

**LIGO Abstracts
Summer 2009**

Analyzing Elastic Deformations of Test Masses in LIGO

Mahmuda Afrin Badhan

Mentors: Michael Landry, Rick Savage, and Phil Willems

Initial length calibrations of kilometer-scale gravitational-wave detectors assumed test masses behaved as rigid bodies within the audio detection band ($\sim 40\text{Hz}$ - 7kHz). Studies done by S. Hild in 2006 [1] on GEO600 test masses depicted deformations in the form of flexure caused by application of local forces. Assessing these surface displacements using the Gaussian beam of the interferometer has shown increasing divergence from the pendulum response for frequencies near and above 1 kHz. Similar behavior has been observed in LIGO end test masses (ETMs). We have studied the behavior of test masses under the influence of sinusoidally varying forces using the finite-element modeling software COMSOL 3.5. A weighted displacement variation due to the flexure is dependent on radial distance of the force application and stiffness of mass. We employ this understanding of test mass flexure to suggest a compensation scheme for the length calibration procedures of LIGO 4km interferometers.

[1] Hild, S., Photon Pressure Induced Test Mass Deformation in Gravitational-Wave Detectors, University of Hannover, October 5, 2007

Design and Analysis of a Telecentric ETM Imaging System

Jesse Amato-Grill

Mentor: Mike Smith

In order for the arm cavity (AC) of Advanced LIGO to remain on-resonance, the beam must be centered on both the Input Test Mass (ITM) and End Test Mass (ETM). The purpose of this study is to develop an optical system, located on an optical table behind the ETM, which detects the angle and lateral displacement of the beam in the AC; the error signal generated by this system will be used to control servos that align the beam. Additional constraints include limited physical space for the ETM Imaging System (EIS), the surface area of the optical detectors, and a requirement that the beam angle and lateral displacement measurements will be minimally affected by (small) rotations of the optical table itself. Employing the paraxial approximation, the ABCD formalism for Gaussian beam propagation was used to model a system of ideal lenses which images both the beam waist inside the AC and the wavefronts incident on the ETM, utilizing Gouy Phase as a parameter to distinguish between the two imaged planes. The same system was then remodeled using stock CVI lenses, while the beam-reducing refracting telescope was replaced with an off-axis spherical mirror telescope.

Construction of a Low Noise Voltage Controlled Oscillator for Use in Advanced LIGO

C. Isaac Angert

Mentor: Daniel Sigg

We have assembled and are testing a low noise voltage controlled oscillator (VCO) to be used in upgrades to the laser frequency control loop at the LIGO interferometers as part of the Advanced LIGO project. We aim to achieve close in phase noise below -150dBc at 10kHz carrier offset, combined with a frequency range of plus-minus 1MHz at a nominal 80MHz output frequency. Tests performed on the VCO show that the design achieves its noise goals, although more tests are needed to establish its phase noise performance. We give a summary of the VCO design and theory and an overview of the work accomplished for the project thus far.

Characterization of Hierarchical Searches for Continuous Gravitational Waves

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Mentor: Gregory Mendell

The Einstein@Home project searches for continuous gravitational waves, such as those emitted by a non-axisymmetric rotating neutron star. If they could be detected, the ellipticity of the star could be derived, and that could be used to determine its composition. In the code of Einstein@Home, there are two different search methods: the Hough search and the StackSlide search, which act on the maximum likelihood statistic. Currently, the Hough search is used. To test which of the two search methods is the most efficient at detecting gravitational waves, a script in python was written to run the C codes to make fake data with an injected signal and perform a hierarchical search on the data. The python script did one-thousand iterations of this for each amplitude of the injected signal for both of the search methods. When comparing the results of the StackSlide search and the Hough search, the Hough search was found to be more efficient. Because of computational time, the simulations were scaled down from what would actually be done, and to further explore the question, it would be good to create more accurate simulations.

Optical Levers

Iain Barr

Mentor: Riccardo DeSalvo

The optical lever system at the Laser Interferometer Gravitational-Wave Observatory (LIGO) is used to make precise measurements of the angular position of optical components. In this paper I will investigate various factors that effect the optical lever system planned for advanced LIGO along with estimates of error found experimentally and ways to limit them. I will also make a comparison between the use of a CMOS camera and a quad photodiode (QPD) for detecting signal from the optical lever.

Damage Indicators for Indium-Gallium-Arsenide Photodiodes

James S. Benhardus

Mentor: Vernon Sandberg

An electrical model of the Indium-Gallium-Arsenide (InGaAs) photodiodes used at LIGO Hanford Observatory (LHO) is developed. Dynamic resistance, saturation current, open-circuit voltage and short-circuit current is measured. The noise profile for various light sources is analyzed, and primary sources of noise at various frequency bands is determined. Changes in dynamic resistance and leakage current as indicators of photodiode damage is explored.

Wiener Filter Optimization for Seismic and Acoustic Noise Cancellation at the LIGO 40m Interferometer

Clara Bennett

Mentors: Rana Adhikari and Jenne Driggers

In order to detect gravitational waves, an interferometric detector must be sensitive to extremely small changes in length. As such, isolation of the detector components from outside vibration is imperative to prevent the signal from being obliterated. However, no isolation system can ever completely filter noise from the instrument, so we must try to subtract the remainder from the measurements. The essence of Wiener filtering is to independently measure sources of noise—in this case, through seismometers, accelerometers, and microphones—in order to estimate their contribution to the signal error and remove it. Being unable to measure every degree of freedom for every interferometer element, we sought to find the configuration of witness instruments at the LIGO 40m lab that optimized Wiener filtration. The isolation system, represented by experimental motion transfer data and a simple analytical model, was studied to determine which modes are likely to contribute the most to the error and to avoid blind optimization attempts. Finally, a careful assessment of the noise in the witness sensors and the data acquisition path provides an estimate of the best possible noise cancellation that can be achieved with the given set of instruments.

Investigation of Silica Fibers in Advanced LIGO Suspensions

Andrew D. Bohn

Mentors: Alastair Heptonstall and Norna Robertson

When the LIGO interferometers are upgraded to their 'Advanced' configuration, their sensitivity will be so great that they will be limited at low frequencies by the thermally excited motion of the atoms in their mirror suspensions – Brownian noise. The aim of this project is to investigate key suspensions upgrades, vital to reducing detector thermal noise, increasing sensitivity and allowing LIGO to see further into the universe. High strength and low mechanical energy losses are two key properties of fused silica fibers, the proposed suspension material for Advanced LIGO. With 400 micron diameter fibers, we measured strength against polishing time to establish how quickly surface abrasions heal. A 50-minute polish produced fiber strengths over 65 kilograms without establishing an upper limit, however the data indicates that additional polishing would yield diminished effects. Five 288 micron diameter fibers were pulled and broke above 30 kg, the strength requirement. Such a diameter reduction would reduce the vertical bounce frequency peak by a factor of 1.39 in future enhancements. We have modeled an experiment to verify the non-linear thermo-elastic theory implemented to significantly reduce noise in Advanced LIGO. Fibers with predetermined parameters have been pulled and preparations for future experiments are currently ongoing.

Photothermal Measurements of Optical Coatings for Advanced Interferometric Gravitational Wave Detectors

Robert H. Cole

Mentors: Eric Black and Greg Ogin

An important noise source for next generation gravitational wave detectors arises from the expansion of the test mass mirrors and the change in refractive index of the mirror coatings due to statistical fluctuations in the mirror temperature. These so-called thermo-optic effects were studied using a cavity-assisted photothermal experiment where the same laser was used to both cyclically heat a test mirror and probe the response using a Michelson set-up. The two orthogonal polarizations in the beam were separated into an amplitude-modulated "pump" beam and a phase-modulated "probe" beam. This enabled the Pound-Drever-Hall technique to be used to stabilize the laser frequency. The test mirror was placed at one end of a Fabry-Perot cavity increasing both the response of the mirror

and the sensitivity of the probe by a factor of the finesse of the cavity. By scanning across a range of pump frequencies, the experiment can be used to determine relevant material properties of mirror coatings such as thermal conductivity and the coefficient of thermal expansion.

Enhancing and Validating a New Very-Low-Latency Gravitational-Wave Search Pipeline

Mireia Crispín-Ortuzar

Mentors: Kipp Cannon and Chad Hanna

One of the main sources of gravitational waves are compact binary coalescing systems. The detection pipelines used in S5 and before are not capable of providing fast sky location information. A new low-latency, stream-based pipeline has been developed to address this shortcoming. The pipeline, still in prototype stage, aims to analyse the data and produce results in a short latency period, to allow optical follow-up. The improvement of this new LIGO detection software implies revising, testing and validating its different elements. Both the efficiency of the algorithm and its ability to process the signal and filter the noise need to be considered. This includes optimizing the template bank and developing and checking accurate and reliable chi-squared-like tests. We should be able to extrapolate any technique for multiple detectors, so that the already existing coincidence test may be improved and added to the low-latency pipeline.

Development of a GigE Phase Camera for LIGO

Zachary Cummings

Mentors: Joseph Betzwieser and Aidan Brooks

I have developed a phase camera that utilizes a CCD to spatially resolve the laser wavefront for the Laser Interferometer Gravitational Wave Observatory (LIGO). Since LIGO aims to detect fluctuations in space-time by means relative phase shifts in interferometer light, it is necessary to reduce the noise associated with thermal lensing effects on the mirrors. The ability to resolve the light with a multi-pixel CCD allows for the analysis of the relative phase and amplitude of each pixel which facilitates improved diagnostics as well as the development of a more precise thermal compensation system. I have found that a CCD camera with gigabit ethernet (GigE) capabilities can be used to image and quantitatively characterize heterodyne beats set to 1 kHz.

Effect of Mirror Size and Misalignment on LIGO Interferometer Performance

Logan R. Daum

Mentor: Hiro Yamamoto

The current Advanced-LIGO simulation software could not account for the effects of tilted mirrors in the interferometer. This functionality was added to improve the accuracy of the simulation. The code was first written in Python and then integrated into the existing simulation software in C++. The modification was successfully able to show the effects of tilted mirrors.

Implementing Timing Noise Corrections in Pulsar Data Analysis

Ina Domanska

Mentors: Pinkesh Patel and Joseph Betzwieser

Pulsars are a promising source for emitting detectable gravitational waves. The search algorithm relies on matching the actual signal with signal templates. The templates are sinusoidal waves with parameters that include frequency and frequency derivatives. Pulsars are known to both glitch, causing sudden changes to these parameters, and exhibit timing noise, which is a slow random walk in phase and frequency. These effects reduce the sensitivity of the search. By including data from radio observations of astronomical sources we can correct for these glitches.

Multiply Resonant EOM for the LIGO 40-meter Interferometer

Stephanie Erickson

Mentors: Rana Adhikari and Koji Arai

The Laser Interferometer Gravitational-Wave Observatory (LIGO) uses a Michelson interferometer with Fabry-Perot cavities to sense strains induced by gravitational waves. Length sensing and control is achieved through locking the optical cavity lengths to the laser wavelength. For locking, an electro-optic modulator (EOM) is utilized to modulate the phase, creating frequency sidebands. For the upgrade of the 40-meter prototype interferometer, used to test systems before implementation in the full-scale observatories, there will be three modulation frequencies: 11 and 55, and 29.5 MHz, used for control of the mirrors in the main interferometer and mode cleaner, respectively. The purpose of this project was to design, build and test a triply resonant circuit for the 40-m upgrade, allowing three modulations to occur inside one EOM rather than several, reducing wavefront deformation, power loss, and problems with alignment. Resonance will allow for lower driving voltages and suppression of harmonics. The designed circuit has resonance at the necessary frequencies, with roughly equivalent gain and an impedance of 50Ω at each peak. Several iterations of the circuit were built, and the performance of each was evaluated by measuring the transfer function and impedance, and by observing the sidebands using an optical spectrum analyzer.

Comparative Study of Losses in Maraging Steel and LM001 Zr-Based Bulk Metallic Glass in a Geometric Anti Spring Filter

Pu Gong

Mentors: Riccardo DeSalvo and Andrey Rodionov

The dissipation properties of the maraging steel which are widely used in the seismic isolation system have been studied by using a Geometric Anti Spring (GAS) filter system. In our experiment, we use two mini GAS filter, one is made of Maraging steel and the other glass steel, side by side to find out the difference in properties between different materials. Our focus includes hysteresis, stabilization, and Q-factor.

Application of Used Percentage Veto for Data Characterization

Tomoki Isogai

Mentor: Gabriela Gonzalez

A challenge for Laser Interferometer Gravitational-Wave Observatory (LIGO) is to understand the origin of non-astrophysical transients that contribute to the background noise, obscuring real astrophysical signals. To help this effort, there are a number of environmental and instrumental sensors around the site, recording data in digital format, in "channels". In the past, we developed a method called "used percentage veto" to eliminate corrupted data based on statistical correlation between transients in the gravitational wave channel and in the auxiliary channels. In this project, we developed a way to apply this method for data characterization to find the physical origin of such transients. After identifying statistically correlated channels, a follow-up code clusters coincident events between gravitational wave channel and auxiliary channels, and thereby classifies noises by correlated channels. For each selected event, the code also gathers and creates information that is helpful for further human investigation. We present several successful examples on how this method helped identify the source of several transients. The method will contribute to find problems and to characterize data for the ongoing LIGO science run.

Numerical Thermal Noise Modeling

Melodie Kao

Mentors: Stefan Ballmer, Yanbei Chen, and Phil Willems

The limiting noise of Advanced LIGO will be thermoelastic noise, caused by the deformation of and consequent temperature gradient through the LIGO mirrors and coatings from laser radiation pressure. The elastic deformation of the mirrors not only causes the mirrors' center of masses to appear displaced, but it also combines with the change in temperature to change the coatings' indices of refraction. The consequent phase change generated in the laser light is similar to what would be detected when a gravitational wave passes through the observatories. While several analytical models of thermal noise and elastic noise have been developed already, these separate models fail to account for the coupling between the different noise sources. This project used Finite Element Analysis software to examine the expansion and temperature gradient produced in a simple mirror from a gaussian profile laser. This data was then combined in MATLAB to simultaneously model thermal and elastic noise. Central to this model is the integration method used, which can be applied to future more complex multi-coating models to achieve greater accuracy.

Studies of the Thermal Compensation System

Josh P. Lawman

Mentors: Phil Willems and Aidan Brooks

The thermal compensation system of Enhanced and Advanced LIGO must meet strict requirements. This project has characterized several performance parameters of the TCS laser system. We have measured the reflectivity of bare and AR-coated fused silica for 10.6 micron radiation and shown how the light power level reflected from the compensation plate can be minimized by proper choice of the input polarization. We have also characterized the vibrational noise performance of various optical mounts used by the TCS system, using single-element and quadrant infrared photodiodes. We discuss the relevance of these measurements to TCS performance.

Automation of the Search for Gravitational Waves From Soft Gamma-Ray Repeaters

Scott Liao

Mentor: Peter Kalmus

The Flare analysis pipeline is a gravitational wave search that focuses on the emissions of soft gamma-ray repeaters (SGRs). Upon reception of an events list, a list of SGR burst event triggers containing information including the sky position and relevant GPS times of the occurrence, the pipeline consults data from the LIGO interferometers. After processing, the pipeline either returns a positive result if gravitational waves have been detected with confidence or returns gravitational wave strain and gravitational wave emission energy upper limits.

The project focuses on making the Flare pipeline online. Rather than having to create events list and sending them in long after the actual event, the events can be processed as they occur. Triggered searches are initiated by new reports of SGR events. From the reports and data quality queries, relevant data segments are determined and an events list is created and sent for processing. The results are then recorded and the user notified once the job is complete. Real-time and automated processing will allow for up-to-date analysis during the sixth science run (S6).

Gravitational Wave Astronomy Using a Network of Advanced Interferometers

Anahita Maghami

Mentors: Anand Sengupta, Ajith Parameswaran, and Sanjit Mitra

The objective of this project is to find the best location where a new detector could be built and help improve the network of gravitational wave detectors. Specifically, the project is about finding enough figures of merit to justify the need of a new detector in the Indian subcontinent, called INDIGO. The main motivation is reviewing the figures of merit currently used to evaluate a new gravitational wave detector and modifying some metrics in order to become more precise about them. The current metric includes the assumption that all the detectors in the network are identical; however in our search we have released this assumption and we are able to examine different combinations of gravitational wave detectors. The results are being considered in two types of coincident and coherent search. The primary results show improvement in detection ability of the network in the cases where the technology used in INDIGO can compete with the technology of the rest of the detectors in the network. Namely, when INDIGO uses the technology of either LIGO or Advanced LIGO, the rest of the network has to be in the same track in which case, we can see a positive contribution to the network.

Mitigating the Output Mode Cleaner Beam Jitter Noise Contribution to the LIGO Interferometer Gravitational Wave Output

Denis Martynov

Mentor: Valery Frolov

An output mode cleaner (OMC) is used to remove the RF sidebands and higher order modes. Three tip-tilt mirrors (small suspended optics) are used to direct light into the OMC and to control the radius of the outgoing laser beam. Two of them have curvature for focusing the beam and one of them is flat. So the two tip-tilt mirrors form the mode-matching telescope. The motion of the tip-tilt mirrors produces the power fluctuations on the OMC output, which is indistinguishable from the DARM signal. In order to isolate the mirrors, they are suspended from a metallic frame using wires with a diameter of 370 μm . However, the vertical resonances of the wires due to their S-shape turned out to be near 150 Hz. These resonances contribute to the interferometer noise in the most sensitive frequency range 100-250 Hz. A possible solution of this problem is to add blade springs to improve the vertical isolation of the mirrors and make the suspension wires as straight as possible to move the eigen frequencies of the wire resonances out of the DARM most sensitive frequency range. Each wire is attached to one end of a steel blade, while the other end of the blade is holding the mirror frame. The spring blade vertical resonance is chosen to be 15 Hz. And the straight wire has the lowest vertical resonance at 350 Hz. This redesign of the tip-tilt mirror isolation is expected to reduce the OMC input beam jitter noise contribution to the DARM noise by at least two orders of magnitude in 100-250 Hz range.

Multivariate Statistical Classification of Inspiral Triggers

Tristan L. Miller

Mentors: Alan Weinstein, Anand Sengupta, and Kari Hodge

Gravitational wave detectors, including LIGO and Virgo, are used to search for gravitational waves from inspiraling compact binary systems such as pairs of neutron stars or pairs of black holes. Since the waveform for these systems has been modeled, the search uses matched filtering with template waveforms. The resulting candidate event triggers go through a data pipeline to filter out noise, but there always remain a significant number of "glitches", which are jumps in the noise that imitate gravitational wave signals. Unfortunately there is no single variable which distinguishes signals from noise. This project attempts to combine the existing variables into a single multivariate statistical classifier using the method of random forests of bagged decision trees, a type of machine-learning technique. This method is analyzed, characterized, and prepared for slotting into the data pipeline. Future research will attempt to optimize the technique, and use it to analyze data from S6, the next scientific run of LIGO.

Fiber Noise Suppression for Auxiliary Locking at LIGO

Connor Mooney

Mentors: Aidan Brooks and David Yeaton-Massey

The process by which a gravitational wave interferometer is brought to its operating point is called lock acquisition. A coupled signal recycling cavity will be added in the next generation of LIGO interferometers, making lock acquisition more difficult. This paper describes an auxiliary locking technique designed to decouple the arm cavities from the rest of the interferometer. In the proposed technique, a stable frequency reference is transferred to the far ends of the cavities via optical fiber and phaselocked to an auxiliary beam which is used to lock the cavities. We used a Mach-Zehnder interferometer to characterize the phase noise introduced to a 1064 nm beam by a 50m polarization-maintaining fiber. We are currently testing a noise cancellation scheme in which the beam is double-passed through the fiber and phaselocked to a frequency reference using an acousto-optic modulator. An analysis of noise sources and the results of noise cancellation will be reported in the presentation.

Investigating Subsurface Newtonian Noise and Deep Seismic Activity

Thomas O'Keefe

Mentors: Riccardo DeSalvo, Jan Harms, and Vuk Mandic

Current ground based gravitational wave detectors are unable to examine frequencies below approximately 10 Hz. Density fluctuations in the environment of detectors which cause variations in the gravity gradient field are one of the primary contributors to this lower frequency limit. The effects of these perturbations, known as Newtonian noise, cannot be shielded but can be reduced by constructing detectors further from the noise sources. Since density fluctuations are strong at the earth-air interface, Newtonian noise is significantly weaker deep underground than at the surface. Five seismometer stations were deployed at the Sanford Underground Laboratory in order to determine the magnitude of the gravity gradient noise at various depths. Construction of the stations required insulation of the seismometers from air currents and temperature fluctuations. Sensor boards were installed at the sites to monitor environmental conditions. The data produced by this array of stations might aid in determining the feasibility of modeling seismic activity so that Newtonian noise could be subtracted from gravitational wave detector data. Correlation measurements between the signals from neighboring stations would provide the most relevant results for this noise subtraction technique.

Vetoos for Transient Gravitational-Wave Triggers Using Known Instrumental Couplings

Aaron B. Pearlman

Mentors: Rana Adhikari and Ajith Parameswaran

The data of interferometric gravitational-wave (GW) detectors usually contain a large number of environmental and instrumental noise transients that are not easily distinguishable from possible GW signals. To perform a sensitive search for GWs, it is necessary to either eliminate or "veto" these noise artifacts. An earlier work (Ajith *et al.* 2007) had presented a "physical" veto strategy based on transferring the noise recorded at a detector subsystem to the detector output using measured transfer functions. The idea is that if the noise coupling is *linear* and the transfer function is unique, then the noise in an instrumental channel X can be transferred into the GW channel H using the transfer function from X to H . If a candidate GW trigger in channel H is causally related to one in channel X , then they must be consistent with the transfer function. Thus, the transferred noise can be cross-correlated with the data from the detector output to determine if a candidate trigger originates from one of the detector's subsystems. We implement this veto strategy in the data characterization of the LIGO detectors. We also generalize this strategy for the case of *bilinear* noise coupling.

Systematic, High-Statistics Testing of Source Localization Algorithms

Anthony E. Raymond

Mentors: Chad Hanna and Antony Searle

Using Bayesian statistical inference, the sky-location of certain astrophysical compact binary systems which are coalescing can be estimated to within a few square degrees on the sky. Software injections modeling these systems will be studied, and our ability to detect their sky-location will be analyzed as a function of their component masses and spin orientations.

Robustly Detecting Un-modeled Gravitational Wave Bursts with Bayesian Inference

Munier Salem

Mentor: Antony Searle

Gravitational wave bursts emanate from a large variety of astrophysical sources. For many of these events, the resulting LIGO device signals are poorly modeled. To compensate in these poorly constrained instances, correlations among multiple detectors may be used to extract a coherent signal from the noise. Methods of Bayesian inference provide powerful tools for this signal extraction, incorporating our prior knowledge of the expected signals into the data analysis. A rigorous Bayesian approach removes tacit assumptions of the frequentist methods, which can significantly improve detection of weak events. The analysis becomes more difficult when

glitches are included. The standard approaches assume that the only energetic deviations from noise are actual detections, and thus fail to reject these instrumental artifacts. To make LIGO analysis useful, we need to include prior information regarding the nature of energetic glitches. Compiling various statistics on the nature of these false alarms, we can inform our model by creating glitch priors to inform the analysis.

Development of an Optical Gyroscope for Ground Tilt Sensing in Advanced LIGO

Michelle Stephens

Mentors: Alastair Heptonstall and Peter King

The LIGO gravitational wave detectors are scheduled to undergo major upgrades, known as Advanced LIGO, to improve their sensitivity by a factor of ten. Low frequency isolation of LIGO's suspension systems from seismic noise is achieved actively using seismometers to feed forward to hydraulic actuators. The sensitivity of the seismometers to translations meets design specifications at detection band frequencies. As the interferometer length is altered by test mass motion at lower frequencies, however, there is a non-linear coupling of mirror motion to the output signal of the interferometer. Below approximately 10 Hz, coupling of ground tilt and rotation into the horizontal seismometer signal becomes problematic, and at lower frequencies the signal becomes dominated by tilt. Using a ground tilt sensor in parallel with the seismometers, it is possible to remove this component of the signal before driving the hydraulic stages. This sensor must be capable of sensing small rotations; at 0.2 Hz, the sensitivity requirement is 3×10^{-9} rad/ $\sqrt{\text{Hz}}$. A laser-based optical ring gyroscope, operating on the Sagnac principle, is currently being developed. Counter propagating beams will be locked to a triangular cavity using Pound-Drever-Hall locking. The rotation rate of the ring can be determined through the feedback signal used to lock the cavity. We report here on the current status and progress of this project.

Gravitational-Wave Image Analysis

Dan Stratman

Mentor: Kipp Cannon

Using a network of gravitational-wave antennas, an image of the gravitational-wave sky can be produced using procedures similar to those used in other imaging systems like radio interferometers. The geometric time delay between two detectors receiving the signal can determine from where in the sky a gravitational wave is coming to within a circle about the axis of the two detectors. LIGO detectors, however, suffer from being unable to accurately measure a large set of different "modes" on the sky, except for a small subset to which the detector is sensitive. To correctly identify the sensitive modes, a singular value decomposition technique is used to determine a new basis for functions on the sphere at one particular instant in time. Each mode is then rotated about Earth's spin axis and a second singular value decomposition is applied to get a basis for a full rotation. This new basis is then used both to represent the sky images and to correct for the modes that the detector pair cannot accurately measure.

Development of a Long Range Michelson Readout at the 40m Interferometer

Christopher A. Zimmerman

Mentors: Rana Adhikar and David Yeaton-Massey

Low noise performance of displacement sensors critical is critical to many fields, including to the operation of many systems within LIGO interferometers; high sensitivity (on the order of $1\text{E}-10$ m/rHz) sensors are used throughout LIGO, including optical suspensions, seismometers, and vibration isolation tables. Here several interferometric designs for a displacement sensor are examined in the context of readout scheme and shot noise limited sensitivity, with emphasis on attaining a power output function of two fringes in quadrature from the use of wave plates and other polarization components to induce phase shifts at two or more photodetectors. Many low noise sensors are currently available, but combining this with a large operable range has yet to be effectively done. Design changes that would lead to low noise sensors than are currently used are explored, including multiple photodetectors, outputs in quadrature, and maximizing the portion of power that is detected. A prototype of a dynamic long range Michelson readout based on the proposed designs was then constructed at Caltech's 40m interferometer and tested in order to optimize performance sensitivity and practicality.