

### **Upgrade of Thermal Compensation System for Enhanced LIGO**

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The LIGO thermal compensation system corrects thermal distortions in the optics caused by heating from the main laser beam. A CO<sub>2</sub> laser remotely heats the entire optic in a central or annular heating pattern. The planned upgrade of the LIGO interferometers from Initial LIGO to Enhanced LIGO will include increasing the laser power of the main beam. The increased power will require greater thermal compensation power. A new laser optical table has been set up and the power of the thermal compensation system is being upgraded from 10 W to 35 W. This power upgrade requires intensity stabilization of the laser to reduce noise coupling to the interferometer. Also, the annular mask currently used to create the annular heating pattern will be replaced by conical optics.

### **Automated Optimization of the Damping and Control of the Suspended Optics at the 40m Interferometer**

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The Laser Interferometer Gravitational-Wave Observatory (LIGO) is a facility dedicated to the detection of cosmic gravitational waves and the measurement of these waves for scientific research. The sensitivity to gravitational waves depends strongly on the quality of the optic systems. Optics are suspended as pendula in order to isolate them from high frequency vibrations, and a suspension controller system is used to damp the pendulum modes. The suspended optics should be actively damped at resonance, without applied forces at the higher frequencies in the range of detectable gravitational waves. This project focuses on the optimization procedures for the damping and control of the suspended optics. It was based at the 40 m Prototype Laboratory at Caltech, a facility used to test and develop LIGO technology. Using Matlab programs and different tools and scripts for getting data from the main data acquisition system, a number of programs were written that optimize various aspects of the system. When run, these programs interact with the interferometer, exciting or changing the damping of the suspended optics in order to collect the data necessary for the optimization. The programs will be executed periodically in order to keep the system optimized as conditions change over time.

### **Investigations With the Prototype Output Mode Cleaner Suspension: A Study of Its Design and Performance**

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The Output Mode Cleaner (OMC) has been designed for use in the Advanced LIGO gravitational wave detectors, and it will work as a resonant cavity to filter unwanted noise from the output signal of a detector. The OMC will consist of a silica bench supporting the cavity optics. It is required to be isolated from ground vibrations to avoid addition of noise to the output signal. The isolation is provided by suspending the bench as the bottom mass of a double pendulum. Aspects of the OMC suspension were tested using a dummy metal bench. Transfer functions were measured to obtain the resonant modes, which were in good agreement with results obtained from a MATLAB model of the suspension. Damping tests were carried out to ensure all the modes can be effectively damped using six optical sensors and electromagnetic actuators. The bending stiffness and elastic modulus of electronic wires that will be connected to the bench were measured to allow investigation of whether they will interfere with the isolation. The tests completed have shown that the suspension is functioning as expected.

### **Timing Synchronization for Advanced LIGO Timing System**

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The demands for the advanced LIGO timing system are to achieve timing accuracy and an overall clock synchronization with a precision of better than 1 microsecond. The new prototype of the timing network employs field-programmable gate arrays as its primary logic units, instead of discrete logic implemented within the initial version of the timing system. These gate arrays were programmed to sustain a reliable transmission of synchronization marks every second, with the individual adjustments for the traveling-time delays to each remote location, and to detect and report occurring synchronization errors, if any. Additionally, the same channel is used to distribute the complete timing information provided by the Global Positioning System. Finally, the system was upgraded to transmit, receive and temporary store various data packets which, if necessary, could be read by an external PC via serial interface.

### **An *in situ* Characterization of the LIGO Optics**

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Power loss due to absorption and scattering by the LIGO optics contributes to decreased laser power and increased shot noise in the LIGO interferometer. Improved characterization of this power loss allows for further improvements to the optics. The absorption by the mode cleaner optics was measured and modeled. The measurement was done by measuring the frequency shifts of the drumhead eigenmodes as the optic was heated. The modeling connected the frequency measurements to the power absorption. The absorption was found to be 18, 42, and 61 ppm for the mode cleaner optics. A study of the scattering from the core optics was also performed. The amount of scattered light was measured at different angles using a photodetector outside of the vacuum viewports. The results were used to determine how much of the total amount of light scattered was due to point defects and how much was due to microroughness.

### **Time-Variable Interferometry for LIGO Lock Acquisition**

Philip Graff

*Mentor: Sam Waldman*

The initial lock acquisition process of the LIGO interferometers requires holding four degrees of freedom to precise lengths at the same time. To simplify this procedure and prepare for the addition of a fifth degree of freedom in Advanced LIGO, we seek to generate a control signal from the interferometer that will isolate the long arm cavity degrees of freedom from the other lengths. This is difficult due to the interference between the many paths that the light may take through the optical cavities. We model the LIGO interferometer using a coupled three-mirror cavity and test locking methods with MATLAB simulations. We use standard Pound-Drever-Hall locking fields with a superimposed periodic pseudo-random phase modulation. The periodicity allows the light to resonate within the long first cavity, while the noisy structure does not allow the shorter second cavity to resonate at any position. The resulting error signal is capable of holding each arm cavity to within one nanometer over large variations in the other cavities. Testing of this method can be done on the 40-meter interferometer and on Enhanced LIGO before full implementation with Advanced LIGO.

### **Reduction of Signal-to-Noise Ratio for Eccentric Binary Inspiral Signals Recovered With Circular Inspiral Templates**

Vibha Laljani

*Mentor: Eirini Messaritaki*

We investigate if matched filtering using circular inspiral templates is adequate for detection of eccentric binaries in Advanced LIGO. The importance of the project for Advanced LIGO lies in the fact that the low-frequency cut off will be at 10 Hz, instead of 40 Hz for Initial LIGO. Thus inspiraling binaries will enter the frequency band earlier in their evolution and will be less circularized than when they enter the Initial LIGO frequency band. Therefore, it is expected that there will be a greater number of eccentric binaries to be detected. We wrote code to compute eccentric inspiral waveforms and to calculate the overlap between those waveforms and circular inspiral templates. The results that we have attained use waveforms and templates to leading post-Newtonian order; all post-Newtonian corrections have been ignored. However, we have completely developed the infrastructure necessary to perform investigations with more accurate waveforms and we recommend that those are performed once higher-order post-Newtonian eccentric waveforms are available.

### **Beyond Dawn: Big Bang Gravitational Wave Background Searches**

Grant Meadors

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Many cosmological models, including inflation, cosmic strings, and pre-big bang theories, predict a stochastic gravitational wave background. LIGO searches cross-correlate signals from two 4 km interferometers separated by 3000 km, providing unprecedented sensitivity to this background around 100 Hz. We obtain an uncertainty of less than  $5 \times 10^{-6}$  in gravitational wave energy density in an isotropic analysis, normalized to the critical energy density for closing the universe, and we develop a technique for mapping the background in terms of spherical harmonics. Results could test cosmology as far back as the Planck time, and may reveal new objects of astrophysical interest.

## **Analytical and Numerical Calculations of Thermal Lensing in TGG and DKDP Crystals for the Enhanced LIGO Interferometer**

Alice E. Ohlson

*Mentor: Antonio Lucianetti*

The Laser Interferometer Gravitational-Wave Observatory (LIGO) utilizes a Faraday rotator for optical isolation. Inside the Faraday rotator are two TGG crystals which are susceptible to thermal lensing, due to internal temperature gradients induced by high laser powers. This effect can be compensated for by a  $-dn/dT$  material, such as DKDP. It is necessary to theoretically and experimentally characterize both the positive thermal lens created by the TGG and the negative thermal lens created by the DKDP over a range of laser powers. The temperature profile in both crystals was determined theoretically as well as with COMSOL, which performs finite-element modeling. The thermal lenses of TGG and DKDP were measured in vacuum and in air at different laser powers, using the z-scan technique to determine the focal length of the optical system. As expected, the effect of the thermal lens was stronger with increased laser powers, with the focal length being shortened by TGG and lengthened by DKDP, although there was no difference between in-vacuum and out-of-vacuum measurements. However, it was seen that the thermal lens created by the windows of the vacuum chamber exhibited a stronger laser power-dependence than the thermal lens created by either the TGG or the DKDP.

## **Newtonian Noise Simulation and Suppression for Advanced Gravitational-Wave Interferometers**

Keenan Pepper

*Mentors: Rana Adhikari and Phil Willems*

The next generation of gravitational-wave interferometers will have mechanical isolation systems so effective that seismic noise will be negligible at 10 Hz and above. In this frequency region (which is important for both massive black hole mergers and the gravitational stochastic background), the dominant noise source will be Newtonian gravity noise caused by fluctuations in the distribution of matter around the test masses. This gravitational force cannot be shielded, even in principle, but its effect can be estimated from independent measurements and subtracted from the output data. In the present work, the vibrations of the vacuum chamber and support columns were modeled with finite element analysis software to estimate their contribution to the Newtonian noise. It appears that this contribution will be at least a factor of ten smaller than that caused by vibrations of the soil and the concrete foundation slab, so initial implementations of Newtonian noise cancellation should ignore the chamber and focus on the ground. To evaluate the feasibility of different filtering algorithms for this application, several multiple-input multiple-output (MIMO) filters were developed with the goal of implementing active cancellation of seismic noise at the 40-meter prototype lab as a proof of concept.

## **Bidirectional Reflectance Distribution Function Measurement**

Riley C. Daniel

*Mentor: Michael Smith*

The purpose of my project was to build a highly sensitive scatterometer capable of measuring back scatter of materials that will be used to control scattered light in Advanced LIGO. This measurement is referred to as the Bidirectional Reflectance Distribution Function (BRDF). The primary material of interest is welder's glass placed at Brewster's angle. The scatterometer functions by shining a laser, which passes through a mirror with a hole, onto the surface of interest. The backscattered light is reflected by the mirror to a lens that focuses the image of the scattering surface onto a photodiode and a camera via a beamsplitter. This allows us to measure the power and to determine if any light is being scattered by dust particles. A chopper is used to modulate the signal so a lock-in amplifier can reject the extraneous noise. The behavior of the light rays in the system are well understood by modeling them in SolidWorks and by carrying out gaussian beam propagation calculations in Matlab. In the coming weeks, several more ordered parts will be implemented, and the system will be calibrated. We anticipate that a successful measurement of the BRDF will be made.

## **Measurements of the Noise Due to Light Scattering in LIGO Beam Tubes and the BSC Seismic Isolation Stack Transfer Function**

Christopher Rinaldi

*Mentor: Brian O'Reilly*

Due to small imperfections in the LIGO mirrors, some photons from the main beam scatter at small angles. Upon interacting with the non-seismic isolated beam tube wall, some of these photons undergo a phase shift and recombine with the main beam creating noise in the gravitational wave channel. To measure this effect, piezo-electric shaker tables were used in conjunction with Endevco accelerometers. The beam tube wall was excited at various frequencies and a coupling function was calculated between the movement of the wall and the gravitational wave channel. "Hotspots" have been found that contribute to the overall noise in the interferometer, requiring future upgrades to fix this problem.

The BSC Stack Transfer Function measures how various displacement inputs are attenuated by the passive isolation system. A complete understanding of this function would allow confirmation of a model provided by the manufacturer and help ensure that no unknown resonances exist that limit the sensitivity of the interferometer. Piezo-electric shaker tables were used to excite the BSC 4 support beams and the effect was observed in the gravitational wave channel. The results were consistent with the level of isolation expected from the model.

### **Investigations of “Mesa” Beams for LIGO**

David Zeb Rocklin

*Mentors: John Miller and Riccardo DeSalvo*

Mirror thermal noise is one of the limiting factors in the sensitivity of current and future gravitational wave observatories including Advanced LIGO. Non-Gaussian beam profiles such as the flat-topped “mesa” beam can be employed in gravitational wave interferometers to reduce the effect of this noise. Mesa beams are generated in a Fabry-Perot cavity by replacing the baseline spherical mirrors with “Mexican Hat” (MH) mirrors which have a different profile. MH cavities differ from traditional cavities in both theoretical and practical ways. MH cavities are a few times more sensitive to tilt, causing increased coupling to higher-order modes that reduces the sensitivity of the device. We use wavefront sensing to demonstrate an error signal that can be used to measure the alignment of the cavity. This technique is vital for automatic cavity alignment.

### **Survey of Newtonian Noise Sources at LIGO Hanford**

Jaclyn R. Sanders

*Mentors: Michael Landry and Frederick Raab*

Advanced LIGO is projected to reach sensitivities such that environmental gravitational attractions, or Newtonian noise (NN), will limit detection of gravitational waves at low frequencies. As gravitational forces cannot be shielded, understanding the sources of Newtonian noise and removing the length noise they cause may increase Advanced LIGO’s sensitivity. The main sources of Newtonian noise at LIGO Hanford are coherent vibrations of finite objects near and Rayleigh waves in the ground beneath the test mass. Accelerometers were mounted on the seismic isolation support piers to determine their modes and magnitudes of oscillation, and found significant resonances at approximately 10 Hz and 14 Hz. Seismometers were arrayed around the Y-end station to determine the approximate magnitudes and coherence length for the incoming Rayleigh waves. The coherence length was found to be approximately 4 m. It was also shown that the foundation slab of the building does not have significant resonances and transmits seismic waves in the same manner as the ground outside of the building. According to BENCH estimations, the seismic noise can reduce astrophysical range by as much as 50%.

### **Folded Sideband Resonant Output Mode Cleaner for LIGO 2-km Interferometer**

Gregory F. Snyder

*Mentor: Richard Gustafson*

I investigate a folded sideband resonant output mode cleaner for the LIGO two-kilometer interferometer. Three successive optical table-based triangular 10-meter OMC cavities have been built which resonate sidebands at 29 MHz; we started with a 2.5 meter one-fold cavity, and presently have a 45-inch five-fold cavity. A carrier-based dither lock was implemented and the cavity behavior studied; locks are minutes in duration. A sideband-based, carrier independent dither lock was devised. Alignment and noise have been challenging; we estimate a length noise of order 1 nanometer. The noise-induced conversion fraction of a phase modulated carrier-sideband test signal (token noise process) is reported and analyzed.

### **Application of Artificial Neural Networks to LIGO Compact Binary Coalescence Searches**

Rebecca Tucker

*Mentor: Alan Weinstein*

The LIGO compact binary coalescence analysis is developing robust methods for separating signal from background. When a gravitational wave candidate is detected in two or more interferometers in coincidence, it is subjected to a series of follow-up tests to determine whether it is legitimate. These “follow-ups” do not use all the potentially useful information available from the detectors. Artificial neural networks were developed for this analysis so that unused information could be included to help rank event candidates in an unbiased way. Gravitational wave injections into the inspiral pipeline and background events (accidental coincidences) were used to train the networks. It was found that the neural networks separated signal and background more effectively than the current ranking statistic. Neural networks can be a potentially powerful tool in the search for compact binary coalescence signals in the LIGO data.

### **Bumps in the Big Bang: Simulating Fluctuations in a Gravitational Wave Background**

Madeleine Udell

*Mentors: Stefan Ballmer and Vuk Mandic*

Gravitational wave backgrounds predicted by inflation, string theory, and pre-big-bang cosmology may provide a rare opportunity to test these theories of the beginnings of the universe. Phase transitions in the early universe as far back as the Planck scale would produce gravitational waves and amplify existing vacuum fluctuations in the gravitational wave background. By 2013, LIGO detectors may be sensitive enough to detect the gravitational echoes of these processes. The size of the spacial variations in the background would reveal evidence of the structure of the universe at the time of these transitions. Here, we implement and test an analysis to determine the size of inhomogeneities in the gravitational wave background using spherical harmonics. We simulate the signal in each detector from a given spherical harmonic map, and recover the injection from the data by correlating the signals in each of the LIGO interferometers.

### **Next-Generation Radio Frequency Photodiodes for Gravitational-Wave Interferometers**

Alice Z. Wang

*Mentors: Alan Weinstein and Rana Adhikari*

The Laser Interferometer Gravitational-wave Observatory detects gravitational waves by sensing minute relative displacements of test mass mirrors using the interference formed by laser beams which are modulated at radio frequencies. The light beams are detected by multiple radio frequency photodiodes monitoring the displacements and angular motion of the interferometer. This project entails the design, development, and testing of a new radio frequency photodiode preamplifier for improved performance. Instead of a resonant circuit around the photodiode and a single tank filter for the unwanted first harmonic signal as in the circuit currently used in the interferometers, the new design uses parallel capacitor-inductor tank circuits to increase diode capacitance insensitivity, decrease signal nonlinearity, and optimize signal isolation. Test results from a prototype circuit as well as circuit analysis models show improvements made on the radio frequency photodiodes. Data gathered from this project also provide useful component specifications for future photodiode development.

### **Automated Analysis of the Transverse Modes of a Stabilized Laser Beam Transmitting Through a Mode-Cleaning Optical Cavity**

Joshua Weiner

*Mentors: Alan Weinstein and Rana Adhikari*

The LIGO interferometers can be sensitive to gravitational waves once all non-fundamental noise sources have been made negligible. One such non-fundamental noise source is unwanted "junk" laser light at the gravitational wave readout port of the interferometer. The next generation of interferometric gravitational wave detectors based on the current LIGO detectors, called Advanced LIGO, will include an optical mode-cleaning cavity known as the Output Mode Cleaner (OMC) that filters out the "junk" light while transmitting the rest of the light to the gravitational wave readout port. A similar OMC is already being tested at the 40 meter prototype interferometer. An automated mode-scanning process to analyze the content of the light exiting the 40 meter lab's OMC, which will be useful for tuning the OMC alignment and quantifying readout noise, was developed with the aid of digital image processing.

### **Beam Pointing and Its Effects on Intensity Stabilisation**

Alan Zablacki

*Mentor: Peter King*

The principal goal of this project is to study the performance of an acousto-optic modulator (AOM) as the power actuator of a single-frequency, single-mode, solid-state diode-pumped laser. This involves measuring the beam propagation to determine parameters such as the beam waist and beam quality, in order to set up an optical system which maximises diffraction efficiency of the AOM. We obtain the beam pointing measurement introduced by the AOM, and determine the relative intensity noise and the AOM transfer function. We design a servo loop based on the transfer function, to suppress the noise level and compare that to shot-noise to allow us to determine whether we are shot-noise limited.