO Livingston Detector
Brian C. Seymour
Mentors: Arnaud Pelè, Marie Kasprzack, and Adam Mullavey

Mirror misalignments of the Fabry Perot Cavity mirrors can change the cavity length. This source of noise can couple into differential arm length of a gravitational wave detector. This paper explores length change due to angular misalignment, and then extends it to the effect of angular noise on the two cavity system. We will also provide results from an experiment where we use mechanical modulation to measure the main angular components that are believed to couple most strongly to the differential arm length. The angular noise coupling model and experimental results will be used in combination to understand the angular noise contribution to differential arm length noise.

Mode Spectroscopy for Mirror Metrology
Kaustubh Singhi
Mentor: Koji Arai

The mirrors in the LIGO detectors are not ideal, and have imperfections due to various reasons such as manufacturing defects, thermal defects, etc. These imperfections introduce a total loss in the light resonating inside the cavity arms of the interferometer and thus have to be budgeted in the total budget loss. The total loss in aLIGO is estimated at ~100ppm out of which ~20 ppm is budgeted for the mirror imperfections, more commonly called the mirror figure error. It is the second highest contributor to the total intensity loss and hence it is significantly important to be able to characterize this loss. Mode Spectroscopy is something that we will be using to do this. We will do our experimentation on the 40m prototype, which is quite similar to the aLIGO. We will scan the cavity for various 'Higher Order Modes' and compare our results with the ideally expected values. Using this data, we will try and produce a mirror map telling us what are the defects in the mirror and how much is the total cavity loss due to the mirror figure error.

Implementing Real-Time Calibration in Advanced LIGO Control Software
Dane W. Stocks
Mentor: Joseph Betzwieser

The digital error and control signals of Advanced LIGO's differential arm length control servo are used to reconstruct gravitational wave (GW) strain, h(t). Currently, three different calibration pipelines produce h(t) with varying errors and latencies. The real-time operating system in the front end computers runs CALCS, which performs infinite impulse response (IIR) filtering and control operations on 16384 Hz clock cycles. Current limitations of these filters yield systematic errors which a second pipeline, the GDS, corrects in low-latency using finite impulse response (FIR) filtering on computers distinct from the front end computers. The third pipeline, the DCS, implements FIR filtering to condition archived data, and is used to recalibrate entire data sets when dropouts occur in real-time. To prepare for O3 in late 2018, we construct a new, self-contained calibration pipeline in the front end computers which uses FIR filtering to calculate h(t). This new front end model will replace the current calibration system in place, removing the redundancy of multiple, separate pipelines while reducing latency in control room access to calibrated GW strain.

FPGA Based Heterodyne Frequency Readout
Vineeth Krishna Talasila
Mentors: Johannes Eichholz and Christopher Wipf

In the Advanced LIGO detectors, the coating Brownian noise is expected to be the largest of the thermal noise sources at their most sensitive frequency band. The LIGO Voyager upgrade aims to reduce this thermal noise by operating the optics at cryogenic temperatures and replacing fused silica test masses with silicon. In order to characterize Brownian noise in the candidate coatings on silicon mirrors, two similar optical cavities which are dominated by coating Brownian noise are used in a differential measurement. Two independent lasers are locked to the cavities which are then interfered to produce a beat signal, whose frequency noise represents the differential length fluctuations due to coating Brownian noise. An All Digital Phase Lock Loop(ADPLL) was designed and implemented in a Field Programmable Gate Array(FPGA) on a Red Pitaya board, to demodulate the frequency information from the beat note and pass it on to the Data Acquisition system. Based on the input noise measurements of the Analog to Digital Converter, the required readout noise of 1mHz/sqrt(Hz) from 10Hz to 10kHz can be achieved. The ADPLL comprises of a Numerically Controlled Oscillator(NCO) which is locked to the input signal, two digital IIR low pass filters in cascade and a PI controller as a servo for the frequency readout. Several compression techniques were used to reduce the size of Look-Up Tables in the NCO, due to the limited availability of ROM.

Laser Spectroscopy for Mirror Metrology
Naomi Wharton
Mentors: Koji Arai and Rana Adhikari

The LIGO gravitational wave detectors are specialized Michelson interferometers each with two arms that are four kilometers in length. Each arm of the interferometers forms an optical cavity capped by semi-transparent mirrors by which laser light is transmitted and reflected. Imperfections on the surfaces of these mirrors cause optical power losses in the cavities that must be minimized for optimal performance. In a cavity with perfectly spherical mirrors, the modes of a Gaussian beam will resonate at equally spaced frequencies. In reality, surface perturbations cause the resonance peaks of several higher-order (Hermite-Gaussian) modes to shift in the cavity transmission spectrum. The aim of this project is to use cavity scan techniques to measure deviations in the spacing of these higher-order modes. By comparing these experimental deviations with theoretical mode spacings, we can learn about the physical properties of the cavity mirrors. Our ultimate goal is to use Bayesian inference techniques to recreate the surface perturbation map of a mirror from its cavity transmission spectrum.

In-Vacuum Heat Switch
Adele Zawada
Mentors: Christopher Wipf and Johannes Eichholz

LIGO Voyager is a design concept for a cryogenic interferometric detector that aims to reduce the thermal noise in the mirrors by switching to crystalline silicon substrates and operating at 123K. A clamping mechanism is being designed that can attach to the mirrors to provide fast and efficient cooling, and then be released during operation to prevent coupling seismic noise to the system. Studying the rate of heat transfer across the interface between polished silicon and the contacting surface of a potential heat switch mechanism is important research for this project. By creating a temperature gradient inside a cryostat with a known amount of injected heat and measuring the temperatures on both sides of the interface, it is possible to determine the heat flow. This method was used investigate how the thermal heat transfer of the interface changes depending on contact pressure and surface quality. The set up was also used to investigate the heat flow across optically bonded silicon pieces to evaluate the effectiveness of different curing strategies post-initial contact.