PMA **Advanced RF Photodiode Signal Processing Development**
Ellery Ames
Mentors: Vern Sandberg and Dick Gustafson

We are developing a new RF photodiode circuit topology that is designed to decouple the tuning of the circuit from an internal capacitance of the photodiode, resulting in better phase stability of the signal. The frequency carrying the gravitational wave signal is separated out from the rest by a series of LC-traps, each of which resonates at only one frequency. This simple design, allows for quick tuning and characterization of new photodiodes. A SPICE simulation package, SwitcherCADIII is used to quickly and efficiently design circuits. Testing and characterization of circuits is done electronically using an injected test signal and also with a test optical setup. Initial results indicate the topology has potential; further analysis of the test data will be needed to determine if replacement of the existing photodiodes is in order.

PMA **Investigating a Parametric Instability in the LIGO Test Masses**
Hans Bantilan
Mentor: William Kells

We investigate a parametric instability in the LIGO interferometers that has the potential to adversely affect instrument sensitivity. Such an effect arises from the excitation of mirror test-mass acoustic modes by an incident optical field, and the subsequent resonant scattering of the optical carrier mode into a superposition of higher-order optical cavity modes. This instability can be described by a single characteristic quantity termed the parametric gain R. The work involves developing code to evaluate R for various acoustic and optical field patterns on the surface of a mirror test-mass. An FEM software package is used to calculate acoustic mode deformation patterns of an advanced LIGO test mass, and FFT code is used to numerically simulate relaxed optical field patterns in an interferometer arm. By determining the R value under different conditions, the extent of parametric instability in the interferometers is systematically mapped.

PMA **DC Readout at the LIGO 40-Meter Interferometer**
Darcy R. Barron
Mentor: Sam Waldman

Currently, Initial LIGO is using RF phase modulation of the input beam to encode the output gravitational wave signal. The new DC readout scheme for Advanced LIGO will use amplitude modulation of the main laser field as the gravitational wave signal. This new method will eliminate several noise sources. The DC readout requires new in-vacuum hardware, including a mode-matching telescope and an output mode cleaner. The purpose of this project is to characterize the components of the DC readout experiment at the LIGO 40-meter interferometer and install the setup in the vacuum chamber of the interferometer for testing.

PMA **Optomechanical Alignment Instability in the LIGO Mode Cleaners**
Jenne Driggers
Mentors: Alan Weinstein and Rana Adhikari

In order to increase sensitivity to weak gravitational wave signals in the Laser Interferometer Gravitational Wave Observatory (LIGO) it is important to reduce all noise sources. In particular, core optics hang from pendulums to mechanically filter seismic noise. In combination with the high-powered laser used in the interferometer, these pendulum systems can cause an interesting problem. If the laser beam is not hitting the mirror in the center, the radiation pressure of the light can push the mirror out of alignment. If the torque due to the laser light is larger than the damping torques of the pendulum and the servo, the cavity can become unstable. As LIGO prepares to upgrade its system, including adding higher-powered lasers, it is useful to determine if the higher power will cause the cavities to become unstable. We are developing a model of this optomechanical alignment system to study the instability and determine the specifications of a servo to control it. We have also assembled and used a laser-based system to test the photodiodes in the Mode Cleaner servo, and have built and implemented a low-pass filter to improve the Mode Cleaner servo as part of an effort to measure and model this instability.

PMA **Seismic Disturbances' Effects on the Mode Cleaner Suspension Filtered by the Seismic Isolation System HAM-SAS**
Michael Forte
Mentor: Virginio Sannibale

A new seismic isolation system, Horizontal Access Module Seismic Attenuation System, [HAM-SAS] for Advanced LIGO, based on the mechanical properties of the harmonic oscillators is under construction. Such system will be mainly used to isolate the mirrors of the optical resonant cavity (Mode Cleaner) from seismic and anthropogenic noise. The propagation of the seismic and instrumental noise through the mechanical system and the effects on the control of the mirror suspensions were studied using computer modeling. Different methods of attenuation were used on the model to create an ideal compensator; one to dampen the resonant peak of the mechanical system and keep the table steady while being worked on.

PMA **Thermorefractive Noise and Electrocaloric Dissipation**
Cameron Gibelyou
Mentor: Phil Willems

In materials with temperature-dependent permittivity, the application of a dynamic electric field induces temperature gradients and thus irreversible heat flow, leading to dissipation of energy. When the applied electric field is the optical field of a laser beam in LIGO, the energy dissipated due to this phenomenon—which is known as the electrocaloric effect—can be related to thermorefractive noise, a particular type of thermal noise in the interferometer, by the fluctuation-dissipation theorem. By computing the amount of electrocaloric dissipation, then, it is possible to determine an analytic expression for thermorefractive noise in the LIGO optics, based on various known quantities and materials parameters. Such calculations may be performed in two distinct cases: the laser beam can be assumed to penetrate the entire bulk of the optic (as in the beam splitter), or it may be assumed to penetrate only the surface coating and then reflect back (as in the mirrors). This paper examines both situations assuming optics of infinite radius but finite thickness. Future research might extend the present analysis to more strictly realistic geometries, such as the case of optics with finite size.

PMA **Thermal Self-Locking in a Fabry-Perot Cavity: Constructing and Verifying a Dynamic Model**
Michael Goldman
Mentor: Eric Black

For Advanced LIGO, it is crucial to understand precisely how temperature fluctuations in the optics caused by high circulating laser power and non-zero absorption affect the resonator system. This study addresses a mechanism whereby the thermal expansion of an absorptive optic causes the Fabry-Perot cavity to lock to the side of a resonance peak. This lock has been observed to persist stably for several minutes. Previous evidence of this effect had been obtained by dithering the laser frequency and observing the reaction of the locked system but the existing static model did not explain this behavior. That model was used as a basis for the construction of a dynamic model that could predict the system's response to frequency dithering. Understanding this dynamic behavior is important, considering gravitational waves effectively dither the LIGO cavity length. Using a small test cavity, various qualitative observations of the locking mechanism were made that support the static and dynamic models. Further research will include taking data with frequency dithering to refine the dynamic model and performing additional experiments to further confirm the static model.

PMA **Searching for Gravitational-Wave Bursts of Arbitrary Waveform**
Rubab Khan
Mentor: Shourov K. Chatterji

One class of signal LIGO is searching for consists of short duration gravitational wave bursts of a priori unknown waveform. Potential sources include core collapse supernovae and the coalescence of binary black holes. To detect such events, existing search algorithms project the LIGO data stream onto various time-frequency bases and then search for regions of excess signal energy. One of these search algorithms, the Q Pipeline, determines the statistical significance of events based solely on the peak signal observed in the time-frequency plane. This project investigated extensions to this approach that also consider the statistical significance of arbitrarily shaped regions in the time-frequency plane by exploiting the advantages of data clustering. After considering various aspects of different data clustering methods, density based clustering algorithms were chosen to be the best fit for our purpose due to its ability to find arbitrarily shaped clusters and reject noise. A density based clustering function has been implemented, extensively tested, and integrated with the standard Q pipeline burst search algorithm.

PMA **The Study of Upconversion of Seismic Noise Into the 50-200 Hz Gravitational Wave Detection Band**
Jeremy Leach
Mentors: Ken Franzen and Valera Frolov

Upconversion, the process by which two frequencies couple to produce power at their sum, is a common phenomenon in signal analysis when an output signal contains nonlinear terms in the input signal(s). This is believed to be the cause of some of the most important and yet least understood features in LIGO's gravitational wave detection channel, particularly broadband noise between 50 and 200 Hz. Power in this band appears to be correlated with low-frequency seismic noise (.1-10 Hz), which leads researchers to believe that increased power in the 50-200 Hz band is in fact the result of upconversion. The purpose of this project is to quantitatively characterize this upconversion. This will be accomplished using a variety of software programs to calculate the bicoherence, a measure of nonlinearity, between various channels. Many of these software tools are still in the testing phase, but they will soon be used to better understand seismic upconversion by measuring the bicoherence in LIGO's gravitational wave detection channel under various seismic conditions.

PMA **Estimating Instrumental Correlations Between Collocated Gravitational-Wave Interferometers**
Milivoje Lukic
Mentor: Vuk Mandic

One of the sources targeted by LIGO is the stochastic background of gravitational waves, that could be either cosmological or astrophysical in nature. The gravitational-wave stochastic background search is performed by cross-correlating outputs from two interferometers. For collocated interferometers, this method is susceptible to instrumental correlations. This project focuses on developing and implementing a new technique of estimating and suppressing instrumental correlations between different interferometers. In particular, we estimate instrumental correlations by time-shifting the output of one interferometer by ~1sec, i.e. sufficiently long so that gravitational-wave correlations are expected to disappear. This technique could lead to a factor of 10 improvement in sensitivity to the stochastic background of gravitational waves.

PMA **Development of a Noise Budget for the LIGO 40-Meter Prototype Interferometer**
David Malling
Mentor: Alan Weinstein

The Laser Interferometer Gravitational Wave Observatory (LIGO) 40-meter prototype interferometer at Caltech is operated as a test bed for new concepts and technologies for application to the full-scale, four-kilometer LIGO observatories. The observatories are constructed to measure strain changes in their main arms up to a factor of 10^{-18}, requiring extremely precise measurements to be made with a high signal-to-noise ratio. An understanding of the different types of noise affecting interferometer readings is essential to gravitational wave detection. The 40-meter prototype uses hardware developed for the next generation of gravitational wave detectors; an understanding of the contribution of noise to this hardware is critical to their implementation in the full-scale observatories. To construct a noise budget for the 40-meter prototype, existing noise budget software developed originally at the observatories has been modified to account for the Advanced LIGO hardware in the 40-meter. The program has also been modified for reuse in future experiments. Results show the effect of the detuned resonant sideband extraction configuration of the interferometer on noise signal levels.

PMA **Developing Tools to Display WaveBurst Results in Near-Real Time**
Lisa Mauger
Mentor: Igor Yakushin

The search for gravitational waves using LIGO interferometer detectors includes the examination of short duration signals called bursts expected to emanate from a range of astrophysical sources. The WaveBurst algorithm is currently used to identify instances where strong short duration signals in the gravitational wave channel are coincident on all three LIGO interferometers. Adapting the current online analysis framework to process data in real time provides more rapid identification of time increments that contain signals of this nature. Additional tools created for the WaveBurst analysis pipeline incorporate improved error handling and progress verification to decrease the amount of user supervision required. Tools for improved system monitoring were added to provide detailed status reports. This online processing upgrade makes WaveBurst trigger results available in real time during science runs while increasing the flexibility of the framework and accommodating common system delays and difficulties automatically.

PMA **Development of a High Frequency Burst Analysis Pipeline**
Jeff Parker
Mentors: Rick Savage, Greg Mendell, and Malik Rakhmanov

LIGO's current searches for gravitational waves take place in the sub-8 kHz regime. Sensitivity drops off for higher frequencies, but a narrow peak occurs at the free spectral range (FSR) frequency, 37.52 kHz. A channel with sufficient sampling rate has only been recently installed, and analysis at this frequency is uncharted territory. An analysis pipeline to be used for determining detection efficiencies has been created. The pipeline consists of two main components. The first component is the frequency and sky position dependent detector response which takes an arbitrary waveform and modifies it to what would be outputted by the detector and added to interferometer noise. For signals with a frequency near FSR, the peak in sensitivity causes resonance and an exponentially decaying ringing in the modified signal, with a decay time of about 2 ms. The second component is an excess power algorithm, used to determine if a signal is present by looking for power greater than expected due to noise alone. The analysis pipeline allows us to inject signals from sources located at various positions in the sky and compute detection efficiency near FSR, as well as compare the all-sky average efficiency to that at low frequencies.

PMA **Spatially Directed Searches for Gravitational Wave Bursts**
Chris Pointon
Mentor: Peter Shawhan

Currently LIGO and other gravitational wave interferometers are collecting data in the hope of detecting of a wave with known or unknown form. This is done currently over the entire sky. In this project the issue of doing gravitational wave searches at discrete points of the sky rather than the current method was addressed for unknown '*burst*' waveforms. An algorithm was developed to test the antenna response of arrays of two, three, four and five detector networks which was specifically focused on the value of the second highest response minimized or averaged over the polarization angle of the wave. Results obtained show that over the entire polarization range that the two detector array provides no new constraints on measurement. Results for three, four and five detector arrays yielded more positive results as the detector number increased with an average minimum of the second highest response at roughly 0.15 for a four detector network measuring a source at the galactic centre. Finally injected gravitational waves were detected using a modified version of the current LIGO detection algorithm to study the ability of making detections when studying a small number of sky points.

PMA **Studying Black-Hole Mergers With Networks of Gravitational-Wave Detectors**
Stephen Poprocki
Mentor: Patrick J. Sutton

The goal of this project is to quantify and compare the ability of several coherent data analysis techniques, applied to the LIGO and LIGO-Virgo gravitational-wave observatory networks, to detect the gravitational-wave signal of merging binary black holes. Predicted black-hole merger signals for system masses of 20-200 solar masses were injected into a standard 24-hour set of simulated LIGO-Virgo data. Using the LIGO-Caltech computer cluster, the Xpipeline coherent analysis software package computed time-frequency maps for each of the standard likelihood, hard and soft constraint likelihoods, elliptic polarization likelihood, and the total energy detection statistic. Receiver operating characteristic plots were made to compare the performance of each likelihood statistic.

PMA **Characterization of an Advanced Converter Design**
Rachel Reddick
Mentors: Joshua Myers, Paul Schwinberg, and Daniel Sigg

The Laser Interferometer Gravity-Wave Observatory [LIGO] uses analog-to-digital [AD] and digital-to-analog [DA] converters in its sensing and control systems to permit communication between computers and hardware. The upgrade to Advanced LIGO will be more sensitive and requires the use of more converters. The goal of this project is to test a new converter design, which is less expensive and has lower noise levels than the current converters. Comparing the response of the converters to known test signals permits an assessment of the converters' performance. Results so far indicate that the new analog-to-digital converters have significantly lower noise levels than the previous converters. Data gained from this project will be used to determine what changes will need to be made for the final converter design.

PMA **Optical Lever Noise**
Royal Reinecke
Mentors: Alan Weinstein and Rana Adhikari

In the LIGO interferometers, optical levers are used to monitor and control the angular motion of the suspended mirrors. Optical lever servos are essential for establishing or regaining lock, so the better they perform, the faster lock can be achieved, thereby increasing the total amount of time that useful data can be taken. My particular project deals with characterizing the various sources of noise in the optical levers at the 40m prototype interferometer at Caltech. I have studied the optical lever noise at the 40m due to mirror motion caused by the servo, electronic noise, and noise due to optical lever laser intensity fluctuations. This information can be used to determine the contributions of the various noise sources to the total noise. From this data, I am working to reduce the dominant sources and lower the overall noise in the optical lever system.

PMA **Suppression of LIGO Mirror Vibrational Mode Q's**
Matt Seaberg
Mentor: Eric Black

There is some concern that parametric instabilities due to coupling of optical cavity modes and mirror vibrational modes could occur in AdvLIGO. Likelihood of this occurring depends strongly on the mechanical Q's of the mirror vibrational modes. In this experiment we investigate the possibility of suppressing these Q's by placing copper ringbands around LIGO mirrors. Measurements are made at the Thermal Noise Interferometer, which is used to measure coating thermal noise in AdvLIGO mirror prototypes. Initial results indicate that Q's are indeed suppressed, although more research is necessary to confirm this. Also observed are undesirable vibrations that cover up coating thermal noise. Further work to design ringbands that do not exhibit this characteristic is in progress.

PMA **Analysis of the LIGO Output Mode Cleaner**
Matthew Sieth
Mentors: Keita Kawabe and Dick Gustafson

Gaussian beams are converted into higher order Hermite-Gaussian modes within LIGO when the beam wave fronts are either misaligned or mismatched with the optics. These modes do not contain any gravitational wave information and are problematic at the AS port photodiode in several ways. The LIGO output mode cleaner is an optical cavity placed between the beam splitter and AS port photodiode, which is intended to reject higher order modes. Two generations of the output mode cleaner have been tested at the LIGO Hanford Observatory with limited success. While both output mode cleaners showed some good characteristics, they also generated an enormous amount of noise. The noise mechanism for the output mode cleaner has not yet been fully understood. We have analyzed the output mode cleaner via simulation in order to gain an understanding of the noise mechanism. Through simulation we have discovered a possible candidate for the noise mechanism involving the coupling between the fundamental carrier and higher order sidebands. The validity of this mechanism remains to be tested in further research.

PMA **Effect of Ring Dampers on Thermal Noise in LIGO TNI**
Cacey Stevens
Mentors: Eric Black and Akira Villar

The Laser Interferometer Gravitational Wave Observatory (LIGO) was developed to detect gravitational waves from astronomical sources. However, noise and instabilities are preventing LIGO from detecting waves within its targeted frequency range. These various kinds of noise must be suppressed to actually detect gravitational wave signals. Ring dampers made of copper have been designed and placed on an output mirror of one of the optical cavities. Copper rings are expected to decrease parametric instabilities in the cavity by lessening the vibrational mode Q's of the mirror. Thermal noise of the mirrors, which is a significant part of the noise budget, may increase due to the placement of rings. The ring dampers are tested in the Thermal Noise Interferometer (TNI), and measurements were made to find any changes in thermal noise due to the rings.

PMA **Finding Nearby Sources of Continuous Gravitational Waves**
Grant Webb
Mentors: Greg Mendell and Mike Landry

Asymmetric compact spinning objects such as neutron stars are thought to be sources of continuous gravitational waves. Although these periodic signals are expected to be weak, LIGO may be able to detect them by powerful match filtering and power-averaging techniques. Currently LIGO ignores the effects of proper motion, which has a significant effect on the phase and beam pattern of gravitational waves produced by nearby sources that are monitored for an extended period of time. We have edited existing C code to create a fake signal, which accounts for the source's proper motion. To search for signals we use the maximum likelihood statistic without accounting for proper motion. After analysis we have determined the loss of detection efficiency as a function of observation time when the proper motion parameters are included in the source simulations but are not included in the search method.

PMA **No Project Title**

Alexei Zaliznyak

Mentor: Duncan Brown

Abstract not submitted