

LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY  
-LIGO-  
CALIFORNIA INSTITUTE OF TECHNOLOGY  
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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| <i>Final Report</i>   | <b>LIGO-M030165-00-P</b> | <b>10/29/2003</b> |
| <b>LIGO Construction and Initial Operations</b><br><b><i>NSF Cooperative Agreement PHY-9210038</i></b><br><b>Final Report</b> |                          |                   |
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# 1 Project Summary

The Laser Interferometer Gravitational-Wave Observatory (LIGO) detectors use laser interferometry to measure the distortions of space-time between free masses to directly detect passing gravitational waves. The objective is to open the field of gravitational-wave astrophysics.

Scientists, engineers and staff at the California Institute of Technology (Caltech) and the Massachusetts Institute of Technology (MIT) are commissioning the LIGO detectors. Caltech has primary responsibility for the project under the terms of a Cooperative Agreement<sup>1</sup> with the National Science Foundation (NSF). LIGO is a national facility for gravitational-wave research, providing opportunities for the broader scientific community to participate in detector development, observations, and data analysis. LIGO welcomes the participation of outside scientists in these endeavors.

The LIGO Scientific Collaboration (LSC) is the organization comprising the scientific community. This includes Caltech and MIT scientists and engineers responsible for data analysis, advanced R&D and the development of advanced subsystems for LIGO. This Collaboration will exploit the initial detector and is pursuing the development of second-generation detectors. The LSC has its own management structure with shared participation in its governance, and corresponding obligations and privileges. The initial LIGO system comprises one three-interferometer detector system. The sites allow for expansion of the facility to a multiple-detector configuration.

The NSF Cooperative Agreement of May 1992 initiated LIGO Construction and Construction Related Research and Development. Project schedule and cost estimates were reviewed by the NSF during September 1994 and presented to the National Science Board in November 1994. The total funding established by the Board for Construction and Construction Related R&D were \$272.1 million and \$20.0 million respectively. In addition, the NSF provided \$68.7 million for Operations through September 30, 2001 for initial operation of the facilities plus installation and commissioning of the detectors (ultimately \$68.58 million was actually funded).

The end date of the original cooperative agreement was September 30, 2001. We requested and received an extension to June 30, 2003. The extension was desirable for three reasons: first, to complete the procurement of the LIGO Data Analysis System hardware (we achieved a better price-performance ratio by delaying the procurement of computer equipment); second, to finish the observatory facilities (We added a Storage and Staging Building at Livingston and a Laboratory Building at Hanford. Originally these items were removed from the scope to manage risk and contingency. However, favorable Facility bids allowed us to return the scope. Experience also indicated that the facilities were needed.); and third, for installing and commissioning the Detector (We

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<sup>1</sup> NSF Cooperative Agreement No. PHY-9210038, "Laser Interferometer Gravitational Wave Observatory LIGO"

held budget for equipment and supplies needed to complete the installation and commissioning of the Detector.)

This is the Final Report for the effort covered by the cooperative agreement. The total cost of the project was \$360.68 million. Of this, \$292.1 million was for construction of the facilities and delivery of the components for the initial complement of three detectors, and an additional \$68.58 million was allocated for initial operations of the observatories and installation and commissioning of the detectors. The LIGO construction effort is complete, on cost and virtually on schedule.

Current LIGO Operations are funded under NSF Cooperative Agreement No. PHY-0107417, including the operation of the observatories, commissioning, and initial science runs.

## **2 Facilities**

The scientific program for LIGO is to test relativistic gravitation and to establish the field of gravitational-wave astrophysics, a brand new thrust for astronomy. The initial LIGO detectors will offer an advance over all previous searches by two to three orders of magnitude in sensitivity and bandwidth. For the first time, it will be possible to detect foreseeable signals due to neutron star binary “inspirals,” for example, from as far as the Virgo Cluster (15 mega parsecs distant). At this sensitivity it is plausible, though not certain, that we will make the first observations of gravitational waves. If signals are not observed, we will have established challenging upper limits on the gravitational-wave flux, far beyond the capability of any previously existing technology.

The initial LIGO system comprises one three-interferometer detector system at two observatory sites in Hanford, Washington and Livingston, Louisiana. The sites provide space and infrastructure support for the eventual expansion of the facility to a multiple-detector configuration.

### **2.1 Observatories**

The LIGO facility design envisaged a progression of increasingly sensitive interferometers capable of extending the physics reach of the observatories. LIGO incorporated critical design features to optimize ultimate performance capabilities. These features include a building foundation and infrastructure that provides a clean, quiet environment for the instruments; a four kilometer long “L” shaped ultra-high vacuum beam tube that reduces optical losses due to residual gas to negligible levels; and a system of large vacuum chambers and pumping subsystems capable of providing a flexible envelope for a wide range of detector designs.

#### **2.1.1 Hanford Observatory**

The LIGO Hanford Observatory, located on the U.S. Department of Energy Hanford site in eastern Washington, comprises five major experimental halls spread over five miles. A 1.2-meter diameter ultra-high vacuum tube connects these halls. Three support

buildings house laboratories, offices, and an amphitheater. Two additional buildings support maintenance and operations. Approximately 90,000 square feet of this space is under tight environmental control to minimize contamination of sensitive equipment. The physical plant was designed to minimize vibration.

The Hanford Observatory houses two interferometers with arm lengths of four kilometers and two kilometers. The four-kilometer detector is installed in vacuum chambers in the corner station and the two end stations. The two-kilometer detector is in vacuum chambers in the corner station and the two mid stations situated halfway down each arm. The two interferometers share two kilometers of beam tube along each arm. The beam tube is sized to eventually accommodate up to five interferometer beams, and the current station buildings can accommodate up to three interferometers to allow future growth.



*Figure 1. Aerial View of the Hanford Interferometer*

### **2.1.2 Livingston Observatory**

The Livingston Observatory, located in the pine forests of Louisiana between Baton Rouge and New Orleans, is the site of a single four-kilometer detector (L1). During LIGO's Second Science Run (S2) this interferometer achieved the highest sensitivity ever recorded for a detector of astrophysical gravitational waves. As one example, the benchmark detectability range for binary neutron star inspirals exceeded one mega parsec, making L1 the first truly extragalactic gravitational-wave detector.



*Figure 2. Aerial View of the Livingston Corner Station*

The environmental noise due to logging activity in the Livingston vicinity limited the observational duty cycle during the S2 run. Livingston's engineering resources have focused on the development of external pre-isolator (EPI) systems for mitigating this problem. After an intensive development program we have selected a low-noise active hydraulic stabilizer system (HEPI), which is now entering production in Louisiana and is on track for installation early next year.

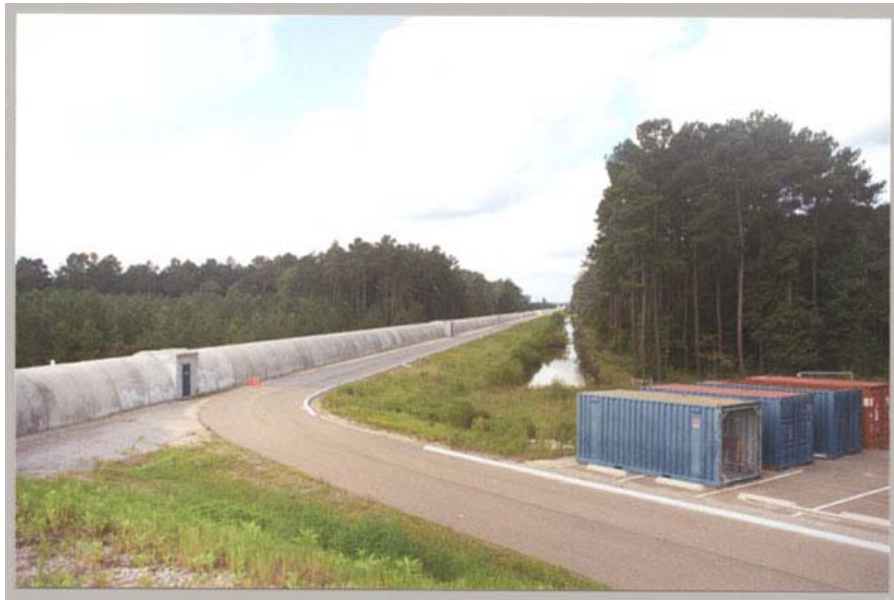
### **2.1.3 Educational Outreach**

We have established a rich Outreach Program at the Hanford and Livingston Observatories, centering on activities both within the observatory communities and at the national level.

Informal science programs at both observatories have attracted several thousand visitors each year to hear about LIGO science and explore these facilities. Visitors ranged from families with children, through school-age groups to retirees and members of local clubs. We have publicized tours in area newspapers, on the Internet, and by radio. This boosted tour attendance in the Hanford area for the first half of 2003 to approximately 1500 visitors, which is a large number for a rural area where the population of the entire county is only 150,000.



*Figure 3. BSCs (Beam Splitter Chambers) in the Corner Station at Livingston*



*Figure 4. Livingston Beam Tube Enclosure*

Both observatories continue to offer internships to teachers, who enrich their teaching experience while also enhancing LIGO outreach by developing science exhibits and hands-on activities. These media are used by observatory visitors and disseminated to other classrooms through observatory web pages. Collaborative programs offering high school students and teachers research experiences and enhanced technical training continue with Gladstone High School in Oregon and the Louisiana School for Math, Science and the Arts. The Fourth Annual Student Science and Engineering Exposition at Gladstone High School exhibited the work of more than 100 students, who worked in the

program this year, to community members and representatives from the Oregon legislature.

We have continued an active Research Experiences for Undergraduates (REU) program that involves 20+ students in LIGO research. This program also reaches important groups underrepresented in science through cooperative programs with our collaborators, especially at University of Texas, Brownsville, Southern University of Baton Rouge in Louisiana, and Salish-Kootenai College in Montana. For example, Native American students working with Professor Olson at Salish-Kootenai College have developed an important diagnostic archiving tool to support LIGO data runs.

Both observatories have formed Local Educators Networks that involve potential end users of LIGO educational outreach in the planning of our outreach activities. These networks include members of local colleges, K-12 teachers, museum staff, community development proponents, scientists involved in educational activities, and education professionals. The emphasis this year was to assess LIGO's educational efforts to date, identify the community's greatest educational needs, and assess LIGO's assets for filling those needs. The result was a proposal to the NSF that partnered LIGO with the Southern University of Baton Rouge science and education departments and the Exploratorium, to develop a major outreach center in Louisiana, and development and training programs for exhibit-based education. At Hanford this also led to discussions with other outreach organizations at Pacific Northwest National Laboratory, the Association for Science Teaching Through Astronomy, the Columbia River Exhibition of History, Science and Technology and the B-Reactor Museum Association to coordinate future outreach activities in the Hanford area.

We also developed a vision toward expanding our national outreach effort. LIGO has continued to maintain web pages to serve a national Internet audience that includes casual browsers, professional scientists, and media professionals. We have enhanced our media "contact" pages and the use of the Caltech Public Relations office to coordinate and serve media requests for information, interviews and visits. We are also working with the NSF staff to address the need for a LIGO video to serve the national audience and requests for video footage by major television programs. The NSF has issued a request for proposals for a 25-minute video, which has generated interest from a number of production companies.

### **3 Detector**

The effect of a propagating gravitational wave is a quadrupolar deformation, which alternatively elongates space in one direction while compressing space in the orthogonal direction and vice-versa, at the frequency of the wave. A Michelson interferometer operating between freely suspended masses is ideally suited for detecting these anti-symmetric distortions. The differential strain is converted into changes in light intensity at the output port.

Sensitivity limitations arise from two sources: extraneous forces on the test masses and a limited ability to measure the response of the test masses to the gravitational-wave strain.

The thermally excited motion of the test mass and the suspension imposes a fundamental limitation, intrinsic to the method used to perform the measurement. This is managed by selecting low-mechanical-loss materials, and designs that capitalize on them. Seismic motion imposes forces on the mirrors by direct coupling through the isolation and suspension systems, a technical noise source that is minimized through proper design of those systems. Seismic motion can also couple to the test masses as a result of the time-varying mass distribution near the mass (Newtonian background).

Fundamental sensing limitations also arise due to the statistical nature of the laser light used in the interferometer and the momentum transferred to the test masses by the photons (linking the sensing and stochastic noise limitations to sensitivity). Technical noise sources that limit sensitivity include frequency noise and intensity fluctuations in the laser light. Scattered light, which adds random phase fluctuations, can also mask gravitational signals.

In the limit that the instrument is short relative to the gravitational wavelength, valid for LIGO, longer arms yield bigger signals, in contrast to most competing noise sources, which remain constant with length. This motivates our four-kilometer long baseline. Generally, the scientific capability of LIGO is defined within the limits imposed by the physical settings of the interferometers and by the facility design, by the design of the initial detectors, and ultimately by future interferometers implemented to progressively exploit the full capabilities of the facility.

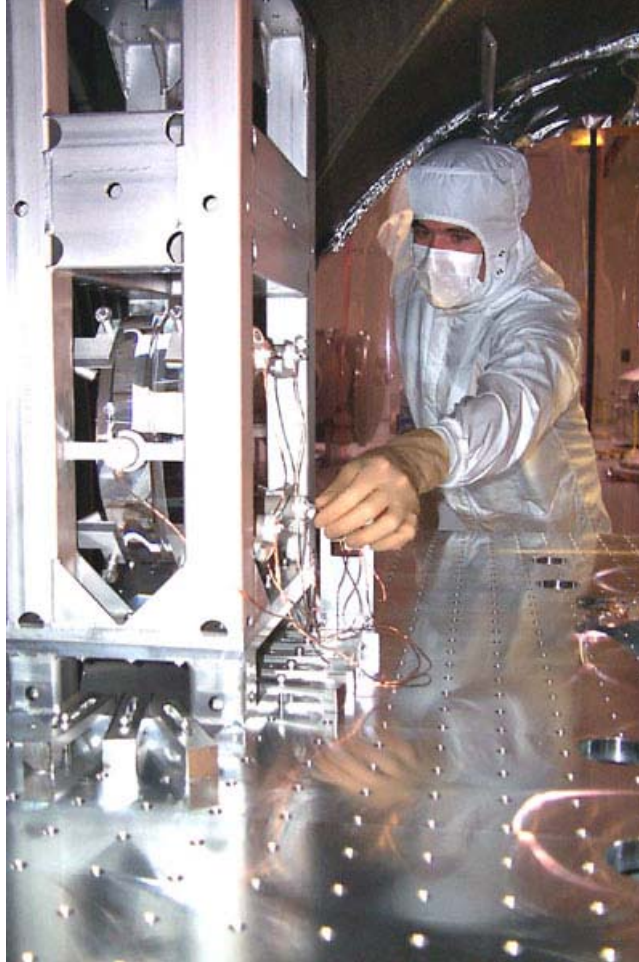
All three interferometers have been installed. We are now in the process of “punctuated” commissioning wherein periods of engineering and scientific data taking alternate with intensive periods of adjustment and improvement.

### **3.1 Commissioning**

The process of bringing a complex scientific instrument like a LIGO detector into full operation is not simply a matter of assembling the pieces and flipping the “on/off” switch. To achieve the required sensitivity, the interferometers go through an extended commissioning phase—we diagnose the performance of each element to understand how it limits detector performance and adjust or modify each to eliminate sources of noise. From the beginning, the commissioning plan invoked periods of intense work on the detectors interspersed with operational periods, where the detectors are operated around-the-clock, recording data for off-line analysis. Initially, these operational periods were designated Engineering Runs, since the main purpose of the added analysis was to aid in the subsequent commissioning activities.

During the last year, LIGO began an important transition with Engineering Runs giving way to Science Runs. The first Science Run, dubbed S1, was held at the end of August 2002 and lasted 17 days. Its primary purpose was to provide data for analysis in the search for gravitational waves. The detector noise floor during this first Science Run was approximately a factor of 100 above design sensitivity, still better than the sensitivity of any previous searches using multiple interferometers in coincidence. For example, the range at which the interferometers could detect the inspiral of a binary neutron star pair

(one of the benchmark gravitational-wave sources) encompassed the entire Milky Way galaxy. LIGO would not be expected to find gravitational waves at this sensitivity since such events might occur only once every  $10^5$  years in our galaxy, but the data could be used to set better upper limits than had any previous direct searches.



*Figure 5. LIGO Staff Installing a Mode-Matching Mirror and Suspension into a Vacuum Chamber*

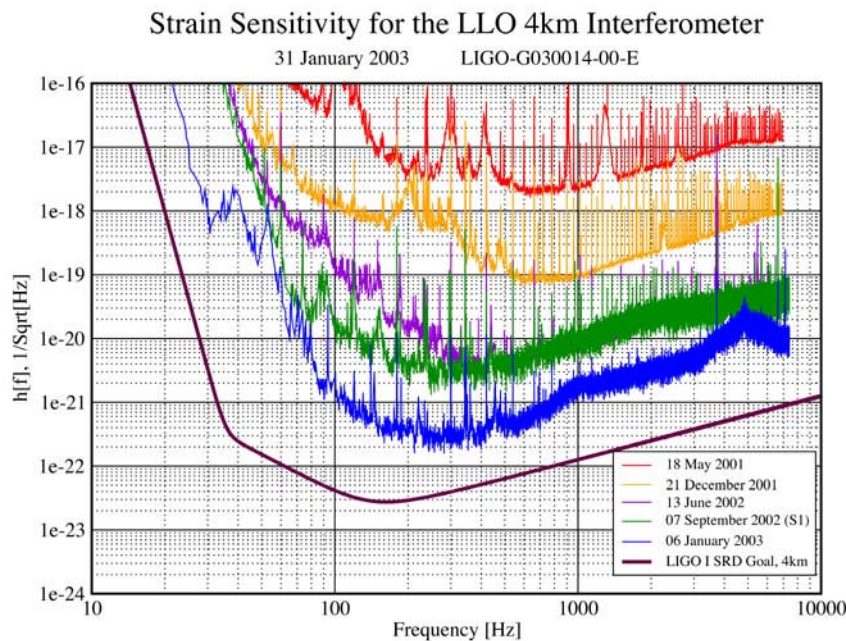
S1 was successful by several measures. The interferometers operated reliably, without major hardware or software failures. The duty cycle (fraction of the total run that each interferometer was locked and collecting Science Data) ranged from 42 percent to 73 percent, with triple coincidence time totaling about 23 percent of the run. Noise levels were somewhat variable because some of the alignment control systems were not yet operational, but sufficient diagnostics were in place that the sensitivity could be tracked reliably enough for scientific analysis.

After S1, the commissioning team working on the detectors made impressive progress, as illustrated in Figure 6. This plot shows the evolution of the detector sensitivity for the Livingston interferometer since first operation in 2001. The green curve shows the sensitivity at the time of S1, and the blue curve shows the ten times improvement

achieved over the next six months. Similar improvements were achieved with the Hanford interferometers.

These improvements set the stage for the second Science Run (S2), which took place between February 14 and April 14, 2003. This run lasted eight weeks. Building on lessons learned during S1, we improved procedures for monitoring performance and, as a result, achieved better stability. The interferometers again ran reliably during the longer run, and the increased sensitivity did not reduce interferometer availability (between 37 percent and 74 percent).

Most importantly, with the improved sensitivity, S2 represents the first time the LIGO detectors had the ability to see potential sources in other galaxies, notably the Andromeda galaxy. Once again, LIGO could not yet expect to see gravitational waves, but it still represents a significant step toward the design sensitivity.



*Figure 6. Strain Sensitivity History for the Livingston Four-Kilometer Interferometer*

The commissioning process will continue through 2004 to extract the very best performance from the current interferometers. Another set of detector improvements was initiated immediately after S2, to be completed before the next Science Run. As LIGO progresses, the Science Runs will grow longer, and the intervening tuning periods become shorter as we make the transition into full operation.

### 3.2 Seismic Remediation

Operation of the Livingston four-kilometer interferometer has been limited by local vibration disturbances. This has prevented operation during most daytime periods and some high-activity weekend periods. The interferometer has operated successfully for scientific running during night and other quiet periods.

From the beginning, we provided extra space in the design of the external supports for each vacuum chamber for additional isolation, if needed. This design allowance now permits us to respond to the high level of disturbance in Livingston. LIGO foresaw that additional isolation could be provided by active systems. During early LIGO development, fully active pre-isolators were studied by the LIGO MIT group using modified commercial hardware from Barry Controls.

Insights gained from this work motivated custom pre-isolator development for future use in advanced detectors. A Stanford group proposed a pre-isolator based upon a hydraulic actuator. In January 2001, this system was selected, after careful review, as the baseline pre-isolator for an advanced detector.

The hydraulic pre-isolator was also considered a candidate for pre-isolation in Livingston when it became apparent that an accelerated implementation of supplementary isolation would be needed. A review in March 2002 adopted the hydraulic pre-isolator (HEPI, the “E” stands for “external”) as the baseline choice for this application and approved a rapid development program. As insurance to achieve the required performance, a vigorous program to develop a backup actuator was also initiated. The LIGO group at MIT proposed a magnetic actuator (MEPI) for this alternate test program.

Based upon a thorough comparative review of the test programs, we have decided to implement the HEPI system in Livingston.

### 3.3 RFI Remediation

Radio frequency and electromagnetic interference (RFI and EMI) investigations indicate that we are suffering contamination from switching-mode power supplies and cross coupling from digital electronics to low-level analog electronics. We have successfully reduced RFI and EMI in some subsystems by modifying power supplies (to linear models) and changing cable configurations. We are now executing a comprehensive plan to address these sources of contamination in stages.

## 4 Data and Computing

The Data and Computing Group is responsible for

- Modeling and simulation support for the LIGO interferometers and their commissioning;

- The laboratory data archival and computing infrastructure support, and data distribution outside the LIGO Laboratory;
- The general computing infrastructure to support laboratory operations.

The modeling and systems group develops and maintains models to simulate LIGO interferometer performance and behavior. The data archival and computing infrastructure group has primary responsibility for hardware and software systems for collecting, storing, distributing, and analyzing astrophysical and physics environment data. The general computing group implements and maintains the infrastructure of personal computers, web and email servers, and network communications that support scientific, engineering, and business activities.

## 4.1 Modeling and Simulation

We refer to the time domain simulation program developed for LIGO as the “end-to-end” model<sup>2,3</sup>. This computer software simulates evolutions of major elements of the LIGO detector environment, including laser fields and optics, mechanical object motions, control system signals and various types of noise as realistically as possible. It has been used both during the design of subsystems and the associated interferometer commissioning activities. A notable example of a design task was the development of the length control system used for lock acquisition. Prediction of the performance of the as-built LIGO is an example of its application during commissioning.

LIGO is a complicated electro-optical plant including a large number of servo control systems. A number of critical interactions are inherently non-linear. Response function and loop gain variations over time cannot be neglected. There are a large number of noise sources that need to be modeled as realistically as possible and whose effects must be considered when designing control systems. We designed the lock acquisition procedures using a complex simulation. Based on physical models of optics and fields, we developed a relatively simple algorithm for controlling the detector, and we revised it to be robust with realistic disturbances and noisy environments by testing the lock acquisition code in the LIGO simulation. When we tested the lock procedures on the actual LIGO detector, we achieved lock using this code with only minor modifications. Efforts continue to develop better lock acquisition codes and reliable alignment control systems taking into account the complex and significant physical effects of radiation pressure and thermal heating.

There are abundant *technical* noise sources that can degrade the sensitivity of the LIGO interferometers. Some of the noises are due to non-linear effects caused by interactions

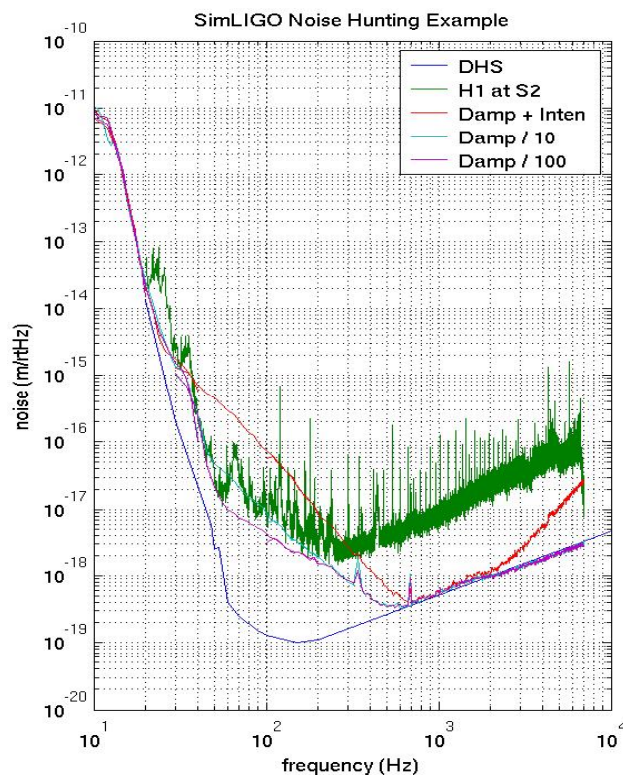
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<sup>2</sup> H. Yamamoto et. al., "End-to-End Simulation Program for Gravitational-Wave Detectors," Gravitational Wave Detection II, Frontiers Science Series No.32, Seiji Kawamura and Norikatsu Mio, editors, pages 331-336, 2000.

<sup>3</sup> B. Bhawal et.al., "The LIGO End-to-End Simulation Program," to be published in Proceedings of the Moriond Conference on Gravitational Waves and Experimental Gravity (March, 2003), LIGO Document No. LIGO-P030038.

between sources. Some of the noise sources are difficult to predict quantitatively using actual calibration measurements. Furthermore, it is important to correctly understand the effects arising from the combination of a number of different noise sources. The end-to-end simulation program with realistic detection systems handles these issues properly. The LIGO simulation cannot fully predict quantitatively all noises, but it can provide a good, reliable profile of the noise structure by incorporating various actual measurements. With this profile in hand, optimal tuning of the sensitivity can be done systematically.

The end-to-end simulation model for the initial LIGO configuration incorporates most of the as-built core optics hardware and control systems. In addition to the principal physically limiting noise sources -- seismic, thermal, and shot noise -- measured electronic noise sources (technical noise sources) are also included when appropriate.



*Figure 7. The Sensitivity Curves Calculated Using the Simulation Compared with Sensitivity Measured During the Second Science Run*

Sensitivity curves calculated using this simulation package are shown in Figure 7. The figure also shows the sensitivity measured at the Hanford four-kilometer interferometer during the Second Science Run (H1 at S2) as well as the LIGO Design Requirement (“DHS” on the figure). Three simulations assume different gains for alignment control using the optical lever signal. This provides an explicit example of how the simulation may be used to explore ways to improve LIGO performance. The difference at high frequency is due to the reduced input power used during S2 (0.8W) relative to the design value of 5.5W.

The model used to generate these sensitivity curves was also used to design an improved lock acquisition algorithm and an alignment control system in a realistic environment where noises and gain fluctuations play important roles. During these studies, two important things were discovered about the detector. The first was that the Schnupp asymmetry (differences of positions of two input test masses relative to the beam splitter) at the Hanford and Livingston four-kilometer interferometers was incorrect. A second result derived by comparing model behavior with the as-built interferometers was that a signal used to sense mirror alignments was incorrectly interpreted, which made it difficult to implement the alignment control system.

## 4.2 LIGO Data and Computing System for Data Analysis

The LIGO interferometers and associated physics environment monitoring systems generate a combined stream of continuous data at approximately seven Megabytes per second. Data handling systems must support a number of independent scientific analyses both on site (at the observatories) and off-site (using archived data). Uses include:

- Computationally intensive and parallel pipeline processes to detect astrophysical signals in the data stream; these must run quickly enough to keep up with data acquisition;
- Data processing and conditioning to provide reduced data sets;
- Data distribution for detector diagnostics;
- Data archival and retrieval, including metadata summaries and "raw" data.

Several working groups within the LIGO Scientific Collaboration (LSC) perform the astrophysics analysis of the LIGO data. Scientists within the LIGO Laboratory participate in these activities as members of the collaboration. LIGO Laboratory data analysis resources are available to the LSC members under terms defined in the LSC White Paper<sup>4</sup>.

The LIGO Data Analysis System (LDAS) comprises the hardware and software provided for these tasks.

LDAS consists of four separate sites. Table 1 summarizes the capabilities of the systems that will be installed.

Similar hardware has been installed at each of the sites, although the size of the installation has been scaled according to data rates and computational needs. The sites operate autonomously. A large volume robotic data archive has been situated at Caltech. It is anticipated that the initial LIGO configuration will generate at least one integrated year of data during science runs at design sensitivity. The installed systems meet or

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<sup>4</sup> [http://www.ligo.caltech.edu/LIGO\\_web/lsc/lsc.html](http://www.ligo.caltech.edu/LIGO_web/lsc/lsc.html)

exceed the requirements for pipeline analysis and archival capacity for the initial LIGO configuration.

**Table 1. LDAS Characteristics by Site**

| <b>Site</b>       | <b>Computational Capacity</b>        | <b>Storage Capacity</b>                        | <b>Network</b> |
|-------------------|--------------------------------------|--|----------------|
| <b>Hanford</b>    | 140 nodes (2 CPU ea.)<br>740 GFLOPS  | 28 TB (nodes)<br>140 TB (tape)<br>30 TB (SAN)  | 1000 Mbps      |
| <b>Livingston</b> | 70 nodes (2 CPU ea.)<br>370 GFLOPS   | 14 TB (nodes)<br>140 TB (tape)<br>15 TB (SAN)  | 1000 Mbps      |
| <b>CIT</b>        | 210 nodes (2 CPU ea.)<br>1117 GFLOPS | 42 TB (nodes)<br>1200 TB (tape)<br>50 TB (SAN) | 1000 Mbps      |
| <b>MIT</b>        | 112 nodes (1 CPU ea.)<br>130 GFLOPS  | 8 TB (nodes)<br><br>4 TB (SAN)                 | 1000 Mbps      |

LIGO matched the LDAS configuration to the science mission, namely the search for astrophysical signatures of gravitational waves, which are expected to be rare and weak. Sequential integration of the hardware was guided by the need to support incremental Mock Data Challenges designed to validate the inter-operability of LDAS software and hardware and also to validate the scientific integrity of the search algorithms and their implementation; and the need to support increasing demands during engineering runs and commissioning activities as the interferometers are brought on line.

The LDAS Preliminary Design Document (LIGO-T990001) defines the requirements for the hardware needed to execute the LIGO pipeline data analysis. These match the science analysis goals and data usage models discussed in the LSC White Paper.

The most challenging calculations performed on-site are to search for compact object binary coalescence. These calculations are easily done in parallel and require only limited inter-node communications. An MPI-based Linux-cluster ("Beowulf") architecture is suited to this class of problem and was selected as the architecture for the LDAS sites.

For compact object coalescence and for transient events (supernovae--SNe), low latency (a rapid response) is desirable. This follows from the desire to quickly notify other observatories (neutrino, optical, radio, gamma, and gravitational-wave) in the event of detection. In addition, astrophysical searches constitute an end-to-end analysis that can provide unique insight into detector behavior and performance. For these requirements, there are LDAS facilities installed at each observatory on-site.

More computational power and larger data sets are needed to look for continuous wave sources. Since these are nominally stationary signals, they do not need to be processed real time. For such analyses, larger off-site computational facilities will be used. These

include computing resources distributed across the LIGO Scientific Collaboration (in the US, EU, and Australia).

In addition, a certain class of source searches (e.g., the stochastic gravitational-wave background) requires that data sets from different detectors be cross-correlated over extended periods of time. For this purpose, data stored in the collaboration Tier 1 (LIGO Laboratory) and Tier 2 (collaboration) computing resource sites will be employed. The most computationally demanding searches may also use other non-LIGO facilities available as national resources centers.

Linux clusters have been purchased and installed at Livingston (LLO), Hanford (LHO), MIT, and Caltech (CIT). The LHO, LLO, and CIT clusters are comprised of dual 2.66 GHz P4 Xeon processor nodes, each provided with two Gigabytes of RAM and a Gigabit Ethernet (1000 Mbps) interconnect. The scale of computing requirements was set by the compact binary inspiral and coalescence search: 70 nodes were allocated per interferometer. Thus the initial LIGO complement of computational capacity within the LIGO Laboratory corresponds to 70 nodes at Livingston, 140 nodes at Hanford, and 210 nodes at CIT. The MIT cluster consists of 112 single CPU nodes with clock speed of 1.1 GHz. These were used in a prior implementation at the two observatories to support earlier engineering and the first (S1) Science Run.

For data archival at the observatories, each site has installed a 140 Terabyte tape robot controlled under Sun Microsystems integrated storage area network management software environment, SAM-QFS with four STK9940B tape drives. These systems provide on-line look back capability for one year of full raw frames data. This capacity supports site-based detector commissioning R&D and local investigations.

We successfully archived data from the latest Engineering Runs (E7 - E9) and the first two Science Runs (S1, S2) at Caltech's Tier 1 data center. In addition, a number of reduced data sets important to detector commissioning activities (termed "trend frames") from Hanford and Livingston are also permanently archived at Caltech. LIGO began operations using IBM's HPSS (High Performance Storage System) archival utility and then migrated successfully to Sun's SAM-QFS system. At the present time, the LIGO data archive contains the following HPSS data:

- 60 Terabytes of data: 1994 40-Meter facility data, all Engineering Runs (E1-E7), and the first Science Run (S1).

The later SAM-QFS system currently holds:

- 67 Terabytes of data: (E9 and S1, S2).

### **4.3 Information Technology Support Group**

The four LIGO Laboratory sites (CIT, LHO, LLO, MIT) are unified by wide area network (WAN) links.

### 4.3.1 MIT

MIT operates under the local university IT infrastructure. We have installed a virtual control room that allows MIT LIGO scientists to access the observatory control room network. This equipment is used on a regular basis.

### 4.3.2 Livingston

The observatory local area network (LAN) consists of a Gigabit Ethernet (1000 Mbps). We have installed a local commercial firewall (PIX) to provide security. The local LAN has been expanded to cover all building facilities presently on the site.

Currently the connection to the LIGO WAN is via dual T1 lines (2 x 1.544 Mbps). In the very near future, this will be upgraded to full Gigabit Ethernet (1000 Mbps). This is being coordinated with Louisiana State University (LSU).

### 4.3.3 Hanford

A Memorandum of Understanding (MOU) between the NSF and the DOE provides for ESnet access at Hanford. Last year, the WAN connection was upgraded to OC3 and now provides high bandwidth access to and from the observatory. The observatory is also installing a LAN Gigabit backbone identical to the Livingston configuration. The LAN has been expanded to all site facilities.

### 4.3.4 Caltech

We maintain the LIGO Laboratory LAN at Caltech separately from the university IT infrastructure. The laboratory owns a number of long distance fiber-optic interconnections between on-campus distributed facilities. It owns and maintains four different Class C subnets to support data and computing activities, general computing activities, and inteferometer control systems development.

We have implemented a local Virtual Control Room, identical to the one at MIT, to provide Caltech LIGO scientists access to the observatory control room network.

## 5 Campus Research Facilities

LIGO operates a 40-Meter prototype ( $1/100^{\text{th}}$  the length of the actual observatories) on the Caltech campus. To prototype advanced LIGO optical configurations and controls, a fully instrumented suspended-mass interferometer is needed. The 40-Meter facility fulfills this function. However, it is not possible to install full-size seismic isolation, suspensions, and optical components into the 40-Meter facility vacuum.

The LIGO Advanced System Test Interferometer (LASTI) facility is designed for developing and testing full-scale advanced and improved LIGO systems, without

disrupting or delaying scientific operations at the observatories. Located in a high-bay laboratory built for the purpose on the MIT campus, LASTI comprises a suite of vacuum chambers and beam tubes (with a much-reduced 16 meter baseline), seismic isolation supports, lasers, and electronic and computing infrastructure closely replicating those at the observatories.

Graduate students, REU (Research Experiences for Undergraduates) summer students, visiting students, and visiting scientists have contributed to all aspects of the project in these facilities. In particular in the 40-Meter facility, REU students have contributed to the design of the main interferometer optical plant and the length and alignment control systems, to the configuration and commissioning of the pre-stabilized laser, digital suspension controllers, suspended-mass input mode cleaner, and optical lever alignment sensing systems, and to the simulation of lock acquisition and dynamics of the dual-recycled interferometers. We will continue to involve students and visitors with all aspects of the project and its goals. The research facilities are popular tour destinations for local students, journalists, scientific visitors, and dignitaries.

## 6 Advanced R&D

A portion of the annual operating funds is dedicated to research directed towards the development of advanced LIGO detectors. This effort is strongly collaborative with other institutions in the LIGO Scientific Collaboration (LSC). Advanced systems currently being studied include:

- Systems and Interferometer Sensing and Control – a signal-recycled interferometer configuration is a primary focus.
- Seismic Isolation – current isolation systems are largely passive although we are installing some active components in Livingston to overcome unexpectedly high levels of anthropomorphic noise. Advanced detectors will require active seismic isolation.
- Suspensions – initial LIGO uses a single stage mirror suspension. The University of Glasgow GEO<sup>5</sup> lab is developing a quadruple suspension for the core optics in an advanced LIGO detector. In addition, we have a program to study alternative suspension materials and geometries.
- Optics – sapphire optics are being studied as an alternative to fused silica.
- Optical Coatings – programs are in progress to find coatings for both sapphire and fused silica with improved (reduced) optical and mechanical losses.
- Pre-stabilized Laser – programs to develop 200 W laser sources continue at Adelaide, Stanford, and Hannover.

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<sup>5</sup> GEO, British-German Cooperation for Gravity Wave Experiment, <http://www.geo600.uni-hannover.de/>

- Thermal Compensation - the initial prototyping of the two schemes for thermal compensation concluded this year and resulted in the PhD thesis of a LIGO student<sup>6</sup>. The lens formed in the substrates due to the absorption of the laser light in the substrate makes the interferometer sensitive to the power level. Thermal compensation allows the interferometer to be used with a wide range of input powers, which permits, for example, better low frequency sensitivity with a reduction in the power. It also allows a trade to be made with the material properties of the substrate; this is useful for sapphire, and necessary in the fallback case for fused silica.

## 7 LIGO Scientific Collaboration (LSC)

A fundamental goal of the LIGO Laboratory has been to become a true national facility available to the scientific community. To accomplish this, LIGO has broadened participation to include the community of interested scientists by creating the LIGO Scientific Collaboration (LSC)<sup>7</sup>. There are now some 430 members from 44 institutions, US and international. The LSC comprises both LIGO Laboratory scientists and those from collaborating groups. The LSC is organized to provide “equal scientific opportunity” to all members. It is growing steadily and will remain open to new members over the coming years. Already the LSC has a significant international presence, including collaborating groups from India, Russia, Germany, the U.K., Japan, and Australia. Our international partners are involved in all aspects of the LIGO research program.

The LSC provides a forum for organizing technical and scientific research in LIGO. The organization is separate from the LIGO Laboratory, with its own leadership and governance, but reports to the Laboratory Directorate for final approval of its research program, technical projects, observational physics publications, and talks announcing new observations and physics results.

Second Science Run (S2) investigations are in high gear. Learning from our experience, we are making a greater effort to coordinate work among the astrophysical search groups, especially in classifying the quality of data segments with respect to “glitchiness,” band-limited noise, and calibration/timing reliability. Discussions are also looking ahead to the Third Science Run (S3), scheduled to proceed towards the end of 2003.

The search for astrophysical signals is organized within the LSC. Collaboration members committed to the initial LIGO detector science runs are responsible for the science in the early phase of observation. The Executive Committee of the LIGO Scientific Collaboration met on June 27, 2003, to consider First Science Run (S1) papers prepared by three of the Search Team Working Groups (Stochastic, Pulsar, and Inspiral) for approval for publication. The results presented in each of the three papers were approved

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<sup>6</sup> R. Lawrence, “Active Wavefront Correction in Laser Interferometric Gravitational-Wave Detectors,” MIT Ph.D Thesis, 2002, P030001-00-R

<sup>7</sup> <http://www.ligo.org>

as the final S1 results of their respective searches. This means that the LSC Executive Committee authorizes the use of these results as approved and final results. After final editing the three papers will be approved for distribution outside of the LSC.

Tasks related to science and engineering runs are also organized within the LSC. LSC members help in the control rooms and participate in taking data. (More than 100 members of the LIGO Scientific Collaboration took shifts at the sites, providing continuous monitoring of the data to ensure smooth operation.)

LIGO is available to all interested researchers through participation in the LSC. To join, a research group proposes a research program and negotiates a Memorandum of Understanding (MOU) with relevant attachments<sup>8</sup>. The proposing group then presents the program to the LSC. When the group is accepted into the LSC, it becomes a full scientific partner.

Currently the LSC schedules three formal meetings each year in March, August, and November. Various working groups meet more frequently. The LSC has prepared White Papers that outline plans for the technical development of LIGO and for science data analysis. Publication policy and conference committees are active in addition to other functions needed to make the LSC a “full service” organization.

## **8 Astrophysics and Data Analysis**

Astrophysical data analysis is a LIGO Scientific Collaboration (LSC) activity with a strong Laboratory contribution. The present effort is organized into four groups with the objective of setting interesting upper limits on the flux from short-term burst sources, stochastic sources, binary inspiral “chirps,” and continuous-wave sources.

This past year we scheduled two science runs, S1 and S2. The S1 data have been analyzed and results have been presented at a number of conferences, including the AAAS Meeting in Denver, February 2003, the APS Meeting in Philadelphia, April 2003, and the Amaldi Conference in Pisa, Italy, in July 2003. Each source search group is finalizing a publication describing the S1 analysis and results. These will be submitted for publication in Physical Review D.

The analysis of the S2 run is currently under way. Preliminary results will be available for internal discussion within the LIGO Scientific Collaboration by the time of the summer and fall meetings.

### **8.1 Search for Un-Modeled (Burst) Sources**

The LSC Bursts Working Group (BWG) is searching for gravitational-wave bursts in the LIGO data. These are short transients (lasting less than one second) of gravitational radiation of unknown waveform. Possible sources include burst signals from supernovae

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<sup>8</sup> <http://www.ligo.org/mou/mou.html>

and black hole mergers for which the physics and computational implications are so complex that analytical calculation of the expected waveforms is extremely difficult. General time-only domain and time-frequency domain search techniques are employed. The search is open to any unanticipated source of gravitational radiation that falls within the general time-frequency considerations.

An additional focus of the BWG is to look for correlations between gravitational-wave bursts and  $\gamma$ -ray bursts (GRBs). A number of GRB progenitors are plausible gravitational-wave burst emitters and correlation with LIGO signals immediately before a GRB (“on source”) and at random times (“off source”) may statistically establish an association<sup>9</sup>.

We searched for gravitational-wave bursts in the S1 data with durations and frequency bands suggested by simulations of stellar collapse: durations between 4 and 200 milliseconds and significant frequency content in the LIGO S1 sensitivity band of 150-3000 Hz.

Our procedure looked for time coincident burst events in all three LIGO detectors, using 96 hours of data when the three interferometers were in science mode simultaneously (of the total 408 hour S1 run). Stringent quality checks on the detector noise levels and the presence of valid calibration information reduced the total observation time to 35.5 hours. With one preferred search algorithm, six coincident events were observed. A rate of 10.6 accidental coincidences was estimated by introducing an artificial time shift between detectors. The upper limit on the number of events above background is calculated to be 2.3 at the 90 percent confidence level, or 1.6 per day. The results and details concerning analytical methods are being submitted for publication.

## 8.2 Search for Stochastic Gravitational-Wave Background

$\Omega$  is a measure of the "stuff" in the universe relative to the total required for a closed system.  $\Omega_{\text{gw}}$  is a measure of the portion of that stuff contributed by gravitational waves. LIGO may someday be able to contribute to an understanding of how big  $\Omega_{\text{gw}}$  is.

Stochastic backgrounds are signals produced by many weak incoherent sources. They are non-deterministic and can only be characterized statistically. Such signals can arise from early-universe processes (analogous to the electromagnetic cosmic ray background) and from present-day phenomena. They give rise to a signal that is correlated between the two detectors. It will have the same spectrum in each detector and is differentiated from detector noise by the inter-detector correlation.

Stochastic signals are expected to be quite weak compared to the intrinsic noise of an individual LIGO interferometer. Consequently, detecting or placing a limit on a stochastic gravitational-wave signal will require long observation periods over a bandwidth a few times the inverse light travel time between the interferometers.

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<sup>9</sup> Finn *et al.*, *Phys. Rev. D* 60, 12110 (1999)

Analysis of the S1 data for the two transcontinental interferometer pairs yielded the following upper limit estimates:

$$\Omega_{\text{gw}} < 23 \pm 4.6 \text{ (H 2km - L 4km)}$$

$$\Omega_{\text{gw}} < 55 \pm 11 \text{ (H 4km - L 4km)}$$

These are interesting experimentally because they represent the best that has been reported to date in the LIGO frequency band. However, we are a long way from values that will interest astrophysicists. Improved sensitivities and longer integration times may allow measurements made with initial LIGO to drive these estimates to levels on the order of  $10^{-6}$ , and theoretical values are on the order of  $10^{-9}$ .

Of more immediate utility, we observed the Hanford two-kilometer/four-kilometer pair to have significant negative, non-zero correlations that are inconsistent with a gravitational-wave stochastic background. We are investigating the sources of this correlation. One known contribution is acoustic common-mode coupling between the two instruments. Mitigation efforts are underway and will be completed for the S3 science run in late 2003.

The results and details concerning the analytical methods used are being prepared and submitted for publication.

### 8.3 Search for Binary Inspirals

The Inspiral Upper Limits Working Group is looking for gravitational-wave “chirps,” so called because the signals emitted by compact binary systems during the last few seconds before ultimate coalescence are in the audio frequency range and increase in intensity and frequency as the bodies spiral ever closer. Our goal is to extract astrophysically significant results (presumably upper limits rather than detections) from the early LIGO data, collected while the detectors have modest sensitivity. To date, the group has focused on low-mass systems, including binary neutron star systems, in which each body is expected to have a mass of approximately 1.4 solar masses.

We search for binary inspirals in the LIGO data using matched filters. This method uses linear filters constructed from the calculated waveforms. Matched filtering requires a good set of template waveforms that accurately predicts the possible signals. Ideally the templates are computed from an exact two-body solution to the Einstein equations for the general relativistic gravitational field. However, the exact two-body solution is not known and we therefore must resort to approximations.

The Inspiral Working Group has completed a search for inspiral signals in the data from the S1 run. The templates used covered pairs of objects with masses between one and three times the mass of the Sun, including neutron stars; the sensitivities of the detectors were such that most potential events throughout the Milky Way and Magellanic Clouds would be detectable. "Trigger" lists from the two four-kilometer LIGO interferometers were combined so that, by requiring consistent times and waveform parameters, a signal

could potentially be detected with high confidence. No such coincident event candidates were observed, nor were any theoretically expected for this observation time and range. However, from the absence of event candidates with high signal-to-noise ratios, an upper limit of  $1.7 \times 10^2$  per year was derived for the rate of inspiral events in a galaxy like the Milky Way, with 90 percent confidence. A paper describing the analysis has been internally reviewed and approved by the LSC and will soon be submitted to Physical Review.

## 8.4 Search for Periodic Signals

The primary astrophysical candidates for periodic emission of gravitational waves are spinning neutron stars, either isolated or in binary systems. Continuous gravitational waves are emitted when there are asymmetries due to rotation about a non-symmetry axis, precession, or stellar pulsations. A subset of these objects is observed in the electromagnetic spectrum, for example as pulsars or in x-ray binary systems. A further subset of these objects spins fast enough that the potential gravitational-wave emission frequency is within the LIGO and GEO band. (For the simplest case the gravitational-wave frequency is emitted at twice the spin frequency.) However, there should be many more neutron stars than those observed, and there is always the possibility of an unknown class of periodic sources. Thus, both targeted and untargeted searches are warranted. Targeted searches include known pulsars, for which the position, spin frequency, and spin evolution are known, and low-mass x-ray binaries, for which the position is known, but a search over a limited frequency band and orbital parameters is needed. Targeted searches could also include positions on the sky (such as that of a globular cluster or the galactic center) for which a search over the other signal parameters is needed. Untargeted searches involve a search over many sky positions and intrinsic source parameters. Since periodic signals are expected to be weak, long observation times are required and the changing velocity and orientation of the detector relative to the source must be accounted for.

The Periodic Upper Limits Group has analyzed the data from the GEO 600 and LIGO detectors taken during the First Science Run, S1. The analysis focused on continuous gravitational waves from the pulsar J1934-2134 at twice its rotational frequency (1284 Hz). No detection is expected for this pulsar at initial LIGO sensitivities, but the analysis sets the stage for future periodic searches. These will target all known pulsars, neutron stars in x-ray binaries, the galactic center, the Gould Belt, supernovae remnants, globular clusters, and eventually all of the sky.

Summaries of the analytical methods and results for pulsar J1934-2134 have been presented at the Amaldi 5 conference. The best upper limit results for the gravitational-wave signal can be used to calculate an upper limit for the ellipticity of the star. The upper limits reported are still at least five orders of magnitude larger than those obtained by assuming that the spin down measured for J1934-2134 is entirely due to the emission of gravitational waves. However, the methods used will lead to interesting upper limits as the search widens, the detector sensitivity improves, and the integration time is extended.

## 8.5 First Science Run Publications

The following publications describe the detector and data analysis results for the First Science Run:

- LIGO-P030008-05-Z, Setting Upper Limits on the Strength of Periodic Gravitational Waves Using the First Science Data from the GEO600 and LIGO Detectors, to be published in Phys Rev D.
- LIGO-P030009-03-Z, Analysis of First Science Data from LIGO for Stochastic Gravitational Waves, to be published in Phys Rev D.
- LIGO-P030010-D-Z, Analysis of LIGO Data for Gravitational Waves from Binary Neutron Stars, to be published in Phys Rev D.
- LIGO-P030011-00-Z, First Upper Limits on Gravitational-Wave Bursts from LIGO, to be published in Phys Rev D.
- LIGO-P030024-01-R, Detector Description and Performance for the First Coincidence Observations between LIGO and GEO, Pre-print – Elsevier Science

## 9 Project Management

### 9.1 Baseline Milestones

All milestones identified in the LIGO Project Management<sup>10</sup> have been completed.

**Table 2. Comparison of Planned and Actual Completion Dates for Project Management Plan Milestones (Facilities)**

| Milestone Description                     | Project Management Plan Date |           | Actual Completion Date |           |
|---|------------------------------|-----------|------------------------|-----------|
|   | Washington                   | Louisiana | Washington             | Louisiana |
| Initiate Site Development                 | 03/94                        | 08/95     | 03/94                  | 06/95     |
| Beam Tube Final Design Review             | 04/94                        |           | 04/94                  |           |
| Select A/E Contractor                     | 11/94                        |           | 11/94                  |           |
| Complete Beam Tube Qualification Test     | 02/95                        |           | 04/95                  |           |
| Select Vacuum Equipment Contractor        | 03/95                        |           | 07/95                  |           |
| Complete Performance Measurement Baseline | 04/95                        |           | 04/95                  |           |
| Initiate Beam Tube Fabrication            | 10/95                        |           | 12/95                  |           |
| Initiate Slab Construction                | 10/95                        | 01/97     | 02/96                  | 01/97     |
| Initiate Building Construction            | 06/96                        | 01/97     | 07/96                  | 01/97     |
| Accept Tubes and Covers                   | 03/98                        | 03/99     | 03/98                  | 10/98     |
| Joint Occupancy                           | 09/97                        | 03/98     | 10/97                  | 02/98     |
| Beneficial Occupancy                      | 03/98                        | 09/98     | 03/98                  | 12/98     |
| Accept Vacuum Equipment                   | 03/98                        | 09/98     | 11/98                  | 01/99     |
| Initiate Facility Shakedown               | 03/98                        | 03/99     | 11/98                  | 01/99     |

<sup>10</sup> Project Management Plan, Revision C, LIGO-M950001-C-M submitted to the NSF November 1997.

**Table 3. Comparison of Planned and Actual Completion Dates for Project Management Plan Milestones (Detector+-)**

| Milestone Description                              | Project Management Plan Date |           | Actual Completion Date |           |
|--|------------------------------|-----------|------------------------|-----------|
|  | Washington                   | Louisiana | Washington             | Louisiana |
| BSC Stack Final Design Review                      | 04/98                        |           | 08/98                  |           |
| Core Optics Support Final Design Review            | 02/98                        |           | 11/98                  |           |
| HAM Seismic Isolation Final Design Review          | 04/98                        |           | 06/98                  |           |
| Core Optics Components Final Design Review         | 12/97                        |           | 05/98                  |           |
| Detector System Preliminary Design Review          | 12/97                        |           | 10/98                  |           |
| Input/Output Optics Final Design Review            | 04/98                        |           | 03/98                  |           |
| Pre-stabilized Laser (PSL) Final Design Review     | 08/98                        |           | 03/99                  |           |
| CDS Networking Systems Ready for Installation      | 04/98                        |           | 03/98                  |           |
| Alignment (Wave Front) Final Design Review         | 04/98                        |           | 07/98                  |           |
| CDS DAQ Final Design Review                        | 04/98                        |           | 05/98                  |           |
| Length Sensing/Control Final Design Review         | 05/98                        |           | 07/98                  |           |
| Physics Environment Monitoring Final Design Review | 06/98                        |           | 10/97                  |           |
| Initiate Interferometer Installation               | 07/98                        | 01/99     | 07/98                  | 01/99     |
| Begin Coincidence Tests                            | 12/00                        |           | 10/01                  |           |

## 9.2 Financial Status

Table 4 summarizes the final costs and provides a comparison to the 1994 cost estimate.

**Table 4. Comparison of Actual Costs with 1994 Cost Estimate**

| <b>WBS</b>                      | <b>Description</b>                    | <b>Cost Estimate (\$K)</b> | <b>Actual Costs (\$K)</b> | <b>Estimated Contingency (%)</b> | <b>Actual Usage (%)</b> |
|---------------------------------|---------------------------------------|----------------------------|---------------------------|----------------------------------|-------------------------|
| 1.1.1                           | Vacuum Equipment                      | 45,635                     | 44,047                    | 17.0                             | -3.5                    |
| 1.1.2                           | Beam Tube                             | 42,442                     | 47,004                    | 13.6                             | 10.8                    |
| 1.1.3                           | Beam Tube Enclosure                   | 18,331                     | 19,338                    | 17.5                             | 5.5                     |
| 1.1.4                           | Civil Construction                    | 49,299                     | 59,695                    | 14.4                             | 21.1                    |
| 1.1.5                           | Beam Tube Bake                        | -                          | 5,570                     | -                                | 13.1 <sup>11</sup>      |
| 1.2.1                           | Interferometer Design and Fabrication | 31,362                     | 40,300                    | 33.4                             | 28.5                    |
| 1.2.2                           | Control and Data Systems              | 12,375                     | 14,960                    | 24.3                             | 20.9                    |
| 1.2.3                           | Physics Environment Monitoring        | 3,456                      | 1,939                     | 5.0                              | -43.9                   |
| 1.2.4                           | Support Equipment                     | 1,594                      | 1,629                     | 5.0                              | 2.2                     |
| 1.3.1                           | Lab Operations                        | 6,027                      | 6,291                     | 11.8                             | 4.4                     |
| 1.3.2                           | Research and Development              | 17,549                     | 15,860                    | 20.3                             | -9.6                    |
| 1.4.1                           | Project Management                    | 11,056                     | 14,566                    | 5.1                              | 31.7                    |
| 1.4.2                           | Support Services                      | 845                        | 820                       | 5.0                              | -3.0                    |
| 1.4.3                           | System Engineering                    | 4,865                      | 16,239                    | 5.8                              | 233.8                   |
| 1.4.4                           | Office Operations                     | 4,345                      | 3,845                     | 5.0                              | -11.5                   |
|                                 | Unclassified Costs                    |                            | (5)                       |                                  |                         |
| <b>Subtotal Completed Tasks</b> |                                       | <b>249,183</b>             | <b>292,098</b>            | <b>17.2</b>                      | <b>17.2</b>             |
|                                 | Contingency                           | 42,922                     | -                         |                                  |                         |
| <b>Total Construction</b>       |                                       | <b>292,100</b>             | <b>292,098</b>            |                                  |                         |
| 2.0                             | Initial Operations                    | 68,580                     | 68,580                    |                                  |                         |
| <b>Total</b>                    |                                       | <b>360,680</b>             | <b>360,678</b>            |                                  |                         |

The end date of the original cooperative agreement was September 30, 2001. We requested and received an extension to June 30, 2003. We needed the extension to complete:

<sup>11</sup> The Beam Tube Bake cost estimate was originally included with the Beam Tube estimate. The actual contingency use percentage is calculated using the Beam Tube estimate as a base.

- the procurement of the LIGO Data Analysis System hardware (We achieved a better price-performance ratio by delaying the procurement of computer equipment.)
- finishing the observatory facilities (We added a Storage and Staging Building at Livingston and a Laboratory Building at Hanford. Originally these items were removed from the scope to manage risk and contingency. However, favorable Facility bids allowed us to return the scope. Experience also indicated that the facilities were needed.)
- installation and commissioning of the Detector (We held budget for equipment and supplies needed to complete the installation and commissioning of the Detector.)

### 9.3 Performance Reporting

Figure 8 shows the time-phased budget, earned value, and actual costs through the end of June 2003 for the construction funds. The construction effort is complete.

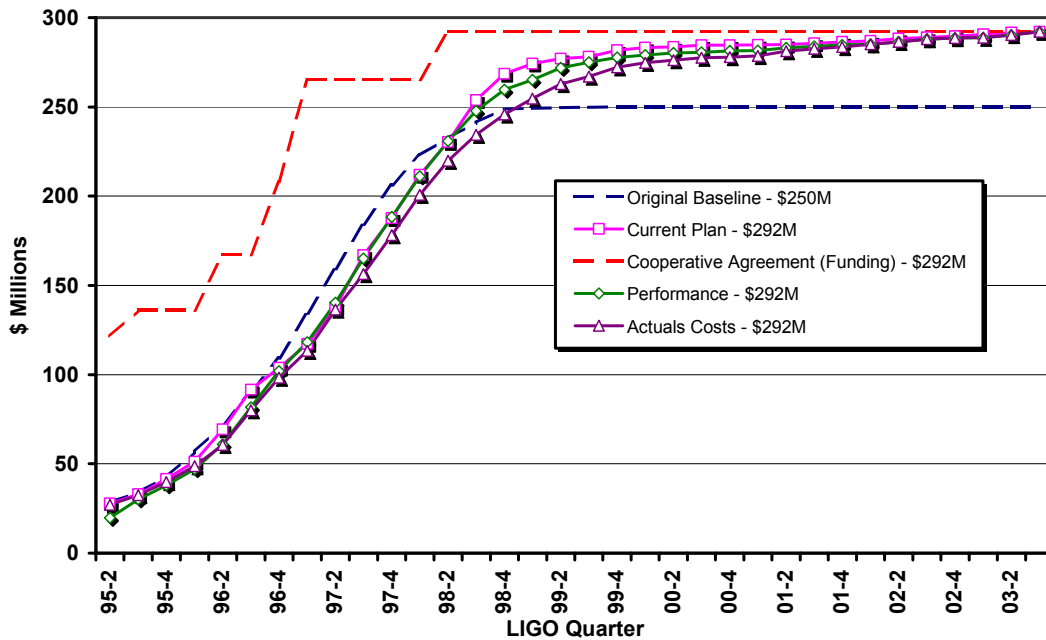


Figure 8. LIGO Project Performance Measurement Chart (Actual Costs vs. Earned Value vs. the Time-Phased Budget)