

LIGO SURF Projects, 2004 **Projects at Caltech**

Nonstationary Noise Detection in LIGO

Jason M. Sussman

Mentor: Eric Black

A gravitational wave is expected to make a difference in the distance between two objects of no more than a thousandth of an atomic nucleus over the distance of a kilometer: interferometric gravitational wave detectors are very susceptible to noise. This project focuses on nonstationary noise from the apparatus itself, which could be misinterpreted as a signal. To gain a better understanding of this noise, an algorithm that records nonstationary events was applied to the data stream of a short-, parallel-arm interferometer. The use of such an interferometer allowed easier recognition of nonstationary noise: if an event occurred in only one of the two arms, it probably has no external cause. By close examination of more of these events, their pattern could be found, allowing the creation of a matched filtering system that would both ignore false positives in LIGO and enable more refined experiments to determine how often these events occur.

Further Consistency Tests for Gravitational Wave Inspiral Searches

Matthew M. Wroten

Mentor: Peter Shawhan

General Relativity predicts that accelerating masses produce gravitational waves. The Laser Interferometer Gravitational-Wave Observatory (LIGO) project is attempting to detect them. One source of these waves is paired inspiraling neutron stars. LIGO uses matched filtering and a chi-squared test to extract such waves from background noise. Although this successfully detects simulated inspiral events, detector noise produces glitches that these tests mistakenly identify as inspiral events too. Thus, an additional class of consistency tests is proposed.

A real inspiral event produces a single, sharp, distinguished peak in the matched filter output. The proposed class of tests compares the peaks produced by alleged inspiral events to the filter output at nearby times. If the peak is not solitary, i.e. if there are many peaks of similar magnitude within a small time interval of the main peak, then the event is rejected as unauthentic.

This class of tests is used on data collected from each of the three detectors (two in Hanford, Washington and one in Livingston, Louisiana) during the third LIGO science run. Then, it is determined which of these tests in what combinations reject as many false events as possible while maintaining minimal loss of real ones.

Low-Frequency Electromagnetic Anti-Spring Control Circuit Development for LIGO

Yanyi Chen

Mentor: Riccardo De Salvo

Seismic attenuation is crucial to gravitational-wave detection. In order to provide a higher level of seismic isolation, a tunable electromagnetic anti-spring of a variable spring constant is to be added in parallel to the metallic anti-spring to fine-tune the combined constant, and bring the system resonant frequency down to 30mHz. The electromagnetic anti-spring can be realized by a control circuit, which consists of a LVDT position sensor, a gain stage (amplifier) with thermal compensation, a voltage saturation alarm and an actuator. We've made necessary modifications to the two existing circuits (the LVDT and the amplifier) to improve the system performance. We've designed the voltage saturation alarm and added it to the control circuit. A printed circuit board merging all parts of the control circuit is being assembled and tested. This system can be applied in future LIGO gravitational-wave detectors to improve their low-frequency sensitivities.

Burst Analysis using R-Statistics, Power and Correlated Excess

Imre Bartos, Pinkesh K. Patel and Péter Raffai

Mentors: Laura Cadonati and Szabolcs Márka

The LIGO gravitational wave Burst Analysis aims to detect short bursts of gravitational radiation. Data from multiple interferometers is cross-correlated in order to remove uncorrelated noise and enhance the correlated signal. Analysis techniques include looking for excess of correlated power over the background noise and for statistically significant excesses of correlation coefficients. The search is performed by two independent codes, one works in the Matlab environment and the other in the LIGO Data Monitoring Tool environment (DMT), in C++. The DMT C++ code is to serve as the online data analysis tool for real-time data analysis. The Matlab code will serve as a prototyping and development tool. Both codes are compatible with each other and produce the same results to machine precision. Thus far, either the

correlated excess or the correlation coefficients were used separately to analyze data. We will study the background and signal distributions within the parameter space spanned by the two variables and seek a way to efficiently combine the results of the two methods. This shall lead to an increase in sensitivity making the algorithm capable of detecting even weaker signals than before. For this we have to use these tools to analyze statistically significant datasets to draw any conclusions. Future objectives include validation, documentation and implementation of these algorithms.

Direct Digital Down-Conversion of LIGO Radio Frequency Photodetector Signals and a Digital Implementation of the PSL Frequency Stabilization Servo

Ester Guidi

Mentor: Jay Heefner

Recent developments in Digital Signal Processing (DSP) techniques and Analog to Digital Converters (ADC) have made it feasible to directly sample the LIGO Radio Frequency (RF) photodetector signals without first downconverting them to a baseband. We would like to take advantage of tools now available in order to sample RF signals and perform direct digital down-conversion. While many other systems in LIGO utilize digital signal processing (DSP), we have yet explored the possibility of replacing analog RF systems with DSP systems. The goal is to eliminate as much analog circuitry as possible in order to maximize noise rejection as well as system flexibility. Using a Stratix DSP Development Kit from Altera, we will test digital down-conversion in the LIGO 40-meter lab at Caltech or in the Lauritsen laser system. Test results will be documented in the final report for the project.

Analysis and Measurement of the Q Factor of a Monocrystalline Silicon Flex Joint for Advanced LIGO Suspensions

Francesco Costagliola

Mentor: Riccardo De Salvo

In order to minimize the thermal noise in the suspensions of advanced gravitational interferometers, a new high-Q model of monocrystalline silicon flex joint is being developed. A theoretical analysis of the vibrational modes of the joint is integrated here with computer simulations, focusing on the behavior of the resonance frequencies and mechanical losses for different applied loads. This analysis is then applied to the experimental measurement of the joint Q factor, comprehending the construction of the experimental setup and the measure of the mechanical losses for varying loads. The dependence of the Q factor on the silicon surface properties is also investigated testing flex joints smoothed via electropolishing techniques.

Comparison of Materials for the MGAS Springs in the Low Frequency Design for LIGO

Anamaria Effler

Mentor: Riccardo DeSalvo

The purpose of this experiment is to determine the best material for the MGAS springs in the suspension system for the low frequency design for LIGO. The best one would be that which allows tuning to a lower frequency with the largest attenuation frequency band, by having a better Q-factor performance and lower hysteresis. The three materials chosen for this comparison are Copper-Beryllium, Maraging and Glassy Metal. A two-blade MGAS spring made of each material is used; we measure its vertical decaying oscillation at progressively lower frequencies using an LVDT connected to a computer (which does the data acquisition).

There have been several problems connected to the setup (beats for example, exchange of energy between different modes of oscillation), which have delayed any results since the whole setup had to be redone and the measurements started from scratch again. But in the following 3 weeks remaining, if there are no more problems, a comparison of Maraging and Copper-Beryllium might be completed. This study will give a recommendation to the best material to be used, reducing the noise limit for the suspension system of the mirrors in LIGO.

Testing General Relativity Using Gravitational Wave Signals From Compact Binary Inspirals

Kevin McCarthy

Mentor: Alan Weinstein

The detection of gravitational wave signals by the LIGO project will allow for precision tests of General Relativity in the strong-field regime. The study of radiation from inspiraling binary systems of black holes or neutron stars holds particular promise for testing GR and bounding alternative theories of gravity. We are working under the premise that an inspiral waveform has been detected by a LIGO detector with a high signal-to-noise ratio, and on studying our ability to test GR and alternative theories of gravity. The technique of matched filtering is used to match the phase evolution of the detected waveform to a number

of varying templates. We investigate the sensitivity of this analysis method to high-order terms in the expansion of the gravitational waveform and quantify bounds that can be placed on parameters of the Brans-Dicke scalar-tensor theory and the mass of the graviton, as a function of the SNR.

Using LIGO to Measure Gravitational Wave Properties Using a Pulsar Source

Michael R. Quinn

Mentor: Alan Weinstein

The LIGO project provides an important new window on the physics of gravitation. The gravitational waves from pulsars are expected to produce very predictable sinusoidal gravitational waves. The simplicity of this waveform provides us with a powerful tool for measuring the properties of these waves. Relativity predicts that gravitational waves are transverse waves that propagate at the speed of light. We wish to investigate whether gravitational waves detected by LIGO with a high signal-to-noise can be used to measure the wave speed and detect the existence of longitudinally polarized waves. We simulate gravitational waves from pulsars and LIGO's response to them to investigate the ability of LIGO to verify the predictions of relativity.

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Péter Raffai

Mentor: Szabolcs Márka

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Gravitational Waves: Burst Signals Detected with LIGO

Jill Palmer Naiman

Mentor: Alan Weinstein

Burst signals are gravitational waves which are short in duration and span a broad range of frequencies. Astronomical sources which are expected to create burst signals are type 2 supernovae and black hole mergers. This project deals with several aspects of such sources including their distribution, duration, bandwidth, characteristic frequencies, and our ability to detect them with LIGO interferometers. For black hole mergers the total mass of and distance to the merger can be found by relating properties of its detected waveform to those of current models. Furthermore, the maximum detectable distance to a merger can be found as a function of mass for a given signal-to-noise ratio for Initial and Advanced LIGO detectors. For core collapse supernovae various models including Zwerger- Müller, Ott-Burrows, and Dimmelmeier-Font-Müller were used to visualize the expected signal-to-noise ratios for various distances and to characterize the physics of the source from the frequency content of the waveform.

Measurement and Improvement of the Q-factor of Monocrystalline Silicon Flex-joints for Advanced-LIGO Suspensions via Electropolishing

Simone Napolitano

Mentor: Riccardo De Salvo

Monocrystalline silicon is proposed as possible material for Advanced LIGO, for its high theoretical Q-factor. In order to measure the Q-factor of silicon-made flex joints, we have prepared an experimental setup that analyzes the mechanical loss at varying loads, under vacuum. Different improvements to the usual proceeding technique are applied to reduce thermal noise. Silicon samples are electropolished with hydrofluoric acid [HF : H₂O, 48% wt] in a polytetrafluoroethylene [PTFE] holder. Scanning Electron Microscopy [SEM] and Auger Electron Scattering [AES] are used to check out the quality of the electropolishing, analyzing both the topography of the polished surfaces and the concentration of the molecular species over the thickness of the sample.

Mirror Reflection Phase Map for FFT Simulation

Xiao Xu
Mentor: Hiroaki Yamamoto

This project is to investigate the effect of the aberrations of the optics' surface on the LIGO performance. Limited by the manufacturing craftsmanship, the surfaces of the optics, which compose the entire interferometer, suffer various aberrations: the Beam Splitters have curvatures of the order of hundred kilometers; the surface of every mirror has roughness of the order of nanometer. The LIGO performance is considerably compromised by these aberrations. Using the program **FFT** to simulate LIGO performance, we hope to get some insight about the size of the effect and to be able to give semi-quantitative predictions in the realistic situation.

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Projects at Hanford

Using the LIGO Physical Environmental Monitor and LIGO Data Tools to Detect and Characterize Impulsive Events

Jonelle L. Walsh
Mentor: Vern Sandberg

When an impulsive event occurs, seismic waves in the form of Love and Rayleigh waves travel along the Earth's surface. These waves travel from the event toward the interferometer where they are detected by the Physical Environmental Monitor (PEM) system at the Laser Interferometer Gravitational Wave Observatory (LIGO) at Hanford, Washington. Alternatively, impulsive events can be detected by using the interferometer itself. Since the interferometer has been carefully designed to be insensitive to ground motion in the frequency band at which LIGO operates, one can treat the test masses of interferometer as stable while the suspension systems and optical levers move with the ground motion caused by Love and Rayleigh seismic waves. Through the analysis of earthquake data; specifically, studying the cross correlations and coherence between the optical lever, coil, and optical sensor channels, the detection and characterization of the impulsive event is made. Furthermore, by comparison with seismometers and other instruments that compose the PEM, the sensitivity of the interferometer to impulsive events is determined.

Study of the Alignment Drifts of the LIGO Interferometers during the Third Science Run (S3)

Yulan Qing
Mentor: Luca Matone

LIGO, an acronym for Laser Interferometer Gravitational-Wave Observatory, is constructed to observe gravitational waves of cosmic origin. It uses a recycled Michelson interferometer with Fabry-Perot arms and suspended mirrors to sense the very small strains anticipated from astrophysical sources. The detector's sensitivity, however, deteriorates with the misalignments of the suspended optics. In this project we first analyzed the data from the Third Science Run to quantify the misalignments of the optics that are tolerated by the lock acquisition phase of the machine. The result of this analysis showed that the acquisition phase can tolerate misalignments of about 10% of the beam divergence. In the second part of the project, we quantified the angular fluctuations as recorded by the Wave Front Sensors and we analyzed the dominating spectral frequencies. We found that the typical angular excursions are on the order of nano-radians for the differential ETM angular degree of freedom. We plan to analyze the angular fluctuations under different seismic excitations.

Development of Burst Event Analysis Tools for High-frequency Gravity-Wave Channels

Robert W. Robertson

Mentors: Rick Savage and Greg Mendell

The sensitivity of a LIGO 4km interferometer peaks at multiples of the cavity free-spectral-range frequency ($N \times 37.5$ kHz). It is therefore interesting to search for events at these frequencies and perform a coincidence analysis between the two 4 km interferometers at Livingston, LA and Hanford, WA. Using simulated data, we develop tools for this search including a trigger code using time-domain filtering and excess power statistics to find events in a narrow band around the first free-spectral-range frequency and develop a heterodyning and downsampling scheme to alleviate data acquisition rate and storage concerns.

StochMon, a Monitor in the LIGO (Laser Interferometer Gravitational Wave Observatory) Data Monitoring Tool (DMT) Environment for Real-Time Observation of the Instrumental Sensitivity to the Gravitational Wave Stochastic Background

Marc J. Cenac

Mentor: Brian O'Reilly

The Laser Interferometer Gravitational wave Observatory (LIGO) is a facility designed to detect gravitational waves of cosmic origin. Each of the LIGO gravitational wave groups, who look for specific types of waves caused by different astrophysical sources (i.e. black holes, binary star systems, the big bang), is designing a DMT monitor to track the sensitivity to their search via a figure of merit tailored to the particular search. The StochMon project is to write a monitor in C++ that uses online data to track the sensitivity of a detector or detectors to a stochastic background of gravitational radiation. StochMon's figure of merit for stochastic sensitivity is generated by a signal-to-noise ratio equation that represents how faint a stochastic background could be detected over a period of time. The goal of this project is to have StochMon running as a prototype version of an independent DMT monitor by the end of August so that it can be used in LIGO's fourth science run (S4) which is scheduled to begin in November 2004.

Commissioning of the Photon Calibrators

Evan A. Goetz

Mentor: Daniel Sigg

The photon calibrator system is designed to be an independent means to test the response of the LIGO interferometers to an external force. The external force is due to radiation pressure of photons recoiling off the end test masses. We want to know the interferometer response as well as calibrate timing through the electronics. Calibration of the interferometer is crucial in order to determine gravitational wave parameters. The uncertainties of the overall calibration are determined by viewport window reflection, angle of incidence, test mass reflection, interferometer transfer functions, and initial amplitude calibration measurements. We compare the photon calibrator measurement to the current amplitude calibration measurement using the coil actuators.

Measuring the Sideband Dynamics in Individual Sidebands and Carrier of the LIGO Interferometer Recycling Cavities

Richard P. Garrelts

Mentor: Dick Gustafson

Last summer, an optical heterodyne system was designed and tested on the LIGO 2k interferometer. This summer's work is the implementation of this heterodyne system on the LIGO 4k interferometer and study of the beam's individual components (carrier and sidebands). The purpose of the system is to measure the optical buildup, variation, and noise characteristics of the carrier and associated frequency modulated sidebands within the recycling cavity. The heterodyning of optical control signals from the interferometer enables the study of signals in the radio-frequency regime by adding the optical output from the interferometer to a frequency shifted test beam that has been transmitted through a length of single-mode optical fiber. The combined beam is then registered on a radio-frequency photodiode, the output of which is sent to a radio frequency analyzer and monitoring data acquisition (DAQ) channels to measure both static averages and the dynamics of amplitude differences between the two sidebands. Our aim is to measure these height differences to within five percent accuracy at a bandwidth of 20 Hz. Monitoring of these signals will take place at a sampling rate of 1 kHz.

Modeling of Laser Frequency Noise Suppression in LIGO

Alyssa J. Cramer

Mentors: Rick Savage and Paul Schwinberg

The Laser Interferometer Gravitational-Wave Observatory employs nested control loops to stabilize the frequency of the laser light. We consider the inner two servos used in the Hanford 4 kilometer interferometer, the Frequency Stabilization Servo (FSS) and the Mode Cleaner Servo. Models of both servos have been generated using MATLAB's Simulink software. Measurements of the recently commissioned tabletop FSS are in good agreement with the model. Estimates of the performance of both the independent and combined servos are presented. Predictions of suppression of various noise sources are discussed. A test plan for production of new tabletop FSS electronics modules is included.

Measurement, Tracking, Control and Analysis of the LIGO Interferometer Optical Sidebands Deviations Off Resonance in the Mode Cleaner Cavity

Timothy P. Bodiya

Mentors: *Dick Gustafson, Daniel Sigg and Paul Schwinberg*

The mode cleaner in the LIGO interferometers is a three mirror resonant Fabry-Perot cavity that picks out the lowest order Gaussian mode from the input light. In addition, the mode cleaner converts phase noise in the input light into amplitude noise on the output light. This will have a negative effect on the performance of the interferometer and in turn the detection of gravitational waves.

The deviation from resonance of the radio frequency sidebands of the laser is measured by modulating the center frequency of the laser so that there will be an error signal at radio frequencies in the measured power. The light is detected on an 1811 photodiode after the mode cleaner and then amplified, and demodulated by both the radio frequency and center frequency modulation. After each demodulation, the signal is filtered. A lock-in amplifier then reads the signal and using this signal, the deviation of the sideband off resonance can be calculated. This signal tracks the deviation in the length of the mode cleaner. It has been shown that the mode cleaner length drifts by approximately 5 micrometers per week. In depth analysis of the movement is forthcoming.

Development of a Fast Data Acquisition Channel

Jack A. Buttane

Mentors: *Dave Barker and Daniel Sigg*

A set of data acquisition units samples the signals from the LIGO interferometers and supporting sensors such as seismometers. These units convert the analog signals to digital data, sampling at 16384Hz or less. A fast channel, sampling at 262144Hz, was developed and the necessary software changes were made to the data acquisition system. A heterodyne algorithm was developed to sample data from a narrow frequency band and record at a much lower rate. A frequency band of interest is the next free-spectral-range of an arm cavity at 37.500 kHz where the gravitational-wave sensitivity peaks up again with a full-width-half-max of 200Hz. A calibration was performed to relate the measured digital data to displacement sensitivity of the interferometer.

Exploratory Development of Algorithms for Searching for Periodic Pulse Signals

Alexander Levin

Mentors: *Dick Gustafson and Greg Mendell*

We present a mathematical construct that provides a method for detecting periodic gravitational wave pulses. These pulses can arise from, say, spinning neutron stars in very eccentric orbits around black holes. Using a multitude of fake data (generated in MATLAB), we test several algorithms for finding signals buried in gaussian noise, and attempt to extend our methods to increasingly weak signals. Our goal is to determine the time between consecutive pulses, as well as the details on the underlying sinusoids. The main method involves taking short Fourier transforms (SFTs), and averaging the power spectra of appropriate ones, based on where we believe the pulses might be; this is in fact a search over several parameters of the pulses. We hope to better understand the waveforms we are dealing with, and eventually apply our algorithms to real interferometer data.

Interferometer Locking Using Non-Resonant Secondary Amplitude Modulated Sidebands

Jennifer M. Lindahl

Mentor: *Dick Gustafson*

The purpose of this project is to implement and test a carrier independent locking scheme for the power recycling Michelson cavity [PRM] of the LIGO gravity wave interferometers. This scheme involves beating a non-resonant set of amplitude modulated sidebands against the PRM resonant sidebands reemerging from the PRM, obtaining a pseudo Pound-Drever-Hall error signal for the common and differential PRM lengths (I+ and I-). We aim to lock the interferometer using this alternate locking scheme, and to conduct rudimentary measurements of the gravity wave channel noise level achieved.

Projects at Livingston

Using E2E to Study the Impact of the Motion of the Input Optics on the Performance of the LIGO Interferometer

Raghuveer Dodda

Mentor: Sanichiro Yoshida

The laser beam generated in the LIGO interferometer passes through an optical arrangement (a set of suspended mirrors, lenses, and a triangular cavity collectively called the 'input optics') which seeks to alter the characteristics of the beam (the phase, orientation and the modal content) such that the beam resonates in the main cavity of the interferometer. However, the ever present ground motion transfers to the input optics via their suspension points and manifests itself as noise in the beam.

The main objective of the project was to simulate this process by altering Simligo, the existing numerical simulation model for LIGO (which was created using E2E). An Input Optics module that can receive realistic ground noise has been constructed and added to Simligo. This updated model can be used to simulate the motion of the input optics to study their effect on the beam characteristics and on the performance of the LIGO interferometer. Studies on lock-loss mechanism using this model will also be planned.

Simulation of LIGO's Mode Cleaner

Nafis S. Jamal

Mentor: Sanichiro Yoshida

LIGO's mode cleaner is responsible for performing various modifications to the laser beam before it is sent to the arm cavities. This cavity reduces the laser's frequency and amplitude noise, filters any incorrectly polarized light, decreases the beam's motion, and filters out all higher order modes. If the mode cleaner is not properly functioning, it may easily negatively affect the entire interferometric system. Through my research project, I created a box in LIGO's end-to-end modeling system to simulate this laser cavity. I primarily focused on modeling the negative feedback mechanism that stabilizes the mode cleaner. In order to accomplish this stability, the length sensing control (LSC) moves the apex of this triangular cavity, MC2, such that the overall optical path length is an integral multiple plus one-half of the laser's wavelength. Along the feedback loop, I had to procure several digital filters that would properly translate the error signal from the photodiode to MC2's position motion. A finalized mode cleaner box may be incorporated in E2E's SimLIGO, allow analysis on how the output beam from the mode cleaner influences the arm cavities, and, most importantly, allow us to study the dynamics of the mode cleaner itself.

Construction of Small and Large Optics Suspension E2E Box File with Realistic Table Motion

Kristen L. Rogillio

Mentor: Dr. Sanichiro Yoshida

The input/output optics (IOO) at the Livingston Laser Interferometer Gravitational-wave Observatory (LIGO) is made up of several suspended optics positioned with the laser to improve the efficiency of interferometer. The optics are suspended from a cage and placed on optical tables in vacuum chambers. Our group is making a simulation of the IOO that is to be as realistic as possible. The table motion was estimated using two different methods. The estimated table motion is given to e2e suspension box files as suspension point input. To simulate the local damping mechanism, the suspension box calculates the optic's motion both with the local damping servo on and off. The damped optic motion appears 300 times smaller than the free-hanging motion at the suspension's resonance frequency, while at the microseismic frequency range both are at the same level. When finished, the resultant box file along with the input data will be given to Nafis Jamal, another SURF student, who is completing the mode cleaner portion of the simulation.