LIGO Undergraduate Research Projects – 2008 (Preliminary)

Projects at Caltech

Development of advanced techniques in analysis of LIGO data: searches for signals, detection confidence, exploration of the physics and astrophysics of GW sources
Mentor: Alan Weinstein (ajw@ligo.caltech.edu)
Abstract: LIGO completed its two-year science run at design sensitivity in November, 2007. The LIGO Scientific Collaboration is searching intensively for a broad range of GW signals in these data. At the same time, we are preparing for first detections of GW signals, by developing "detection confidence" procedures. Once firm detections are made, we want to extract parameters describing the signal and the source, and develop ways to learn more about the properties of gravitational waves themselves and the information they give us about astrophysical sources in the presence of strong and rapidly changing gravitational fields. During this summer, we will be developing techniques to maximize what we can learn from the LIGO data, in searches for (1) compact binary coalescences, and (2) bursts from supernovae or GRB progenitors. Strong computing skills, knowledge of statistics, and experience in data analysis are recommended. Students interested in this project should contact Alan Weinstein, ajw@ligo.caltech.edu . A research proposal will be required.

Techniques in precision interferometry at the Caltech 40 Meter Prototype GW detector (3+ students)
Mentors: Alan Weinstein (ajw@ligo.caltech.edu) and Rana Adhikari (rana@caltech.edu)
Abstract: LIGO operates a 40 meter long prototype interferometric gravitational wave detector at Caltech that is being used to develop and test the technologies for lock acquisition, control, and readout of the Advanced LIGO interferometer. During the summer of 2008, we will be pursuing a variety of goals, including: automated beam scanning and aligning; adaptive filtering for noise cancellation; automated optical alignment system development; analysis and mitigation of noise in the gravitational wave readout; development of auxiliary optical cavity lock acquisition systems; and more. Skills in computing, lasers and optics, and laboratory work are recommended. Students interested in this project should contact Alan Weinstein, ajw@ligo.caltech.edu, and Rana Adhikari, rana@caltech.edu . A research proposal will be required.

Design and construction of an optical lever receiver
Mentor: Michael Smith (smith_m@ligo.caltech.edu)
Abstract: The pitch and yaw angular orientations of the mirrors in each LIGO interferometer with respect to the local coordinates are monitored using optical levers. An optical lever consists of a laser projector that directs a laser beam to reflect from the surface of the mirror being monitored and a receiver that measures the relative position of the reflected beam. Present receivers are sensitive to both the lateral displacement and the angular deviation of the reflected beam. The purpose of this project is to develop an optical lever receiver that is sensitive only to angular deviation of the reflected beam. In addition, the working optical lever system, consisting of a transmitter and a receiver will be used to characterize the angular pointing jitter and the transmitter laser. The student

will analyze the design of an optical lever system using the ABCD matrix formalism for Gaussian beam propagation. An experimental optical lever receiver system will be tested and compared with the analysis.

Detecting un-modeled gravitational wave bursts with Bayesian inference

Mentor: Antony Searle (acsearle@ligo.caltech.edu)

Abstract: Some potential sources of gravitational wave bursts accessible to ground-based detectors are poorly modeled. In the absence of a well-defined signal model, correlations between the several instruments around the globe can be used to reconstruct the waveform and distinguish coherent signals from incoherent instrumental artifacts. The problem has recently been approached from the Bayesian paradigm, revealing that for a fairly general class of signal models (including very uninformative models) the optimal (but typically impractical) Bayesian posterior can be practically computed. Theory and simulations suggest that this new method will improve on the sensitivity of current un-modelled burst searches; it also has the advantage of being clearly and explicitly derived from physical hypotheses.

The project will involve learning Bayesian inference, and designing and efficiently implementing an aspect of the Bayesian search; for example, designing an uninformative model for instrumental glitches that is both physically credible and practically implementable in a given computation budget.

The project would suit a student with some experience of programming numerical methods, interested in learning Bayesian inference and about gravitational waves.

Localizing Gravitational Wave Sources

Mentors: Rana Adhikari (rana@caltech.edu) and Kipp Cannon (cannon_k@ligo.caltech.edu)

Abstract. The world-wide network of gravitational wave antennae can be used to determine where in the sky the astrophysical source is. Coupled with traditional electromagnetic astronomy, this will lead to powerful probes of the universe. This project will entail running simulated signals through the LIGO gravitational wave search pipelines to characterize this localization capability. In the second stage of the project, the simulation will be expanded to include other interferometers in Italy, Germany, Japan, Australia, and India. Strong computing skills, knowledge of statistics, and familiarity with Fourier techniques will be very helpful.

Understanding Light Scattered from the LIGO Mirrors

Mentors: Bill Kells (kells@ligo.caltech.edu)

Abstract. Since the begining of LIGO operation, the images of the LIGO arm cavity beams impinging on their end mirrors has presented a puzzle. These images are taken at large observation angles with respect to the beam (cavity axis), so they are of scattered light. The amount and character of such scattered light is of critical interest for interferometer design since it represents the dominant optical power loss from the system. To the extent it can be reduced the interferometer power and hence GW sensitivity can be increased. Although the cavity beam illuminating the end mirrors is of uniform intensity, the imaged scatter is point like, so that the entire image appears as a "globular cluster" . If the mirror surface were perfectly smooth there would be no scatter; no such images.

Imperfections (dust, surface flaws, deviations from locally flat in the mirror polish) of the reflecting surface cause the scatter, so that these images of the scattered light contain, in principle, complete information on the nature of the surface imperfections. By now we have collected a large number of very high resolution "globular cluster" images from several interferometer mirrors, but only partially analyzed the data (in the camera CCD pixilated
intensity image files). The proposed SURF project is to systematically analyze these electronic images to extract useful physical information about the mirror surface quality.

Some useful skills would be strong familiarity with manipulating large files in various softwares (Matlab, unix, etc.); good understanding of basic optics (or eager interest in pursuing this); and detailed familiarity of the workings (optomechanical as well as digital/firmware) of sophisticated digital cameras.

Understanding Cable Noise in LIGO

Mentors: Mark Barton (mbarton@ligo.caltech.edu) and Norna Robertson (nroberts@ligo.caltech.edu)

Abstract: Test masses and other key optics in LIGO are supported as pendulums to filter out noise from ground motion, and in the forthcoming AdvLIGO upgrade, these will be multistage pendulums. Some of them need to be fitted with multiple channels of sensors and actuators. The cabling that needs to be run between the levels may be stiff and heavy and can potentially degrade the vibration isolation or create thermal noise. The project will have two components: (i) lab measurements to characterize different types and arrangements of cables, and (ii) computer modeling to simulate the cable, first by itself and then as part of actual pendulum systems. We need 1-2 students with interest and skills in mechanical analysis, mechanical measurements and modeling. The modeling will be done largely in Mathematica. Strong computer skills will be required but not necessarily in that language specifically - it will be a good opportunity to acquire experience.

Testing the design of inspiral template banks for LIGO Inspiral Search

Mentor: Anand S. Sengupta (sengupta@ligo.caltech.edu)

Abstract: Matched filtering is used to search for gravitational waves emitted by inspiraling compact binaries in data from LIGO interferometers. One of the key aspects of the detection process is the deployment of a set of templates, also called a template bank, to cover the astrophysically interesting region of the parameter space. The project involves designing a bank of templates placed on a hexagonal grid using computationally efficient methods. It also involves testing and tweaking this bank for a wide variety of source models including *Amplitude Corrected Waveforms*, which are very important for binary black hole searches. It would suit a student with some experience of programming in C. No background in Numerical Programming is essential. The student can learn the vital aspects of the LIGO inspiral data analysis program while contributing to its implementation in the high-mass search.

Thermal Noise Interferometer

Mentor: Eric Black (black_e@ligo.caltech.edu)

Abstract: LIGO's Thermal Noise Interferometer (TNI), located on Caltech's campus, is a dedicated instrument for studying thermal noise issues in advanced interferometric gravitational wave detectors. Current projects include developing and testing aperiodic coatings for interferometer test mirrors, investigating the effects of barrel coatings on thermal noise and parametric instabilities, and measuring thermomechanical properties of coatings for predicting thermo-optic noise. All of these are critical technologies for the next generation of gravitational wave detectors, and each summer we typically have openings for motivated undergraduates. All work is experimental, with a heavy emphasis on lasers and optics as well as low-noise measurement techniques.

For summer 2008, we have openings for two surf students. One will work with a graduate student on photothermal measurements in advanced coatings, and he or she will be involved in developing new coatings that will ultimately set the astrophysical range of second-generation detectors. The second will work with another graduate student to test the performance of a mirror coating that combines the best existing technologies - aperiodic structure and titania-doped tantala as a high-index material - to make what we hope will be the lowest-noise coating ever produced.

Stabilization of Interferometers Using Multiple Carrier Frequencies
Mentor: Sam Waldman (waldman_s@ligo.caltech.edu)
Abstract: This project will explore a technique to stabilize a mechanical instability in advanced LIGO interferometers resulting from light pressure forces. The instability is damped by sending through the cavity second beam of light with a slightly different carrier frequency. One tunes the frequency so that the “stable” equilibrium of one frequency coincides with the “unstable” equilibrium of another frequency. If the system’s parameters are adjusted correctly, the anti-damping force of the first carrier frequency will be overwhelmed by the damping force of the second carrier frequency, and the equilibrium will be stable in the final analysis. As a result, radiation-pressure noise in Advanced LIGO will be substantially reduced without having to implement a complex and unwieldy control mechanism.

Detection of Gravitational Waves using a Global Network of Detectors
Mentors: Sanjit Mitra (smitra@ligo.caltech.edu), Anand S. Sengupta (sengupta@ligo.caltech.edu), Rana Adhikari (rana@caltech.edu)
Abstract. Detection of Gravitational Waves (GW) is an exciting challenge in modern experimental physics. It will not only be an important test of General Theory of Relativity, but also promises a whole new window of astronomy. Several GW detectors are either operational or being proposed all over the world. A global network of interferometric GW detectors can dramatically improve the sensitivity of detection, sky coverage and the ability to localize the sources on the sky. This project will attempt to study and quantify these issues, which, in turn, could assist in proposing the location and geometry of new detectors. The interested candidates should have strong analytic and computational skills

Strategies for Analyzing Gravitational-Wave Data
Mentor: Linqing Wen (lwen@aei.mpg.de)
This project consists of two related parts:

(1) Efficient detection and localization of gravitational-wave sources to help identify their electromagnetic counterparts

This part involves further developments of a systematic approach to analyze data from a network of gravitational-wave (GW) detectors. We will use the well-developed signal processing tool "singular-value-decomposition" (SVD) to recombine GW data from several detectors to form new data channels with characterized sensitivity for GWs from a sky direction. This enables the combination of detection, verification, and localization schemes into a single algorithm. The student will develop and implement optimal localization schemes and compare the results with that of theoretical limits. This involves applications of the existing software tools and developments of new ones for a search pipeline that will run on real GW data using existing LIGO computer clusters.

(2) GPU-accelerated searches for gravitational waves

The graphics processing unit or GPU is rapidly emerging as a powerful and cost-effective platform for math-intensive high performance parallel computing. The current generation of GPUs offers capabilities in the Tflop range, comparable to world-class supercomputer installations. For the summer, the student will develop GPU parallel algorithms for a manageable part of the GW detection and localization pipeline described in part (1). The key is to minimize latency delays in data transfers between host CPUs and GPUs and in the best use of memory elements intrinsic to the GPU architecture. This involves great cares in algorithm designs that depend on choices of GPU cards. The code will be tested at GPU-equipped desktop computers and the results will be compared with those from typical CPUs including the LIGO computer clusters. This is a pilot program to evaluate the potential of a fully GPU-accelerated GW data analysis.

Projects at Hanford, Washington

Enhanced LIGO interferometer upgrade (3 students)

Mentors: Daniel Sigg (sigg_d@ligo-wa.caltech.edu), Keita Kawabe, Michael Landry, Dick Gustafson, Paul Schwinberg, Rick Savage

Abstract: LIGO has finished its 5th science run and has entered the Enhanced LIGO upgrade project. The goal of Enhanced LIGO is to improve the sensitivity of the two 4-km interferometers by about a factor of two. This will significantly increase the detection probability for binary neutron star and black hole mergers and will push detection limits well into and beyond the Virgo cluster of galaxies. This upgrade work includes a high power laser, a novel sensing scheme, a new seismic isolation system and more. We are looking for three students who want to work on an exciting project and are interested in helping to detect gravitational waves.

Projects at Livingston, Louisiana

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

Mentor: Valery Frolov (vfrolov@ligo-la.caltech.edu)

Abstract: At the end of 2007, the LIGO Observatories had completed the S5 science run and had collected one year of the coincidence data. During S5, the LIGO interferometer achieved the designed sensitivity and high duty cycle and delivered gravitational wave data of unprecedented precision. The detection horizon for the binary neutron star inspiral events reached 35 Mpc for 4-km-scale interferometers. Some of the limiting noise sources for the gravitational wave readout are the forces on test masses that result from the necessity to control the interferometer auxiliary degrees of freedom such as the Michelson interferometer, formed by the input test masses, power recycling cavity, and mirror alignment. The student will apply Wiener filtering technique to regress the noise produced by the auxiliary control signals from the LIGO interferometers gravitational wave output in S5 data. We are seeking candidates with exceptional analytical skills and abilities, and aptitude for data analysis. Required skills: Matlab, data analysis.