October 15, 1999

A Search for Gravitational Radiation at LIGO

Oregon Experimental Relativity Group

1. Introduction

With the commissioning of the LIGO Interferometers (IFOs), a new era of sensitivity to gravitational radiation will begin. Recent progress in the understanding and quantification of sources of gravitational radiation has shown that the era of LIGO has reasonable expectations for the discovery of gravitational radiation. Following the discovery of gravitational radiation and the initial tests of General Relativity, one can expect a new astronomy to greatly expand our understanding of the universe.

The Oregon experimental relativity group has joined the LIGO Scientific Collaboration to search for gravitational radiation at LIGO. We expect to help launch a new field of astrophysics and astronomy, based on the detection of gravitational wave sources. **The emphasis of the Oregon research activities is sustained achievement of the ultimate performance of the LIGO interferometers needed for gravity wave physics, and a search for gravity waves associated with gamma ray bursts (GRBs).** To this end, the Oregon group is focusing its effort on the environmental monitoring and data analysis at the Hanford site, and physics analysis aimed at detection of the GRB associated signals.

The path to successful observation of the gravity waves will be a difficult one, relying on detailed data analysis of an evolving nature. Initially there is the identification of spurious noise and faulty performance of the instrument. Success will depend on analysis tools that are able to quickly isolate sources for correction. This also requires a good characterization of the surrounding environmental noise sources. As the performance improves, the irreducible limits of performance will be explored. And finally, the application and improvement of techniques to extract the signal will be undertaken. Data compression will be an important ingredient in this effort.

The expectation of a new astronomy emerging from LIGO follows the history of advances in astronomy and astrophysics opened with new windows of observation, such as the radio window, the X-ray window, and the gamma-ray window. With the development of techniques to explore each of these regimes, dramatic new discoveries have been made. Yet, the dominant matter of the universe remains unidentified, and many questions regarding the early universe stand unanswered.

With new paths to discovery, one can expect these currently recognized areas to be explored and new mysteries to be revealed.

In fact, with the construction of LIGO, we may be on the threshold of another leap in our ability to explore the universe through the use of gravitational radiation as a probe on otherwise undetectable phenomena. The existence of gravitational radiation was indirectly confirmed with observation of the energy loss of the binary pulsar.[1] Still there is no substitute for direct observation of the radiation, which is the motivation for LIGO. Furthermore, with the ability to detect the radiation, a new sensitivity to sources will be possible, opening new opportunities in astrophysics and astronomy.

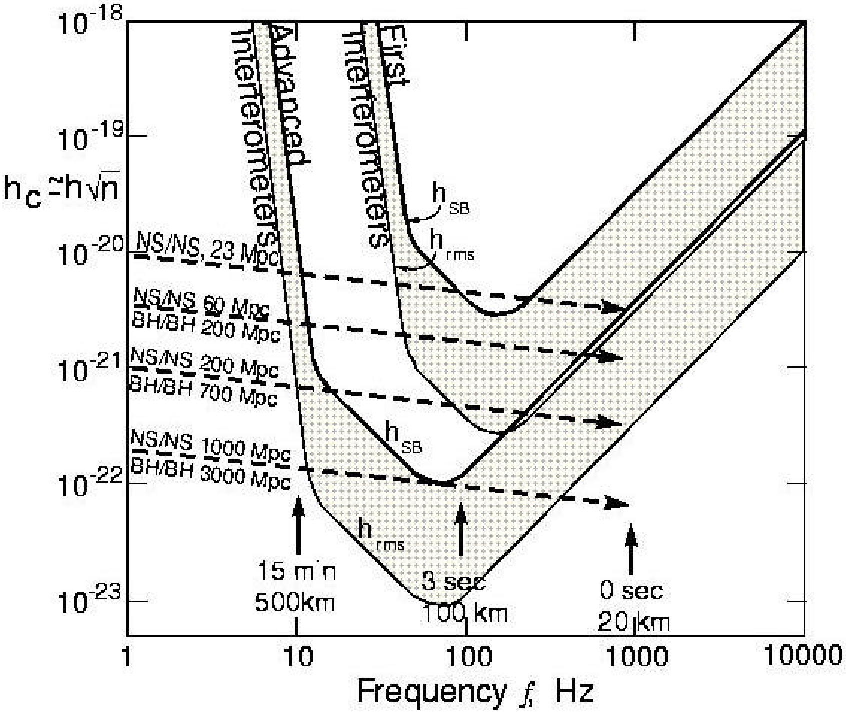

Figure 1. Expected LIGO broad-band noise h_{rms} and sensitivity to bursts h_{SB} [2] compared with the strengths of the waves from inspiral of compact binaries at the indicated distances (from Ref 3). The signal strength h_c is approximately given by $h\sqrt{n}$, where h is the amplitude of oscillation and n is the number of cycles at a given frequency over which the signal is observed. While h_{rms} refers to the LIGO sensitivity for broad-band wave of optimal direction and polarization, h_{SB} is for broad-band waves of random direction and polarization. The arrows at the bottom indicate the time and separation until coalescence of a NS/NS binary, where each NS has mass 1.4 M_{SUN} and radius $\approx$10 km.

Theory of Sources

Many years of theoretical research have led us to our current level of understanding, with qualitative expectations for the signals that might be observed. The principal sources which have been investigated include binary compact star coalescence, supernovae, binary massive black-holes, pulsars, binary stars, and stochastic cosmological background sources. The most promising of these is the binary neutron-star coalescence; estimates of the expected strengths of waves from binary neutron star coalescence are presented in Figure 1. The strength is presented as the strain ($h(t) = \Delta L / L$) observed over the length (L) of the interferometer. $\tilde{h}(f)$ is the square root of the spectral density of the detector's output h(t) in the absence of a gravity wave. The rms noise in a bandwidth Δf at frequency, f, is $h(rms) = \tilde{h}(f)\sqrt{\Delta f}$. Superimposed on the source curves is the LIGO sensitivity.

Figure 1 shows that a detector with a strain sensitivity in the range of 10^{-21} over the frequency range of 50 Hz - 1 kHz would be sensitive to events out to tens of Megaparsecs. Estimates of the number of such events expected in such a volume of space suggest that with some optimism we can hope for a few of the binary neutron star coalescences per year within the reach of the initial LIGO (here labelled first interferometers).[3]

Estimates of possible association with GRBs is less precise (see section 4.3). Some of the GRBs may result from binary inspirals, in which case they would be expected to produce gravity waves within the LIGO frequency range. However, they are likely to be at too great a distance for conventional detection algorithms. Section 4.3 discusses ideas aimed at optimizing sensitivity to these events.

2. Summary of Proposed Research

The emphasis of the Oregon research activities is sustained achievement of the ultimate performance of the LIGO interferometers needed for gravity wave physics, and a search for gravity waves associated with gamma ray bursts. To this end, the Oregon group is focussing its effort on the environmental monitoring and data analysis at the Hanford site, and physics analysis aimed at detection of the GRB associated signals.

The confidence with which one can claim a detection of gravitational radiation or set an upper limit to the possible radiation, from ANY source, depends not only on how the signal interacts with LIGO, but how LIGO interacts with its environment. For a large number of sources, the former is known. The latter work has just begun and depends on identifying and monitoring those external influences which can mimic gravitational waves.

Our research will proceed in the following way. The first step is to identify which environmental effects are most likely to produce signals in the detector. This affects not only the science product, but identification of the important "housekeeping" channels, and is one of the means of reducing from Level 0 data to Level 3 data.

Once identified, the appropriate channels need to be added to the data set such that they are easily accessible to the data analysts, where they will serve a number of purposes: to distinguish between those signals which are real gravitational wave candidates and those which are not; to identify periods of unusable data, or to compensate for known effects so that data need not be vetoed; and to provide a diagnostic tool which can effectively be used to identify fixable sources of noise or problems with the detector's running.

The Oregon group is coordinating its activities within the context of the LIGO Collaboration. We have established a presence at the site of the experiment, with Robert Schofield spending half of his time on site. Others travel to the site when needed.

Our work will consist of the following items. Detailed discussions of each of these follow.

- Environmental Monitoring
  - Weather monitoring
  - Magnetic field studies
  - Seismic characterization
  - Cosmic ray studies
  - Gravity-gradient noise

- Detector Characterization/ Data Analysis
  - Data reduction
  - Transient analysis
  - Gamma Ray Burst studies

3. Environmental Monitoring

3.1 WEATHER MONITORING

Weather monitoring promises to be an important tool for characterizing LIGO interferometers. Pressure changes, for example, may correlate with tilts and laser alignment and will also change the optical path length in the air cavity of the pre-mode cleaners. Wind gusts and rain may be detectable sources of vibration; temperature and relative humidity changes may be sources of signal drift. Multiple weather monitors are important because weather conditions sometimes vary over LIGO's large area. This variability is illustrated by Figure 2 which shows the passage along the Y-arm of an 8 km wide low pressure system that may have been a morning sun-induced updraft. The pressure at the corner and end stations differed by tenths of a percent during the event; temperature, wind speed and direction changed in the expected manner during the event and were thus at times quite different at different stations.

A summary of our contribution in weather monitoring follows. We:

1) helped set up the 5 weather stations,
2) designed, manufactured and installed a circuit to boost the relative humidity signals, compensating for the long cable lengths,
3) wrote the device driver code for the weather stations,
4) wrote code to transfer the data to the EPICS data collection system and developed MEDM screens to display the data in the control room (a simple tabulation of current data is available within the LIGO Laboratory at http://blue.ligo-wa.caltech.edu/perl/epics.pl),
5) have undertaken a calibration of the stations to improve on the factory calibration.

Wind Gust Monitoring

Wind gusts may be more important to monitor than average wind speed. We found that the Davis weather stations installed at the Hanford site count anemometer revolutions for a fixed 2.25 seconds in order to obtain a 1 mph resolution. In addition, there is a variable 0.8 to 3 second read out delay. We have been investigating the possibility of running anemometer clicks (1 per revolution) directly into the data collection system in order to better monitor gusts. A figure of wind speed estimates obtained from an anemometer at Hanford that we connected to both a slow and a fast channel is available at: http://zebu.uoregon.edu/~rayfrey/LIGO/LIGO_UO.html (entitled “anemometer”). The figure shows the importance of finer time resolution for characterizing gusts.

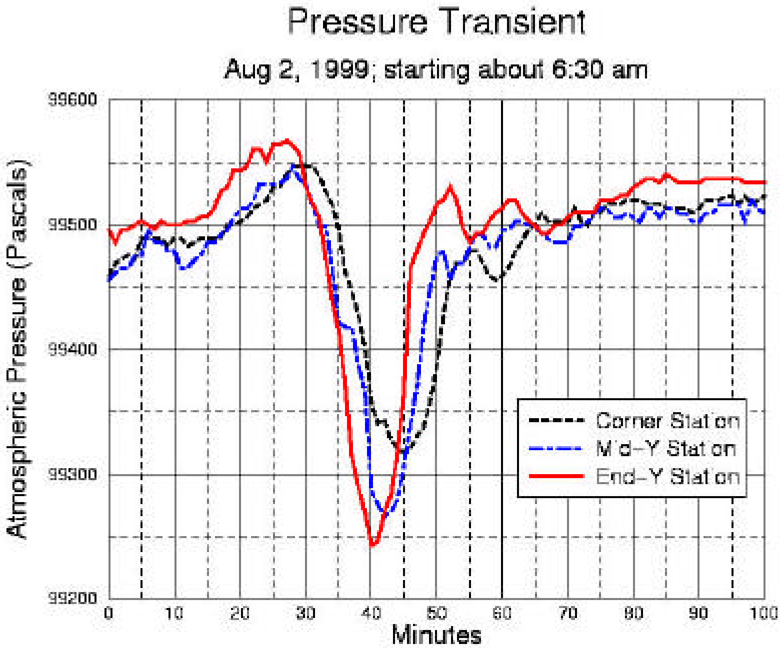

Figure 2.

In addition to completing weather station installation on the X-arm, software maintenance, completing the sensor calibrations, and continuing our investigation of gust monitoring, we plan to search for correlations between weather data and other channels. We found the pressure transient noted above in such a search; no correlations were found between the pressure event and the small number of channels that were on line. Recently, however, we have found a very strong anti-correlation between the piezo voltage of the pre-mode cleaner and atmospheric pressure. The length of the air cavity is controlled by the piezo voltage. The range of the piezo is not enough to compensate for changes in optical path length due to atmospheric pressure fluctuations and it is now apparent that the pre-mode cleaner has fallen out of lock many times due to atmospheric pressure variations. We expect to find more correlations in the future as more channels come on line.

3.2 MAGNETIC FIELD STUDIES

Six permanent magnets cemented to the test masses and other interferometer optics are used to control the position of the optics. The pole strengths and orientations of the magnets are balanced to minimize the coupling of optic motion to time-varying ambient magnetic fields. Even so, the optics will shake if the pole strengths of the magnets are not identical or if different magnets are subject to different ambient fields. To estimate the displacement noise using ambient field data and to better understand this problem for current and future versions of LIGO, we have undertaken four projects. First, measurements of ambient fields inside and outside of BSC vacuum chambers. Second, development of a diagnostic system to generate forces on the optics using externally generated magnetic fields. Third, investigation of the transfer function from outside to inside of the chambers. And fourth, experimental measurements of the gradients produced by optic support structures subjected to known fields. R. Schofield presented a talk at the Stanford LSC meeting detailing progress on these projects; progress is summarized below but additional details are available from the transparencies at http://www.ligo.caltech.edu/LIGO_web/9907lsc/9907trans.html

1) Measurements of ambient fields inside and outside of core-optic vacuum chambers

We have measured ambient magnetic fields inside of two BSC chambers, BSC-8 and BSC-7. The seismic isolation stacks and optical tables were in place but the optics and optic support structures were not. Measurements inside of BSC-8 were preliminary measurements made while R. Schofield was helping install the down-tube assembly. The door was open and the Bartington MAG03 magnetometer positioned by hand. The door was closed for measurements inside of BSC-7; two magnetometers were affixed one foot apart on a plunger and slid along inside of a 4 inch fiberglass tube connecting ports on opposite sides of the chamber. Field measurements were recorded for all three axes of each of the two magnetometers at each location. Approximate field gradients were obtained in a second set of measurements by subtracting the magnetometer signals in a Stanford SR560 preamp. To check these gradient measurements, gradients were also calculated by subtracting 60 Hz field measurements for successive positions along the tube. The two sets of 60 Hz gradient values were in agreement. The positioning repeatability and the relative calibrations of the two magnetometers were determined using generated fields and were both 7% or less for all axes. The absolute calibration of the magnetometers was checked by comparing measured field values and values calculated from coil geometry and current.

The average and standard deviation of the 60 Hz field at seven locations inside of BSC-7 was 3.73 (± 0.22) nT rms. For the three locations in BSC-8 the average was 1.64 (± 0.21) nT rms. The averages of the fields around these chambers were about 3 times higher. A more detailed table of measurements inside and outside of the chambers as well as a comparison with outside measurements by Savage and Weiss [4] and Coles et al. [5] are available at http://www.ligo.caltech.edu/LIGO_web/9907lsc/9907trans.html . Field noise inside BSC-7 averaged about 9.6 (± 1.4) pT/√Hz rms at 50 Hz. Magnetic field gradients at 60 Hz were 2.3(± 0.92) nT/m rms and gradient noise at 50 Hz was greater than 7 and less than 20 pT/m √Hz rms.

A simplified model of the coupling between fields and mirror motion similar to one used by Dennis Coyne[6] but including the measured variation of magnetic fields over the distance between magnets was used to calculate displacement noise from the measured fields and gradients. The displacement noise due to the measured gradients was estimated to be below 2×10^{-20} m/√Hz at 50 Hz. This is more than a factor of three below the allowable level for displacement noise terms in LIGO 1. The displacement noise estimated from measured fields (coupling through torques on the magnets and a 1mm assumed offset of the beam from the mirror center) was more than an order of magnitude below the estimated displacement noise due to measured field gradients. These fractions of the LIGO standard were relatively consistent over the 5-800 Hz frequency range. Magnetic positioning may play a role in future versions of LIGO, such as in the first stage of a two stage optic suspension pendulum, so continuing investigations of the ambient fields will be important for future as well as current versions of LIGO.

2) Diagnostic system for investigating the coupling between optics and ambient magnetic fields

For diagnostic driving of in-place optics, we constructed two 1m diameter coils of 12 gauge varnished copper wire wound on plywood spools. Either 10, 30, 60 or 100 turns can be selected. The coils are mounted on aluminum tripods with a 5 to 8 foot adjustable height. Two coils were built so that the coils could be placed on opposite sides of the chamber in a Helmholtz-like configuration in order to produce either fairly uniform fields or, with the current direction in one coil reversed, fairly uniform field gradients in the central region of the vacuum chamber.

We mapped out the field that the coils produced inside of a chamber for a positioning of the coils that would work for any of the variable BSC configurations. The field produced by the coils in the selected position was measured along the transept of the ambient field measurements mentioned above. The fiberglass tube was then repositioned between a second set of ports to provide an `X' shaped distribution of measurements in the plane containing the main laser beam and the center of the coils. Photographs showing the tube and the experimental set up are available at: http://zebu.uoregon.edu/~rayfrey/LIGO/LIGO_UO.html . To map out the fields for frequencies between 1 and 1000 Hz, the coils were driven in series by a $3V_p$ swept sinusoidal signal from the HP 35670A analyzer. The signal analyzer recorded the ratio of the voltage from the magnetometer inside the chamber to the voltage drop across a resistor in series with the generating coils; this ratio is proportional to the ratio of the measured internal field strength to the generated field strength. At 1000 Hz, the ratio of internal to generated field strength was about 1/20 of its value at 1 Hz because of attenuation due to eddy currents in the chamber walls. Field maps for the constant gradient coil configuration showed that the measured gradients were relatively constant in the central region of the chamber, as designed.

We plan to obtain an audio frequency amplifier to boost the generated fields and to use this diagnostic system to study the sensitivity of several of the core optics to magnetic fields as soon as interferometer signals become available.

3) An approximate transfer function

The swept sine measurements mentioned above can be used to obtain an approximate transfer function for magnetic fields from outside of the chamber to inside. This transfer function is of interest because the planned position of magnetometers that feed into the data stream is outside of the chambers.

An example of the swept sine measurements for a location near the center of the chamber is given in Figure 3. The data have been fit using the functional form that would be expected if the chamber wall were a planar circuit in a normal magnetic field. The fit gives the following ratio of fields with and without the chamber present:

$$B_{chamber} / B_{no-chamber} \cong 1/\sqrt{1+(f/20)^2}$$

Away from the center and above 100 Hz this fit departs increasingly from the data. This departure is thought to be due to the increasing importance of the variation from the assumed geometry for locations that were off-axis and for higher frequencies. We are pursuing more sophisticated models to better describe the data.

Nevertheless, this transfer function, obtained from measurements of generated fields, works quite well for 60 Hz ambient fields. This transfer function predicts an attenuation factor of about 0.32 at 60 Hz. The ratio of the average value of 7 ambient field measurements inside of BSC-7 (mentioned above) to the average of 12 measurements at outside locations around the chamber was 0.35. This ratio for four measurements inside and 7 measurement locations outside of BSC-8 was 0.37.

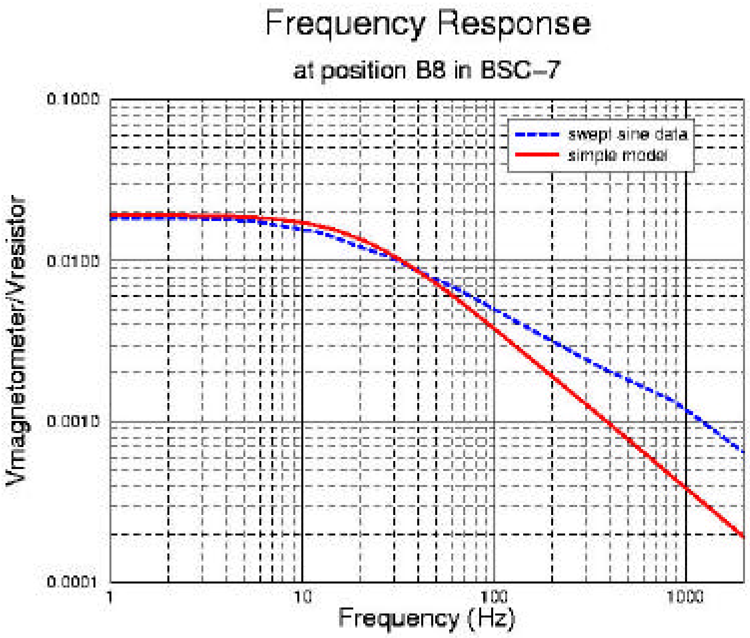

Figure 3.

4) Experimental measurement of gradients produced by optic support structures

Magnetic field gradients produced by eddy currents in optic support structures may significantly increase the displacement noise of an optic. The support structures were not in place for our measurements because it would be difficult and potentially damaging to measure fields near an in-place optic. We plan to measure gradients produced by an isolated optic support structure. The support structure will be subjected to ambient fields and fields produced by our coils.

In addition to continuing with the four projects mentioned above, we plan to investigate sources of ambient fields. We have, for example, suggested that the wall mounted emergency light be moved away from BSC-8 because its transformer is a large source. We have also noticed that the seismic isolation piers are magnetized, in some cases turning a compass needle through 180 degrees at 1m. A back of the envelope-type calculation suggests that the field noise produced by vibrating piers will be small compared to measured field noise but we would like to investigate this further. Field noise produced by lightning strikes may also be a useful area to investigate.

3.3 SEISMIC CHARACTERIZATION

Characterization of local and off-site sources of seismic vibrations is important for present and especially future versions of LIGO. We have begun to characterize local sources by setting up a seismometer in the corner station and attempting to identify the main peaks in the 1 - 100 Hz range. To do this we placed an accelerometer on most major pieces of equipment in order to identify their characteristic frequencies. A number of the seismic peaks seemed to be coming from the small office area air handler. Therefore, we shut it off and found that, of the equipment that will not be shut off during data runs, it produces the largest vibration peaks that we measured in the LVEA (Laser and Vacuum Enclosure Area). The much larger air handler for the LVEA is vibration isolated and comparably quiet. For future versions of LIGO, we may want to isolate the office area air handler. Our labeled seismic spectrum, our tabulation of equipment, specified frequency and measured frequency are available within the LIGO Laboratory at http://blue.ligo.wa.caltech.edu/PEM/lveaNoiseSources.html and http://blue.ligo.wa.caltech.edu/PEM/lveaNoisSrcsSpect.ps .

We have also begun a program of identifying ambient or off-site noise sources, expanding on A. Rohay's work by using two seismometers to identify source direction and setting up our electronics in a van so that we could move in the indicated direction. (http://zebu.uoregon.edu/~rayfrey/LIGO/westofroad.jpg) We shut off all large equipment at the Y-end station and found that the main remaining signal above 1 Hz was a 5-12 Hz signal coming from the direction of highway 240. Because the signal was so constant (even when cars were more than a km apart) we did not at first believe that it was coming from traffic. But time delays pointed towards the road from either side of the road and in the direction of the nearest traffic when we set up at the road. At X-end we found that the largest peak also came from the direction of the nearest road - the internal Hanford road which has traffic until well after swing shift. During the rare breaks in traffic, the peak was not evident. The traffic produced a displacement noise of roughly a nm/√Hz at the end stations. We did not repeat our measurements at the corner or mid-stations because we could not shut down all equipment there.

We also made measurements around the Wannawish dam, about 5 km from the Y-end station and found that it produced vibrations comparable in magnitude to passing traffic at an equal distance. However, since it is considerably further from LIGO than the roads, it is an unlikely source of detectable vibrations in the 1 - 50 Hz range. We plan to continue tracking seismic sources.

3.4 COSMIC RAY STUDIES

A very energetic cosmic ray shower incident on a test mass could, in principle, create a background to gravity wave searches. The two mechanisms usually considered are

(1) the transfer of the particle momenta (impulse) to the test mass;
(2) the loss of particle energy resulting in internal-mode excitations within the test mass.

Depending upon details, the two effects can be of the same order of magnitude. However, all estimates, both external and internal [7] to LIGO have placed the effect of cosmic rays to be a few orders of magnitude below the LIGO sensitivity. Nevertheless, it is desirable to have an independent cosmic ray monitor because (1) it is important to eliminate all possible spurious sources from a potential gravity-wave observation -- the estimates are close enough that perhaps an unforeseen twist on the estimates could be important; and (2) even if the effects prove too small to be observed with the LIGO I interferometer, it will be useful to have a reliable estimate, based upon real measurements, of the effects for LIGO II.

Indeed, a cosmic ray particle detection system is part of the LIGO PEM design [8]. After the system is installed, we will study the data to make sure it meets its physics objectives, possibly tuning the system accordingly.

The detector consists of a pair of scintillator panels, each about 30 inches on a side and read out by two PMTs, one of which will be at high gain to clearly see single muons, and the other with lower gain to avoid saturation for the rare events of interest. After forming a coincidence trigger, the digitized signals are to be shipped, via a VME-based EPICS crate in rack CDS 2X5, directly to one of the mounted disks of the CDS system. The trigger signal, input to the VME timing module, will provide a GPS time stamp for the cosmic event record. These event records are to be inserted in the LDAS (LIGO Data Acquisition System) MetaDataBase. The event rate will be adjusted to about 100 per day by an energy threshold. It is expected that this data pathway could serve as a template for other event-type detector readouts, some of which the Oregon group is pursuing as part of the LIGO Scientific Collaboration, such as wind gusts, thunderstorms, magnetic or power line events, etc.

3.5 GRAVITY-GRADIENT NOISE

Mass motions such as density fluctuations can cause varying gravitational fields which can shake test masses; this Newtonian noise is referred to as gravity-gradient noise. Gravity-gradient noise produced by seismic waves from uncontrollable sources may limit advanced versions of LIGO. Hughes and Thorne[9] have shown that this may indeed be a limit in the 3 - 30 Hz range using a model of ambient seismic motions based on the theory of multimode Rayleigh and Love waves propagating in a multilayer medium. The magnitude of the seismic gravity-gradient noise depends on the proportions of the modes present; Love modes involve only horizontal displacements and no density fluctuations and so, in the idealized case, do not produce varying gravitational fields. The ratio of vertical to horizontal displacement measured previously by A. Rohay at both LIGO sites was used by Hughes and Thorne to constrain the possible mixtures of modes. We are working with the group set up by K. Thorne to help further constrain the possible mixtures of modes by using surface seismic arrays. The first step in this project is to obtain a dispersion relation for ambient seismic vibrations.

In consultation with A. Rohay and G. Gonzalez, we have set up a trial 3 seismometer array (L-shaped with 8 and 32 foot legs) in the desert near the Y-end and collected time series data. The traffic peak was evident in the data even though we made measurements from 8 to 11 pm. We are planning on analyzing the data using MatLab and SAC (seismic analysis code) and then designing a more ideal array.

In addition to characterizing the seismic background that may be important for advanced versions of LIGO, we plan to help investigate potential non-seismic sources of gravity-gradient noise that we have identified at the out-lying stations such as vibrating roll-up doors and roof-access ladders as well as small flocks of cliff swallows and western king birds that we have seen passing near and alighting on the buildings.

3.6 OTHER DETECTOR EXPERIENCE

R. Schofield is located at LHO and plans to continue gaining general experience with the detector in order to contribute to the understanding that will yield the ultimate LIGO performance. So far, in addition to experience in the environmental monitoring areas mentioned above he has:

1) helped install seismic isolation systems in HAM-10, BSC-8, BSC-5 and BSC-4,
2) measured the changing tilt of the concrete slab as HAM - 7 was pumped down, (The difference in tilt was about 5 microradians; this tilt will affect laser alignment)
3) helped test chamber shakers and accelerometers,
4) helped install tilt meters and seismometers,
5) helped install and adjust the recycling mirror in HAM-9,
6) designed and tested an extension to monitor dust in vacuum chambers during installations,
7) written the device driver code, EPICS interface and control room screens for the dust monitoring system.

4. Data Analysis

In this section we present our plans for data analysis. In order to produce the manageable-sized data sets needed for the characterization of the LIGO IFOs, it will be necessary to produce reduced data sets, which we describe in section 4.1. An important goal of the data set reduction work is to evaluate the influence of each of the Physics Environment Monitoring (PEM) channels on the interferometers and to determine which of the PEM channels should be part of the LIGO archive. In section 4.2 we describe our plans for transient analysis of the PEM data. Finally we discuss the potential detection of gravity waves from gamma ray bursts and the connection of this analysis to understanding the PEM data.

4.1 DATA SET REDUCTION

The search for gravitational waves with the LIGO IFOs will be based on the digitized optical interference signals which will be sampled at approximately 16kHz. The raw signals from the three interferometers will produce approximately 8 GB/day or approximately 3 TB/year. Including all of the PEM channels from both sites, the data rate is approximately 15 MB/s, which corresponds to 1.3 TB/day or about 500 TB/year. The size of the complete data set (Level 0) exceeds the capacity of the LIGO central archive located at Caltech by an order of magnitude. The data reduction will proceed through several steps. These data sets produced are labeled as Level 1, Level 2 and Level 3, with Level 3 having the most compressed data.

The first step in reduction will be to reduce the Level 0 data by a factor of 10 to allow it to be stored in the archive (Level 1). This can be accomplished through standard compression techniques (see below) and by discarding unnecessary channels. An important part of our work will involve determining which channels should be saved at Level 0.

Many of the analyses needed for characterizing the IFOs, as well as many of the physics analyses will be extremely CPU intensive and it is likely the LIGO effort can be significantly strengthened by making use of computer resources at the home institutes of the LSC members. The initial work will focus on detector characterization and will make use of the IFO data and a few important PEM channels. We expect that the data sets used for detector characterization will eventually evolve into the Level 2 data set.

One goal of our data reduction work will be to produce software modules to be used in creating Level 2 data sets. Public domain non-destructive compression (e.g. gzip) is presently used in the LIGO frame software and we find gains of better than 50% for both Hanford seismic data and for data from the Caltech 40m prototype interferometer.

Once the detector is well understood, it is possible that Level 3 data, IFO strain data with all known instrumental effects removed, will be the basis of much of the physics analysis. For a two year run this data stream is estimated to be approximately 200 GB, which can be stored on a few high density tapes such as the Sony AIT II.

To the extent that all instrumental artifacts can be removed from the Level 3 IFO data, we do expect a large compression over what is presently obtained with standard public domain software. However, much of the PEM data will be dominated by signals at relatively stable frequencies. For example we expect some feed-through of the 60 Hz AC line currents to be present in the IFO output. This feed-through can potentially come from ground motion, stray magnetic fields, or other instrumental effects [10]. It is possible that the effects of the 60 Hz (and higher harmonics) can be tracked by monitoring the phase of the 60 Hz AC line current. Rather than having to store the digitized line voltage in Level 2 data, it may be sufficient to store only the phase of the line voltage.

Many other environmental effects (e.g. ground motion due to fans) may be treated in similar, but perhaps less efficient manner. To facilitate these analyses we will develop (or test) a number of different "lossy" data compression techniques (filtering, heterodyne, decimation, etc). These techniques can then be deployed as needed. In each instance it will be necessary to study the PEM channels to be sure that any potential effects to the IFO signals can be characterized fully with the compressed data.

In still other cases it may only be necessary to store coarsely binned FFTs for each channels which could then be used to veto periods with "contaminated" IFO data from consideration.

Since the character of feed-through from the environmental effects is likely to change over time, the studies will require relatively large data samples so that the appropriateness of a given technique can be properly accessed.

4.2 TRANSIENT ANALYSIS

Environmental transients such as wind gusts, lightning strikes, cosmic ray showers and earthquakes could potentially produce corresponding transients in the IFO output. In some instances these transients may be large enough to cause the resonant cavities in the arms of the interferometer to come out of "lock". Examples of some of these transients have already been shown in section 3. To study these transients in more detail we plan to develop software modules for the LIGO Data Monitoring Tool (DMT) which will identify transients in the PEM channels and add the time of the transient to the LDAS MetaDataBase. This database will allow us to select only those portions of the data which contain transients and to study the effect of these transients on the IFO output.

It will also be important to correlate these transients with the performance of the LIGO feedback system which is designed to keep the arms of the interferometer in lock. By measuring the rate of large transients, we should be able to predict the performance of feedback system and possibly improve its performance.

The development of the transients tools will necessarily involve processing large amounts of data and will benefit from the work on data reduction discussed above.

4.3 PHYSICS ANALYSIS

In parallel with the detector characterization studies mentioned above, we plan to begin building some algorithms useful for physics analysis. One area of analysis which our group will pursue is the search for gravitational waves associated with gamma ray bursts.

Gamma ray bursts (GRBs), first serendipitously discovered in the 1960s [11] remain largely unexplained. Observations by the BATSE detector, aboard the Compton Gamma Ray Observatory, established that the distribution of GRBs was isotropic, implying that progenitors of GRBs occur at cosmological distances [12]. GRBs detected by BATSE occur at a rate of approximately one day.

Recent observation of optical transients associated with some GRBs have given redshifts to the GRB of between $z = 0.8$ and $z = 4.0$ [13]. It should be noted that not all bursts can be associated with optical transients. This opens the possibility that there is more than one class of GRB. The optical transients which have been observed are consistent with the "fire ball" model of gamma ray production by an electron photon plasma, but the observations are not yet able to constrain the progenitors. Possibilities include the death of massive stars and the merger of two massive objects such as neutron stars [14]. The observation of the optical transients also show that the progenators of the GRB, while associated with galaxies, do not necessarily occur at the galactic center and therefore have a distribution characteristic of objects of stellar masses. If GRBs are due to the mergers of neutron stars (NS/NS) or black holes and neutron stars (BH/NS), gravitational radiation in the frequency band of LIGO should be produced. The challenge for the experimentalist is that the distance to the known GRB progenitors is typically a factor of 100 to 500 more than the 15 Mpc initial sensitivity of LIGO to NS/NS binaries without additional coincidence information.

Fortunately the added constraints given by the time and angular position of the GRB can considerably improve the sensitivity of LIGO to gravitation radiation. For a BATSE detection, the direction of the GRB is determined with an error of better than 2 degrees [15]. For those GRBs originating in directions expected to give the largest LIGO signals, the difference in arrival times of the gravity waves at the two LIGO sites can be determined with an accuracy of better than 0.5 ms. The use of this information to help identify gravitational radiation coincident with GRBs has already been discussed in Ref. [16]. For these optimally positioned sources the gravitational signal will be larger, corresponding roughly to the difference between h_{SB} and h_{rms} lines shown in Figure 1. The gravitation strain will also be larger by a factor of 2 to 5 if the GRBs are due to (BH/NS) mergers, rather than for (NS/NS) mergers [17].

Another constraint comes from the observed time of the GRB. The precise delay between the arrival of gravitational radiation at one of the LIGO sites and the arrival of gamma rays at BATSE is not known and will depend on the details of the development of the electron/photon plasma which produces the gamma rays. The search for gravitational wave signals in LIGO can be concentrated in a time window a few minutes before the detection of each burst compared with a search window of one or two years for a search without an external trigger. One also needs to take into account the fact that there are approximately 300 detected GRBs each year, but also be mindful of the possibility that there may be several different types of GRB, with different (or no) gravitation signal. For example, some GRBs have been associated with Soft Gamma Ray Repeaters (SGR) of galatic origin. It has been proposed that gravitational radiation may also be associated with these bursts [18].

Our work on GRBs will initially concentrate on understanding systematic effects which might give correlations between the two sites. These correlations will weaken the sensitivity of the tests proposed in [16]. For example, there may be correlations in the phase of the AC power between the two sites which could give rise to false signals. Other correlations may be introduced through seismic noise or magnetic fields.

We will also concentrate on methods which can efficiently use all the constraints to either discover gravitational wave signal or to put limits on the gravitational energy emitted from gamma ray bursts in the bandwidth of the LIGO detector. These methods should include completely general analyses of the GRB which make no assumptions about the sources and as well as more targeted searches which use all of the available constraints.

As an intial investigation into this topic, M. Ito has scanned the Caltech 40 meter data for effects associated with observed GRBs. Ito and Rahkola will continue such studies with LIGO simulations to prepare for analysis of 4 km data.

5. Technical Notes and Talks

1. Documentations for Functions and Diagrams Describing 3 Coordinate Systems, Horak and Amasha, ORDOC 98-6, Jul 27, 1998
2. Documentation of All Tests Performed on GWSIM Function, Horak and Amasha, ORDOC 98-7, Aug 3, 1998
3. Ambient and Diagnostic Magnetic Fields Measured in and Around Hanford BSC’s, Schofield , Rahkola, Frey, LIGO-G990104-00-W (in prep.)
4. Frequencies of Large Equipment Sources of Seismic Noise at LHO Corner Station, Schofield, Ito, LIGO-T990091-00-W (in prep.)
5. Generation of Diagnostic Magnetic Fields for Test Mass Chambers, Frey and Rahkola, LIGO-T990092-00-H
6. A Proposal for Gust-measuring System at LIGO, Rahkola, Schofield (in prog.)
7. LHO Weather Station Calibrations, Schofield, Rahkola, Frey (in prog.)
8. Progress in Seismic Characterization of the LIGO Site, Schofield, Ito (planned)
9. Commissioning the LHO Particle Detector System, Frey, Rahkola, Schofield (planned)
10. Search for Gamma Ray - GW Correlations with 40m Data, Ito, Brau (planned)

Talks

1. Ambient and Diagnostic Magnetic Fields Measured Inside of a BSC Vacuum Chamber at Hanford, Schofield, Stanford LSC Meeting, Jul 21, 1999.
2. Data set reduction subgroup update, Strom, Stanford LSC Meeting, Jul 20, 1999.
3. Data set reduction subgroup plans, Brau, Florida LSC Meeting, Mar 5, 1999.

6. Undergraduate and Advanced High School Research

We are involving undergraduates and advanced high school students in the research project, during the school year, and for the summers. In the future we expect to have 1 or 2 students working within the group at the university during the school year, and during the summer we expect to locate 1 or 2 students at the Hanford site.

For the past three years we have been involving these young people in our LIGO work. During the summer of 1997, Sami Amasha worked with the group, doing data analysis with the GRASP package. During the summer of 1998 Sami returned, and Laura Horak also worked with the group under the Oregon Apprenticeships in Science and Engineering program. Sami and Laura worked together to study the signals from binary neutron star inspirals with the GRASP package. During the summer of 1999 Eli Bogart joined our group, again under the Oregon Apprenticeships in Science and Engineering program. Eli studied the seismic data from the Hanford site, and developed primitive transient detection algorithms.

7. The Oregon group

The group members doing research on LIGO are:

Faculty:
- Jim Brau
- Ray Frey
- David Strom

Research associates:
- Evan Mauceli
- Robert Schofield
- Nikolai Sinev

Graduate students:
- Masahiro Ito
- Rauha Rahkola

8. Results from Prior NSF Support

a. NSF award number PHY98-00961, $235,000,   Sept 1, 1998 - Aug 31, 2000
b. A Search for Gravitational Radiation at LIGO
c. Significant progress in developing many tools (both software and hardware) for LIGO research has been achieved. This progress in documented within the body of our proposal. Postdoctoral researchers, graduate students, undergrads, and high school students have been involved, as the proposal describes
d. technical notes in progress (see proposal, above)
e. see preceding proposal for description of results and access to them
f. the proposed work is the planned advancement of the completed work