### Development of Novel Lock Acquisition Procedures at the Caltech 40m Interferometer
Maria Baryakhtar
*Mentors: Rana Adhikari and Alan Weinstein*

A crucial step in an operational gravitational wave detector is lock acquisition, the process of bringing optical cavities to resonance and locking the detector, making it sensitive to gravitational wave signals. The narrow linear regime of the error signal makes the process of lock acquisition at LIGO a challenge; chance is largely relied on to bring degrees of freedom into range of the servo. In Advanced LIGO, acquiring lock will become even more challenging with addition of a fifth degree of freedom, so a reliable auxiliary lock acquisition system becomes crucial for operation. This report describes an auxiliary lock method that uses laser light distinct from the main beam to control arm cavity lengths via frequency doubled Pound Drever Hall locking. The accuracy required of the system is set by required cavity length precision, and noise limits of components of the system are presented and analyzed in this context. Optical fiber transferring laser light to the point of injection into detector arms is the limiting noise source. Fiber noise levels were measured with a Mach Zehnder interferometer and found to exceed limits set by desired locking precision. A fiber noise cancellation scheme is being implemented, and is expected to reduce noise below desired levels.

### Direct Observation of Noise Cancellation Due to Thermoelastic and Thermorefractive Effects
Eric Cahoon
*Mentor: Eric Black*

Thermal expansion and contraction of LIGO mirror coatings due to temperature variations serve to change the effective path length and phase of the laser beam in the arms; this is thermoelastic noise. Similarly, the indices of refraction of the mirror coatings change with temperature, which changes the phase of the reflected beam. There has been recent work done indicating that these two noise sources are correlated with one another and their effects may at least partially cancel. My project is an attempt to verify that this cancellation does exist as a step toward possibly using it in future mirror design. The experiment is done on a simple Michelson interferometer seismically and acoustically isolated from the environment. A chopped $CO_2$ laser provides cyclical heating of the mirror on which the test is performed, and allows control over the amount of coating participating in thermal expansion. Length changes in that arm due to thermal noise are readily visible in the output of the interferometer. For a number of mirrors with different metallic layers underlying their coatings, we hope to observe a definite cancellation and sign change of the phase at the calculated heating frequency.

### Understanding Cable Noise in LIGO
Chihyu Chen
*Mentor: Mark Barton*

Test masses and other key optics in LIGO are supported as pendulums to filter out noise from ground motion, and in the forthcoming AdvLIGO upgrade, these will be multistage pendulums. Some of them need to be fitted with multiple channels of sensors and actuators. The cabling that needs to be run between the levels may be stiff and heavy and can potentially degrade the vibration isolation or create thermal noise. The project has two components: (i) lab measurements to characterize different types and arrangements of cables. For each oscillation frequency, cabling is attached to a test pendulum, and the system's ringdown is measured, then compared to the ringdown of the test pendulum alone, producing the damping factor of the cabling. The test pendulum is designed to have a yaw frequency variation ranging an order of magnitude (0.136Hz to 1.23 Hz) to find the damping factor as a function of frequency, the most important parameter. The stiffness and mass are also measured. (ii) computer modeling to simulate the cable, first by itself and then as part of actual pendulum systems. The modeling is largely done in Mathematica, and will include the damping function, stiffness, and mass determined experimentally.

### GPU Accelerated Algorithms in Search for Gravitational Waves From Inspiralling Binaries of Compact Objects
Shin Kee Chung
*Mentors: Linqing Wen and Kipp Cannon*

Gravitational wave data analysis is a very complex and time consuming task. It involves analyzing terabytes of data generated from gravitational wave detectors while it is crucial to have fast analysis processes in order to enable follow-up observations with conventional telescopes. We applied Graphics Processing Units (GPUs) as a cost-effective way to speed up the data processing. The GPU programs are written in CUDA, a C-like language developed by NVIDIA Corporation. We used the existing search pipelines for inspiral binaries gravitational wave sources from LIGO, replacing its FFT computation with the CUDA FFT library, and we have also applied data-parallelism for the most time consuming modules in the pipelines. The timing performance was compared with the original pipelines. A preliminary result showed a 16-fold speedup.

### Commissioning of the Enhanced LIGO Thermal Compensation System

Justin Cohen

*Mentors: Keita Kawabe and Cheryl Vorvick*

With the increase in laser power called for in Enhanced LIGO, the heating of the input test masses is estimated to be too strong for the Initial LIGO Thermal Compensation System (TCS) to counteract. To boost TCS performance for eLIGO, a new design featuring increased TCS laser power, an intensity stabilization servo, and axicon optical elements has been commissioned. An installation completed in July 2008 resulted in the successful generation of annulus and central heating patterns at the appropriate plane of the input test masses. Intensity stabilization servo electronics have been characterized and transfer functions were measured for use in future commissioning and noise hunting.

### Investigation of Variations in the Absolute Calibration of the Laser Power Sensors for the LIGO Photon Calibrators

Stephanie Erickson

*Mentor: Rick Savage*

A photon calibrator, one method used to calibrate the LIGO interferometers, utilizes a power-modulated laser to induce displacements of a test mass. These displacements are linearly proportional to the power incident on the mass. Therefore, interferometer calibration at the 1% level requires absolute power calibration at the 1% level or better. To realize high-accuracy power measurements a *gold standard* temperature-stabilized photodetector, mounted on an integrating sphere, was calibrated at NIST. This standard is maintained in a controlled laboratory environment to preserve its calibration accuracy. To calibrate the internal photodetector that samples the light power directed to a test mass in an installed photon calibrator, the calibration of the *gold standard* must first be transferred to a similar *working standard*. The principal source of error in calibrating the *working standard* has been identified to be temporal variations in the detector outputs resulting from multi-beam interference effects within the integrating sphere (laser speckle). Other potential sources of error such as beam centering and pointing, and detector temperature variations are several times smaller. A procedure for transferring the calibration has been generated and tested. The overall statistical variations in the derived *working standard* calibration coefficient are less than 0.35% ($1\sigma$).

### Development of a New Thermal Noise Interferometer

Eugene S. Evans

*Mentors: Eric D. Black and Akira Villar*

Mechanical thermal noise in the in the mirrors of interferometric gravitational wave detectors like LIGO is one of the fundamental sources of noise expected to limit the sensitivity of these instruments. The original Thermal Noise Interferometer (TNI) was designed to sense the fluctuations in mirror coating geometry caused by the temperature of the mirrors, and uses large suspended mirrors in its Fabry-Perot cavities. A new TNI has been designed to make use of standard one-inch optics in an effort to reduce the cost and time required to analyze mirror coatings. The experimental setup consists of a 1064 nm Nd-YAG laser locked to a fixed-length Fabry-Perot cavity (mode cleaner) to stabilize frequency, two short suspended Fabry-Perot cavities, and electronic equipment for Pound-Drever-Hall locking. At the beginning of the summer, only a rough conceptual design of this apparatus existed. In the past ten weeks we have drafted an in-vaccum layout of the optics, constructed the vacuum system and seismic attenuation system, set up the laser, mode cleaner and the frequency stabilization servo electronics, and locked the laser to the mode cleaner. For my final report, I will describe the performance of the mode-cleaner/frequency-stabilization system and its contribution to the overall noise floor of the finished instrument.

### Modeling Cable Noise in LIGO

Julian Freed-Brown

*Mentors: Mark Barton and Norna Robertson*

LIGO's test masses and optics are hung as the bottom mass on multistage pendula in order to isolate them from the motion of the Earth. However, cables need to be attached to sensors and actuators on these pendula, which can potentially degrade the vibrational isolation and change the dynamics of the system. To understand the effects of the cabling, we used *Mathematica* to model the cables as collections of small masses connected by springs. With our model, we can quickly and easily look at how the cables affect the pendula, once we have experimentally determined a few of their physical parameters.

### Time Dependent Parameters for Parametric Instability in Fabry-Perot Cavities

Daniel P. Fulton
*Mentor: Bill Kells*

We address the problem of parametric instability (PI) in a Fabry-Perot cavity with AdvLIGO parameters. Three treatments of PI in gravitational wave interferometers exist: (1) modeling the optical cavity as a feedback system on test mass vibrations, (2) considering work done on test mass versus power dissipated, and (3) Langrangian analysis of eigenfrequencies in the coupled cavity-test mass system. All three approaches assume time static parameters. First, we develop approach (1), and resolve it with the other two treatments. This analysis provides a starting point for an evaluation of time dependent parameters in PI. Specifically, we consider the possibility that drift in the resonant frequency of the test mass may inhibit the ability of PI to develop, and evaluate it using these three approaches.

### Independent Displacement Measurement of a LIGO Test Mass

Dorota Grabowska
*Mentors: Mike Landry and Daniel Sigg*

At LIGO, the voice coil actuation system is used to damp out Differential Arm length fluctuations in the interferometer, as part of the DARM control loop. Each part of this control loop needs to be calibrated, including the actuation function that describes the motion of the test masses in response to control signals sent to the coils. The current actuation model is not accurate at all frequencies. A simple way to refine this model is to make direct measurements of the motion of the end test masses. A Michelson interferometer with one arm terminating on the back of an end test mass can directly measure this displacement, i.e. without employing the complex LIGO interferometer, electronics and software. It can also help clarify why the previous model was not accurate at all frequencies by testing several hypotheses, including the hypothesis that the test mass stops acting like a rigid body at high frequencies.

### Simulated Dynamics and Quantum Noise of Signal-Recycling Interferometers With Multiple Carrier Frequencies

Ryan Hamerly
*Mentor: Sam Waldman*

In order to achieve the needed sensitivity, the Advanced LIGO interferometer will operate at much higher laser power levels than its predecessor, and under these conditions, radiation-pressure noise plays a role comparable in magnitude to shot noise. Furthermore, radiation pressure of a single carrier frequency will cause instabilities in the dynamics of the interferometer’s mirrors. As a result, studies have been made into the behavior of interferometers with multiple carrier frequencies. This project uses MATLAB simulations to study the behavior of signal-recycling interferometers with three or more carrier frequencies, determining the conditions under which such interferometers are stable, and calculating and optimizing the quantum noise spectra.

### Automated Noise Budgeting for the LIGO 40 m Test Facility

W. Max Jones
*Mentors: Alan Weinstein and Rana Adhikari*

The Laser Interferometer Gravitational Observatory (LIGO) is currently prototyping new technologies at the 40 m test bed facility at the California Institute of Technology. Because LIGO's success depends critically on it's ability to limit noise sources which may interfere with the detection of weakly interacting gravitational waves, much time and effort has been spent on cataloguing various noise sources. This SURF represents an extension of that effort. A suite of matlab scripts has been developed to automatically compile such a noise catalogue, called a noise budget, for the LIGO sites in Livingston, Louisiana and Hanford, Washington. Efforts have been made in the past to adapt these methods for the 40 m site. These efforts have been hampered by the site specific nature of a noise budget, the constantly changing conditions at the 40 m facility, and an obtuse coding style used in the automated noise budget scripts. The SURF focused on re-writting parts of the automated noise budget suite to make them compatible with the 40 m facility. Efforts focused on the seismic, DARM, PRC, SRC, and MICH noise sources. Furthermore, a magnetometer was installed at the 40 m site to measure the effect of nearly static magnetic fields on the beam splitter optic. It is the intention of the author to add this noise source to a working automated noise budget script for the 40 m facility.

### The Effect of a Massive Graviton on Gravitational Waves Detectable by LIGO From Binary Inspirals

Michael Kaye
*Mentor: Alan J. Weinstein*

General relativity predicts a mass of zero for the graviton. If this is false, gravitational waves from a binary inspiral will take on a form different from that predicted by general relativity in a way detectable by LIGO. The parameters which characterize the gravitational waves emitted by a binary source are its distance from earth, the masses of its member stars, and the mass of the graviton. These can all be extracted from LIGO data via matched filtering against a bank of templates, each corresponding to a different set of possible values for the parameters. A signal to noise ratio is computed for each template, and those with the highest are most likely to represent the actual parameters of the source. By simulating signals with known source parameters and going through the filtering process several times while varying the noise, we can estimate the accuracy with which LIGO will be able to extract the parameters from a signal it receives. Also, by varying the templates in the bank over different sets of dimensions we can examine patterns in the degeneracies (different sets of source parameters which produce a similar waveform).

### Whitened Merger-Waveform Autocorrelation Functions: Implications for Inspiral Event Localization in Advanced LIGO

Ashley King

*Mentors: Rana Adhikari and Kipp Cannon*

Compact coalescing binary emit gravitational waves that LIGO and Advanced LIGO are designed to detect. When using LIGO interferometers as a network of detectors, one can use the coherence between their signals to find the position and phase of gravitational wave sources. These positions can be used to tell astronomers to focus optical telescopes on a sky location to observe the phenomenon's electromagnetic counterpart. We have developed an analytic approach that uses an autocorrelation of gravitational waves signals to approximate this coherent step and to test how precise this localization is. In particular, we have whitened the inspiral merger-waveforms with the Advanced LIGO power spectral density to determine the accuracy of the Advanced LIGO detectors in particular.

### Noise Sources in Advanced LIGO Optical Levers

William Z. Korth

*Mentor: Michael Smith*

Optical levers serve an integral purpose in LIGO interferometer control. It is expected that the scope of optical levers will be expanded for Advanced LIGO. In preparation, much work has been done on determining OL sensitivity in the so-called *fiducial* and *signal* bands, from about 10 μHz to 2 Hz, but little has been determined about OL noise characteristics in the *noise band*, above 10 Hz, in which the OL system must inject no more than a small fraction (tentatively given at 10%) of the total interferometer noise into the system. Considering the improvement in interferometer design sensitivity for Advanced LIGO, noise from optical levers is a potentially pertinent issue. The purpose of this project is to characterize the noise generated by optical levers in this band due to many factors, including shot noise, technical intensity noise, thermal, acoustic and seismic noise, as well as electronic noise from quadrant photodiodes and amplifiers. As there is an effort to incorporate fiber optics into the OL system, the effect of spatial mode instability on noise must also be investigated. This paper presents a quantitative assessment of these various noise sources, and their potential effects on Advanced LIGO sensitivity.

### Improving the LIGO S5 Sensitivity by Subtracting the Noise From the Interferometer Auxiliary Degrees of Freedom From the LIGO Gravitational Wave Output

Nicholas R Langellier

*Mentor: Valera Frolov*

At the end of 2007, LIGO finished the S5 science run, collecting a full year of coincidence data. During the run, LIGO achieved the designed sensitivity, reaching a 35 Mpc detection horizon for binary neutron star inspiral events. Periods of decreased sensitivity, however, contaminate the S5 data, reducing the chance of gravitational wave detection. The decreased sensitivity arises from escalated coherence between the interferometer auxiliary degrees of freedom and the gravitational wave output. This coherence is considered noise if the auxiliary degrees of freedom couple into the gravitational wave output. Employing the digital filtering technique known as Wiener filtering effectively subtracts the noise from the gravitational wave output, regaining a significant portion of the sensitivity lost during the S5 run.

### Development of a Digital Camera Network and Associated Analytical Tools for the Caltech 40m LIGO Prototype

Eric T. Mintun

*Mentors: Rana Adhikari, Alan Weinstein, and Joseph Betzwieser*

The Laser Interferometer Gravitational-Wave Detector (LIGO) uses a network of analog cameras to image the laser at various stages in the device. This network is old and lacks functionality and expandability. This paper details the upgrade of this camera network to one that uses digital cameras on a Gigabit-Ethernet network, as well as the development of a number of software tools that aid in archiving and analyzing the images. This software determines the position and width of the beam profile using both a center of mass calculation and a chi-squared minimization fit to the beam’s theoretical Gaussian shape. It can then pass this information to LIGO’s primary control software (EPICS), which can actuate on it in order to realign the beam position. The fitting software was also modified to determine the peak parameters of resonances in the interferometer’s pre-mode cleaner.

This fit provides a method to determine what percentage of the output beam is comprised of each mode, making it easier remove higher order modes from the laser in later stages of the interferometer. Possibilities for future work on the GigE camera network is discussed, including other potential analytical tools that can build off this software.

### Development of Digital Filtering Techniques to Improve LIGO's Seismic Isolation System

Caryn A. Palatchi

*Mentor: Brian O'Reilly*

In 2007, LIGO (Laser Interferometer Gravitational Observatory) achieved unprecedented sensitivity. However, a limiting noise source is ground motion which changes the length of the interferometer arms and is largely accountable for decreased sensitivity in the low frequency range below 10Hz. To computationally improve the seismic isolation system HEPI (Hydraulic External Pre-Isolation), wiener filtering techniques are here developed for later application with the aim of improving LIGO's sensitivity in the low frequency range.

### Noise Cancellation - LIGO 40m

Sharon Rapoport

*Mentor: Rana Adhikari*

Different noises keep LIGO from detecting gravitational waves. Low frequency, acoustic, thermic and other noises determine the sensitivity curve which we are trying to improve towards the implementation of enhanced and advanced LIGO. Other than improving the hardware, the LIGO team is investing many efforts to improve its digital control systems. Once we improve our sensitivity, we increase the strain we can detect, and expand the detection area deeper in space. Using adaptive control system, it is possible to cancel noises that are coming from known sources. Currently, I am using 6 accelerometers and a seismometer as the noise signals, and monitor the length of the Mode Cleaner as the target signal, in order to try to cancel the low frequencies seismic noise.

### Optical Fiber Stabilization System for AdvLIGO

Jaclyn R. Sanders

*Mentors: H. Richard Gustafson, Paul Schwinberg, and Daniel Sigg*

Advanced LIGO requires a seismic platform interferometer to reduce the relative mirror velocity in the long arm cavities. An arm cavity can be locked independently by injecting laser light through the end mirrors. This requires the transfer of an optical wavelength standard to the end stations using fibers. A fiber stabilization system is required to compensate for thermal drifts and acoustic excitations of the fibers. Acousto-optic modulators (AOMs) are used to add frequency shifts to the outgoing and return light. A feed-forward system then alters the input light to compensate for the fiber noise.

### Detection of Un-Modeled Gravitational Wave Bursts Using Bayesian Inference

Samuel Schoenholz

*Mentor: Antony Searle*

In the identification of un-modeled gravitational wave burst candidates most statistics neglect the occurrence of glitches in the interferometers. This pro ject works to integrate glitches into both the Bayesian and classical paradigms of the analysis. We believe that introducing glitches into the current statistics will both improve their ability to detect un-modeled gravitational wave bursts and make the models behind the statistics more accurate. We begin by developing a glitch hypothesis that searches for single, sine-gaussian glitches. We then present the derivation equations that differentiate between the glitch hypothesis and a background noise hypothesis. We also present methods to regress important parameters in the model from data, and find order of magnitude estimates for the validity of the model. Finally we present a summary of the implementation of this model into the Omega pipeline. We were able to use the code produced to identify glitches in an stream of simulated data.

### Detection of Gravitational Waves Using a Global Network of Detectors

Satish Shrestha

*Mentors: Sanjit Mitra, Anand Sengupta, and Rana Adhikari*

Detection of Gravitational Waves (GW) using Earth based detectors is a challenge in modern experimental physics. Laser Interferometry Gravitational Waves Observatory (Livingston, LA and Hanford, WA) and VIRGO in Italy are prominently active earth based detectors attempting to overcome the challenge. Each detector is confined and sensitive to only certain region in the sky depending on its orientation and location. However, a network of such detectors covers a large portion of the sky. In addition to better sky coverage, it also enhances the detection sensitivity and ability to localize the sources in the sky. In this project, we focus on the study of network of detectors and suggest an optical location and orientation for another ground based interferometric GW detector.