PMA **Study of Seismic Effects on the LIGO Interferometers**
Rachel D. Berkowitz
Mentor: Vernon Sandberg

Einstein's theory of general relativity predicts gravitational radiation to emanate from astrophysical sources. The Laser Interferometer Gravitational-wave Observatory (LIGO) employs laser interferometers to detect this radiation by measuring minute perturbations in an otherwise flat spacetime background. LIGO is an extremely sensitive strain meter, as the common mode (sum length) of the arms is sensitive to change in laser frequency, and has the potential for use as a seismometer. The U.S. Department of Energy has been detonating wells within 50 miles of LIGO as part of decommissioning of the Hanford site. Studying the detection of these and other known seismic events by the interferometers can provide information about the use of LIGO as a seismometer. Using various LIGO software packages and data filtering techniques, we are able to consider the use of LIGO in other scientific applications by filtering the data and looking at power spectral densities and spectrograms. Although some signals are damped out by the time they reach LIGO, others are clearly detectable by the instruments.

PMA **Design and Construction of an Optical Lever Receiver: Analyze, Build, and Test a Prototype Optical Lever Receiver for LIGO**
Aabeg Singh Bhandari
Mentor: Michael R. Smith

Optical levers are used as a reference for establishing the rotational orientation of the mirrors in LIGO. Occasionally they are also used as a signal for damping the oscillations of the mirrors. The optical lever receiver consists of a two-stage afocal beam reducing telescope, which magnifies angle of the input optical lever beam followed by a focus lens that the telecentric focus lens converts the beam angle to a beam displacement, which is measured by a quad photo detector placed at the output of the optical receiver to measure the output beam angle. The function of the optical lever receiver is to measure the angular deviation of the optical lever beam, while ignoring the lateral displacement of the beam. The analysis uses the method of paraxial optical rays and ray matrices (ABCD) as applied to Gaussian beams.

PMA **Improving Searches for Gravitational Waves Using Signal Isolation Tests**
Sebastian N. Cassel
Mentor: Peter Shawhan

The procedure of detecting gravitational wave (GW) signals from binary inspiral sources is reviewed. The characteristics of true and noise-induced signals are discussed and a discriminating test proposed. The approach involves considering the time history of the matched filter output in the vicinity of a recorded event. The test only uses the GW channel data and is complementary to the existing χ^2 veto. The effectiveness of this test when applied to the S4 data of the Hanford 4km detector is presented, and a comparison with previously developed tests offered. The test proposed should produce fewer false positives and ensure more confidence in the output of the detectors.

PMA **Detection Efficiency Studies for Searches for Binary Neutron Star Inspiral Gravitational Waves**
Sarah E. Caudill
Mentor: Peter Shawhan

Detecting gravitational waves from inspiraling binary neutron stars requires a two-dimensional bank of theoretical waveform templates that are described by two parameters, the masses of the neutron stars. The bank construction algorithm utilizes matched filtering to ensure that any gravitational wave signal in the region of interest of the parameter space closely matches one of the templates. The method of template bank construction was analyzed from a study of the LIGO algorithm library (LAL). Accuracy of the expected 0.97 minimal match value was reviewed using ellipses of constant match drawn around each template. Further research will involve improvements to the template placement algorithm as well as generalization of the mismatch measurements to the higher dimensional parameter spaces used for binary black hole searches.

PMA **Wireless Optical Controls of LIGO Suspensions Actuators**
Maria Paola Clarizia
Mentor: Riccardo DeSalvo

An efficient isolation of the light-chain components from platform noise is a key ingredient in all Gravitational Wave interferometric detectors. For Advanced LIGO this is accomplished using sophisticated multi-stage multi-pendulum attenuators. The aim of this work is to study and design of a wireless control for the stepper motors used in the suspension attitude control system through optical (e.g., LED+photodiode) links. The stepper motors are used to rotate masses which permit to tilt the mirrors of the interferometric detector, so as to avoid doing it manually. The choice of wireless links is advantageous since it eliminates mechanical and electrical perturbations on the suspended masses, deriving from the use of a wired link, as well as an excessive load of outgas on vacuum.

A laser diode and a photodiode provide the input signal of a certain frequency: the so produced signal is amplified and then rectified to feed the motor, producing steps and moving the masses. In such a way, the mirror can be easily adjusted, controlling the stepper motor through the input signal provided.

PMA **Thermal Noise in Advanced LIGO Mirrors**
Katherine L. Dooley
Mentor: Eric D. Black

The range of an advanced gravitational wave detector depends critically on the noise in mirror coatings. In order for gravitational wave astronomy to become a flourishing field, new mirror technologies and materials must be developed which exhibit substantially lower thermal noise than those used in the current generation of LIGO. These current mirrors have dielectric coatings made of alternating layers of fused silica and tantalum pentoxide. While these materials have excellent optical properties, mechanical losses in the tantala layer are the dominant source of thermal noise. Our project is part of a large ongoing collaboration to develop mirror coatings that have lower levels of mechanical loss while still exhibiting good optical qualities. One candidate material is tantalum pentoxide with a titanium doping. Preliminary studies have shown that the addition of this dopant reduces the level of internal friction. This summer we received a set of mirrors with prototype coatings incorporating the doped tantalum pentoxide. Our goal is to measure the broadband thermal noise in these coatings directly. We report on progress and results to date of this project and what it means for advanced LIGO.

PMA **Measuring the Long-Term Drift of the Mode Cleaner Length**
Ian W. Duke
Mentor: Valera Frolov

Variation in the length of the mode cleaner cavity causes the RF sidebands to shift away from resonance. This results in oscillator phase noise appearing as amplitude modulation in the transmitted light. We measure drift in the length of the mode cleaner on the scale of several weeks and determine if it is necessary to correct the sideband modulation frequency or the cavity length to minimize this amplitude noise. The measurement is performed by imposing an additional audio frequency modulation of the carrier beam before it enters the RF electro-optic modulator. The magnitude and phase of the beat signal in the mode cleaner transmitted beam give the length and direction of the offset. We also investigate the effect of mode cleaner cavity length variation on oscillator phase noise coupling to the IFO dark port signal by actively varying the length and measuring the resulting oscillator phase noise spectrum.

PMA **A Further Study of Materials for the MGAS Springs for LIGO**
Anamaria Effler
Mentor: Riccardo DeSalvo

The purpose of this experiment is to determine the best material for the MGAS (Monolithic Geometric Anti Spring) springs in the suspension system for LIGO and other GW lower frequency interferometers. This is the continuation and expansion of last year's SURF project I (Anamaria) was involved in. The best blade material would be the one that allows tuning to a lower frequency with the largest attenuation frequency band, by having a better Q-factor performance and lower hysteresis.

The four materials chosen for this comparison are Maraging, Copper-Beryllium, and Glassy Metal LM001 and LM002. A two-blade MGAS spring made of each material is used; we measure its vertical decaying oscillation at progressively lower frequencies using an LVDT (Linear Vertical Differential Transformer) connected to a computer (which does the data acquisition with LabVIEW).

Since we have not reached the data acquisition and analysis stage yet, we cannot present any conclusions at the time this abstract is written, but by the time of the SURF presentation we expect to have at least partial results concerning the Q-factor and hysteresis of the four materials.

PMA **Analysis of the Frequency Dependence of the LIGO Interferometer Directional Sensitivity (Antenna Pattern) and Its Implications for Detector Calibration**
Hunter L. Elliott
Mentor: Richard L. Savage

The current LIGO calibration technique's application is limited to the primary frequency band from DC to 8 kHz. It assumes a constant antenna pattern and approximates the detector's length response, resulting in a systematic, frequency dependent error. The recent addition of a second, high-frequency band centered on the cavity free spectral range frequency of 37.52 kHz requires that the calibration be modified. The effect of the gravitational-wave frequency on the antenna pattern is discussed and quantified. The frequency dependence of the detectors length response is analyzed with emphasis on the gravitational-wave frequencies corresponding to multiples of the cavity free spectral range. A modified calibration procedure is proposed that eliminates the systematic error in addition to allowing calibration in the high-frequency band.

PMA **The Effect of Transverse Shifts on the LIGO Interferometer (Simulation Study)**
Doug J. Fettig
Mentor: Biplab Bhawal

The LIGO interferometers have reached their designed sensitivity level which is greater than any other interferometer ever built. At this point, it is important to have a proper understanding of small perturbations that might still exist (until now these issues did not come to the forefront because other more critical problems needed to be solved in order to approach the expected designed level of sensitivity). This project focuses on how possible existence of transverse shifts in either beam or optics would affect the alignment and sensitivity of these detectors. Two simulation tools are used for this purpose: The time domain simulation package called End-to-End (E2E) model and a static FFT code developed for LIGO. The results are analyzed to look for changes in noise curves, recycling gain, beam intensity profiles etc for both the laser carrier frequency and sideband frequencies. The asymmetries in beam profiles are also looked at to evaluate the effect of such perturbations on alignment sensing.

PMA **Targeted Searches and Coherent Sum Using Q Pipeline**
Sahand Hormoz
Mentor: Shourov K. Chatterji

One class of sources LIGO is searching for consists of short duration gravitational wave bursts of a priori unknown waveform. Potential sources include supernovae core collapse and the merger phase of coalescing binary black holes. To date, existing burst search algorithms have concentrated only on all-sky searches for such events. We have developed an algorithm that allows for maximum sensitivity to a desired sky location, by forming a linear combination, a coherent sum, of data from a network of detectors. To accomplish this, a search is performed over a two dimensional parameterization of signal space. This algorithm was implemented as a part of the Q-pipeline data analysis package, and was tested for various types of simulated data for Hanford and Livingston detectors. A substantial gain on SNR was observed in most cases depending on the incident direction of the gravitational wave; moreover, it was found that for detection purposes it is sufficient to iterate the sum over all possible sky positions. In addition, statistical tests were developed in order to distinguish between glitches and gravitational waves, especially for the two Hanford detectors.

PMA **Modeling of the Effects of Beam Fluctuations From LIGO's Mode Cleaner**
Nafis S. Jamal
Mentor: Sanichiro Yoshida

LIGO's mode cleaner is a triangular laser cavity that forms the Input Optics (IO) along with the subsequent mode matching telescopes. The output beam from the mode cleaner travels through the MMT chain to the core optics, the heart of LIGO, which consists of the power recycling mirror, beam splitter and the two arm cavities. If the incoming beam to the core optics is flawed, LIGO's sensitivity becomes degraded. In my research, I model the mode cleaner's effect on the laser beam and the performance of the core optics. In order to appropriately model the mode cleaner, seismic perturbations as well as stabilizing control forces must be simulated. First, I completed the model of the mode cleaner in the End-to-End simulation environment. To complement the existing length sensing servo, I added to the model the Alignment Sensing Control (ASC) system which uses two wavefront sensors to correct the angular misalignment of the MC mirrors, minimizing the beam pointing angle as well as maximizing power coupled in the cavity. After filtering the error signal from the wavefront sensors, the ASC acts on the pitch and yaw of each of the MC mirrors, attempting to steady the beam. Upon completion, the model may be incorporated into SimLIGO, the simulator of the entire interferometer. I will measure how the beam pointing and amplitude fluctuations at the mode cleaner's output cause power to be transferred into higher order eigen-modes of the laser, resulting in less power coupled into the arm cavities and corresponding noise in the dark port signal.

PMA **Noise Budget Development for the LIGO 40 Meter Prototype**
Ryan T. Kinney
Mentors: Alan J. Weinstein, Rana Adhikari, Osamu Miyakawa, and Robert Ward

The Laser Interferometer Gravitational-wave observatory (LIGO) is an interferometric antenna designed to measure minute perturbations to the local spacetime curvature due to the passing of a gravitational wave (GW). It detects GWs from the fractional change of the lengths of its arms, the strain, induced by passing waves. To achieve the required displacement sensitivities, the noise sources affecting LIGO's data signal must be identified and understood. The process that determines the amount to which any particular noise source contributes to the output signal, noise budgeting, is routinely performed at the LIGO observatories and is needed for the Advanced LIGO 40 meter prototype, which features a more complex optical configuration and control system. A noise budget is developed by measuring the noise spectrum at its entrance to the system (volts per root Hz.), finding a transfer function between the noise input and data output (meters per volt), and multiplying these to get the noise contribution to the output signal (meters per root Hz.). This project consists of identifying a subset of potential noise sources (seismic, auxiliary control servos, etc.) and measuring their input noise spectrum, transfer function to data output, and thereby their contribution to the noise spectrum of the interferometer.

PMA **Non-Gaussian Excess Noise Events in Silicate Bonds**
Richard A. Kirian
Mentor: Eric Black

Silicate bonds will be used in attaching fused-silica ears to the mirrors in Advanced LIGO. Fused-silica fibers will then be welded to the ears so that the mirrors may be suspended. The bond joints will be under shear stress by the weight of the mirrors, and it is expected that relaxation events following non-Gaussian statistics will dump energy into the mirrors. It has been shown that such excess noise events originating from within the fibers can release energy great enough to mimic gravitational waves. We extend that study to include events originating in the silicate bonds. Scaled down fused-silica ears bonded to both fused-silica and sapphire test mirrors are suspended by fused-silica fibers and shear stressed to the level expected in AdLIGO. A shadow sensor focused at the fibers edge measures the vibration amplitude of the fiber, which is our transducer of the noise events. We will discuss the measurement apparatus as well as data acquisition and analysis to date.

PMA **A Further Study of Materials for the MGAS Springs for LIGO**
David W. Koenitzer
Mentor: Riccardo DeSalvo

The purpose of this experiment is to determine the best material for the MGAS (Monolithic Geometric Anti Spring) springs in the suspension system for LIGO and other GW lower frequency interferometers. This is the continuation and expansion of last year's SURF project I (Anamaria) was involved in. The best blade material would be the one that allows tuning to a lower frequency with the largest attenuation frequency band, by having a better Q-factor performance and lower hysteresis.

The four materials chosen for this comparison are Maraging, Copper-Beryllium, and Glassy Metal LM001 and LM002. A two-blade MGAS spring made of each material is used; we measure its vertical decaying oscillation at progressively lower frequencies using an LVDT (Linear Vertical Differential Transformer) connected to a computer (which does the data acquisition with LabVIEW).

Since we have not reached the data acquisition and analysis stage yet, we cannot present any conclusions at the time this abstract is written, but by the time of the SURF presentation we expect to have at least partial results concerning the Q-factor and hysteresis of the four materials.

PMA **Analysis of the LIGO Output Mode Cleaner**
David B. Levitan
Mentors: Keita Kawabe and Richard Gustafson

The beam at the dark port of the LIGO interferometers has a modal composition that is primarily composed of higher order Hermite-Gaussian modes caused by mode mismatching and misalignment of the interferometer optics. These higher order modes are a noise source that can be removed by the use of an output mode cleaner. However, an output mode cleaner at LIGO must transmit three separate frequencies, causing complications in its design. The original output mode cleaner installed at LHO produced more noise than it removed, leading to its subsequent removal. The cause of this noise was never understood completely, and the goal of this project has been to study the reasons why the output mode cleaner did not work as expected using the *e2e* simulation package.

PMA **Population Statistics of Gravitational-Wave Pulsars**
Milivoje Lukic
Mentor: Réjean Dupuis

Gravitational waves emitted by spinning neutron stars provide a direct probe of their internal structure and mass distribution. Searches for gravitational waves from pulsars using LIGO data have already set upper limits on GW emission from several individual pulsars. We use those observations to study the distribution of quadrupole moments of the pulsar population. A Bayesian methodology is developed to use aggregate data from all observed pulsars to determine properties of the entire population, such as the average and maximum quadrupole moment. We estimate the sensitivity of the method on simulated noise for varying signal-to-noise ratios and number of pulsars in our sample. The sensitivity is also predicted for the set of currently known pulsars with the design sensitivity of Advanced LIGO. The method is applied to current results for individual pulsars obtained from the LIGO science runs.

PMA **Analysis and Measurement of the Q Factor in Monocrystalline Silicon Flex Joints**
Sean W. Mattingly
Mentor: Riccardo DeSalvo

In LIGO, monocrystalline silicon flex joints have been proposed as an alternative to alleviate the issue of thermal noise in the wires suspending the mirrors. This experiment analyzes the structure of flex joints and directly measures the Q factor of these flex joints. This is achieved using a double pendulum with two flex joints separated by an intermediate mass and a shadow meter, then fitting the resulting ringdown data against an exponential curve and a sine curve. Silicon flex joints have been mounted on the bottom and top of this setup separately, each time with a maraging steel flex joint on the other end of the setup. Compared with the two maraging steel flex joint control of 383, silicon on top has a Q factor of 584, while on the bottom the Q becomes 1159. These results imply that single crystal silicon is a very high Q factor material, and possibly well suited to serve as a suspension in LIGO. However, other issues still remain with its frailty. The next step is to mount silicon on both the ends of the pendulum to determine the Q factor in this situation, and to reexamine the whole system under vacuum.

PMA **Visualization of the Effectiveness and Efficiency of Potential Inspiral Vetoes**
Paul A. Mayeur
Mentor: Natalia Zotov

Plotting the triggers set by the binary inspiral codes indicating potential event candidates and comparing these to plots of triggers from various channels set by a glitch monitor is an excellent way of indicating stretches of the data where glitching on a particular channel provides an effective veto of inspiral triggers that we can be confident do not represent binary inspiral events. The pair of plots is then compared and coincident triggers are highlighted. A plotting script can at the same time calculate the dead time that a particular veto would require, and its efficiency in vetoing inspiral triggers. MatLab scripts to do this on a small scale exist currently; however, as of now the scripts only handle one particular time interval and one monitor channel which are both hard-coded in. The objective is to make this code more flexible and able to run more quickly and efficiently over many channels. This report explains ways of improving the flexibility and also simplifying and automating this process which may be used in future science runs.

PMA **Study of the LHO 4K Recycling Cavity Sideband and Carrier Response to Excitation and Perturbations**
Grant D. Meadors
Mentor: Richard Gustafson

The response of the LIGO Hanford Observatory 4-Kilometer Interferometer Recycling Cavity to perturbations is studied in this report, as observed when the Recycling Mirror is driven in length. Preliminary observations of power-recycling Michelson interferometry show the sidebands amplitudes to respond oppositely while carrier amplitude remains roughly constant. This suggests that the recycling cavity length is not perfectly matched to input sideband light. Because the sidebands provide a reference system for detecting gravitational waves, it has been suggested that improving the match would improve LHO performance.

An optical heterodyning analysis system for the LHO 4-Kilometer Interferometer Recycling Cavity (pioneered by SURF students Goetz and Garrelts) has been re-engineered to yield a well-defined bandwidth and calibrated to the 1-2% level. In this system, carrier and sideband light from the Recycling Cavity is combined (beat) on a radiofrequency photodiode with a frequency shifted (75 MHz) reference beam fiber transported from the PSL laser system, yielding radiofrequency signals representing the higher sideband (at 50 MHz), carrier (75 MHz), and lower sideband (100 MHz). Demodulation electronics yields DC Root-Mean-Square amplitude signals for the LHO Data Acquisition system.

Further results, analysis, and discussions of the significance are presented in the final report.

PMA **Depressing Thermal Noise in Interferometric Gravitational Wave Detectors Using Non-Gaussian Beams**
John Miller
Mentor: Riccardo DeSalvo

Fundamental thermal noise forms a significant portion of the noise budget of interferometric gravitational wave detectors and is likely to be the principal limiting factor for Advanced LIGO. Non-Gaussian beams have been proposed to diminish this noise without being significantly more difficult to control. A detailed discussion of the benefits garnered by switching from the baseline Gaussian design is presented. In particular, attention is focused on a flat-topped beam, known as the mesa beam, and the non-spherical mirrors which support this field.

An experimental Fabry-Perot cavity has been constructed to generate and characterise this new beam, comparing its behavior to well-understood theory. Preliminary results from this apparatus showing agreement of higher order modes with expectation are presented and indications of further work are given.

PMA **Design of an Output Mode Cleaner to Enable DC Readout in the LIGO 40-Meter Interferometer**
Marcus Q. Ng
Mentors: Alan J. Weinstein and Robert Ward

The LIGO 40 meter prototype interferometer is testing the more complex configuration and control scheme for Advanced LIGO. One aspect of this optical configuration is a "DC readout" system where the output beam (carrying the gravitational wave information) passes through an optical cavity called an output mode cleaner (OMC) to strip away all components of the beam that do not carry GW information (i.e., RF sidebands and HOMs). The project involved modeling the Gaussian beam parameters to select mirror specs and the OMC geometry. The OMC will be a 4-mirror optical cavity, two flat coupling mirrors, one curved folding mirror and one PZT mounted, flat folding mirror. Cavity finesse (coupling mirror transmisivity) and g-factor (ROC and length) are selected to minimize transmission of RF sideband and higher order carrier modes. The mirrors will be mechanically mounted in a stainless steel or aluminum monolith. An output mode matching telescope (OMMT) will precede the OMC to minimize the mismatch in beam waist size and positions for the input beam and OMC. The OMMT, has two spherical mirrors, the focal lengths and OMMT length varied to minimize the mismatch. If time permits, the cavity will be constructed before the end of the summer.

PMA **Thermal Noise Issues: Measuring the Thermal Noise in Silica/Tantala Mirrors Doped With Titanium**
Chinyere Ifeoma Nwabugwu
Mentor: Eric Black

In order to design an advanced interferometric gravitational wave detector, we must be able to predict with a high degree of accuracy the noise floor of the instrument. The most important noise source, the one that sets the ultimate range of the instrument at the frequencies of greatest astrophysical interest, is the thermal noise in the mirror coatings. The dielectric coatings of the current mirrors used in initial LIGO are made from alternate layers of silica and tantala. While these mirrors have good optical properties, the mechanical loss in the tantala layer is significant and is the dominant source of thermal noise. The thermal noise interferometer is the set-up that would enable us measure the thermal noise in newly developed coatings that incorporate titanium doping. In order to make an accurate test of theoretical models, it is essential that we have an accurate calibration. We would report on this measurement and specifically on the calibration.

PMA **Modeling the Performance of Networks of Gravitational-Wave Detectors in Gravitational-Wave Burst Searches**
Maria Principe
Mentors: Riccardo DeSalvo and Patrick Sutton

Gravitational-Wave Bursts (GWBs) search codes typically use a single threshold which is varied to tune the analysis for the detection of GWBs. Lower thresholds allow weaker signals to be seen, but also allow higher false alarm rates from fluctuations in the noise background. Typically multi-detector GWB searches are tuned according to the Nyman-Pearson criterion to achieve the lowest false dismissal probability at a given false alarm rate. To date this tuning is typically done "by hand", which can lead to sub-optimal tuning. The goal of this project is to develop a software tool to simulate the behavior of networks of gravitational-wave detectors in trigger-based searches for GWBs. The software package will be able to estimate the false alarm rate and false dismissal probability of general networks of gravitational-wave detectors, based on the measured properties of the individual detectors in the network. This network simulator could be used for tuning of analyses in actual GWB searches, to maximize the sensitivity of the search. It could also be used for independent validation of the search analysis. It could be used to estimate the sensitivity to populations of signals other than those that were directly tested in the search. Finally, it could be used to estimate the effect on the network sensitivity of uncertainties in the properties of the individual detectors.

PMA **Thermal Self Locking in a Fabry Perot Cavity**
Royal A. Reinecke
Mentor: Eric Black

While investigating new coating materials for advanced LIGO, we have observed an unusual nonlinear phenomenon of high power Fabry Perot cavities—thermal self locking. This phenomenon can, under the right conditions bring the cavity into resonance with the laser and hold it there. This talk will describe conditions required for a stable thermal self lock and present experimental evidence of thermal self locking in a short Fabry Perot cavity.

PMA **Analyzing Double Nail Ended Wires: Minimizing the Resonant Frequency of MGAS Springs for Seismic Attenuation System in Low Frequency Gravitational Waves Interferometers**

Francesca Salsi

Mentor: Riccardo DeSalvo

In order to continue Maddalena Mantovani's work I design and build a digital control for her electromagnetic spring, changing the OP AMP feedback with a computerized feedback (with Lab View), attempting to drive the resonant frequency even lower. I tested a Lab View program simulating the input voltage of a LVDT, and reading the computer generated output voltage with an oscilloscope. I modified and run this program in order to obtain the desiderate results. I found that Lab View is able to make a real time control under 1 KHz (provided the computer is not running other programs, if its only priority is to acquire and control the LVDT voltage). In order to amplify the scan/rate, I modified the Lab View program (deleting everything that was wasting memory [as graphics]), in order to speed up the scan/rate maintaining the real time acquisition. I added an RC filter between the output of Lab View and the input of the amplifier. I controlled that the dephasing added to the waive by the RC filter was negligible. I will start in this week my measurement.

PMA **Investigation of the Effect of Seismic Noise on LIGO Data**

Bonnie K. Schneider

Mentor: Andri Gretarsson

This project presents an investigation of the relationship between seismic noise and LIGO gravitational wave data by examining the data at times of high and low seismic noise. A linear error predictor digital whitening filter was applied to the gravitational wave channel data in the time domain and the results were histogramed to detect outliers. The number and type of outliers were cataloged as a function of seismic activity.

PMA **Investigating the Light Scattering Properties of LIGO Materials**

Shasta Shakyas

Mentor: Michael R. Smith

Beam dumps and baffles made of low scattering, absorptive materials are needed at various locations within the LIGO interferometers to control the stray light due to scattering from the interferometer mirrors and ghost beams. The scattering property of a surface is described by the Bidirectional Reflectance Distribution Function (BRDF). In this project, I designed and built a BRDF measuring apparatus for measuring the BRDF of different LIGO material samples that are candidates for use as baffles and beam dumps in the LIGO interferometers. The BRDF of a surface is determined by shining a laser beam onto the surface of the sample and measuring the fraction of the light power scattered per solid angle. This project will contribute in achieving the required sensitivity of the interferometer by controlling light noise.

PMA **Simulation of the Fluctuations in the Input Beam and Its Effect on the Arm Cavities**

Shivanand

Mentor: Sanichiro Yoshida

The laser is passed through a series of optics (called the Input Optics) before allowing it to enter the main interferometer (called the Core Optics). The input Optics, which mainly consists of the Mode Cleaner (MC) and the Mode Matching Telescope (MMT), improves the laser beam quality. However the ever present ground motion reaches the Input Optics via the suspension point and appears fluctuations in the input beam.

I have tried to study the fluctuation in the input beam caused due to the effect of the realistic ground motion on the input optics. I look at the cavity response under various conditions of the input optics and different cases of the core optics.

PMA **Use of a Digital Micromirror Device (DMD) for Thermal Compensation in Advanced LIGO**

Alexander Z. Smith

Mentor: Phil Willems

The high laser power in the power recycling cavities of Advanced LIGO is expected to be a large contributor of thermal noise. Reflecting photons will transfer energy to the mirrors of Advanced LIGO, heating them up. This change in temperature will not be uniform across the mirror, and the resultant temperature gradients will distort the wavefront of the main laser, creating focusing problems. This project explores the possibility of using a digital micromirror device (DMD) with the existing thermal compensation lasers of original LIGO to project a more precise and adjustable thermal compensation pattern onto the partially reflecting mirrors of Advanced LIGO. A DMD is tested and studied under various conditions in an effort to determine if it can withstand a powerful infrared laser for long periods of time, and if it is even possible for a DMD to be modified for use with an infrared laser. Our experience with the DMD thus far has shown it to be a viable candidate for thermal compensation in Advanced LIGO.

PMA **Oscillator Phase Noise Coupling**
Nicholas D. Smith
Mentor: Daniel Sigg

The LIGO detectors use a variation of the Pound-Drever-Hall reflection locking technique to sense and control the longitudinal degrees of freedom. This involves modulation of the light beam with a radio frequency signal. Phase noise originating from the local oscillator which drives the modulation can contaminate the gravitational-wave readout. This project involves directly measuring the oscillator phase noise coupling to the anti-symmetric port where gravity-wave signals are anticipated to exist. Additionally, a new method of performing the signal demodulation is attempted by deriving the local oscillator signal from the two-omega signal which is available at the anti-symmetric port. The goal of this project is to determine if the new scheme will reduce the oscillator phase noise coupling and thus mitigate the role that oscillator phase noise plays in the noise floor of the detector.

PMA **Verification and Modeling of Coherent Analyses of Networks of Gravitational Wave Detectors**
Leo C. Stein
Mentor: Patrick J. Sutton

In the analysis of gravitational wave (GW) detectors' signals, including multiple detectors gives many advantages, such as the ability to reconstruct the signal, to determine the direction to the GW source, and the ability to distinguish coincident noise glitches from GW signals. We have developed a maximum-likelihood based technique for detecting GW signals, determining the source direction, and reconstructing the waveforms; we compare the method to existing methods in the literature. A computer simulation framework, capable of performing the analyses mentioned, has been developed and is described. We present receiver operating characteristic (ROC) curves for the developed technique, which quantify the detection efficiency as a function of false alarm rate. We discuss the possibility of future work including using a coherent analysis for GW detection from real data in real time, or as a post-processing algorithm for extracting the GW signal out of the noisy data from a previously identified event in order to understand the event which caused the GW signal.

PMA **Possible Improvement of MGAS Damping Performance: A Parallel Inverted Pendulum System Mounted in the SAS Vertical Filter for Gravitational Waves Detectors**
Alberto Stochino
Mentor: Riccardo DeSalvo

One of the greatest obstacles for an advanced ground-based interferometer is the seismic disturbance. In order to obtain a wide observation band, especially at low frequencies, the residual seismic noise acting on the optics needs to be further attenuated. The Seismic Attenuation System (SAS) was developed with the specific objective of achieving sufficient low frequency seismic attenuation. More or less directly all the damping systems of SAS are based on the attenuation capability of a pendulum subjected to oscillations of frequency higher than its resonance frequency. Up to now the MGAS filter has been greatly successful in lowering the level of saturation in vertical damping to 60 dB. The GAS springs show a limit due to their mass non totally negligible. To overcome the same kind of problem in the horizontal damping, SAS mounted counterweights on the legs of inverted pendula. My project is aimed to examine the possibility to extent the same principle to the vertical filter. I designed a system based on the inverted pendulum theory which I'm going to mount in parallel to the GAS springs. Then I'm going to calibrate it in order to obtain the best performance.

PMA **Inverted Pendulum Studies for Seismic Attenuation**
Ilaria Taurasi
Mentor: Riccardo DeSalvo

Seismic motion is an inevitable noise source for interferometers built on the Earth's crust. The signal of an interferometer caused by the continuous and random ground motion is named "seismic noise". The ground motion transmits to the motion of the test masses through different paths; the most straightforward path is that the horizontal ground motion at the suspension point of the test mass causes the its longitudinal motion. For this reason there's the necessity of a seismic attenuation in the horizontal direction. To provide sufficient attenuation and a quasi-inertial stage on which to detect the recoil and actively damp the motion of the suspended chain is implemented an inverted pendulum (IP), a horizontal pre-isolation stage with ultra-low resonant frequency. The purpose of this project is to provide the legs of IP with a counterweight below the elastic joint to damp the effect of the center of percussion center. We'll design the mechanical system and optimize it in order to get best performance. The work will be mainly developed with Ansys, a mechanical software. We'll effect some simulations to find the suitable counterweight for the IP. Since we have not reached the whished results yet, we cannot present any conclusions at the time this abstract is written, but by the time of the SURF presentation we expect to have at least partial results.

PMA **Sights and Sounds of LIGO**

Kyoko Yoshida

Mentors: John Thacker and Brian O'Reilly

The main objective of the LIGO (Laser Interferometer Gravitational-Wave Observatory) project is to detect gravitational waves in space. Within the scientific complexity of LIGO comes the challenge of communicating the project to the general public. This research project attempts to bridge this gap and to relate the LIGO project to the public by audio-visual means. Taking different noises that occur from local trains, vehicles, and especially earthquakes, a movie clip was designed to try to express the noises visually through MATLAB programming. By extracting different kinds of data points that represent the noises, a MATLAB movie clip was made which was then converted into a .mov file through a program called iMovie, connecting visual graphics to the audio sound. This project will serve as the genesis for a future display to public visitors in the new Science Educational Center.