LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY (LIGO)

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LIGO Construction Project Quarterly Progress Report
May 2002

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1. INTRODUCTION

This Quarterly Progress Report is submitted under NSF Cooperative Agreement PHY-9210038[1]. The report summarizes the progress and status of the Laser Interferometer Gravitational-Wave Observatory (LIGO) Construction Project for the fiscal quarter ending August 2002.

Facility construction, including the vacuum systems, is complete with the exception of deferred items as noted below. We have installed the Detectors, and we are commissioning. The original completion date for the Cooperative Agreement was September 30, 2001. We have requested and been granted a no-cost extension through June 2003 to finish commissioning as well as to complete project scope that was deferred to manage contingency and risk.

The project is 98.6 percent complete.

2. FACILITIES

We have completed the construction of the vacuum systems, beam tubes, and the initial complement of buildings. Construction of a Laboratory building at Hanford, and the Storage and Staging building at Livingston, are nearing completion.

2.1. Livingston Storage and Staging Building

The new Storage and Staging building at Livingston is complete. The construction contract is being closed out.

2.2. Hanford Laboratory Building

The construction of the Laboratory building is complete with the exception of the acceptance of the fire detection and suppression system by the Hanford Fire Marshal, and the landscaping. We are in the process of moving in.

2.3. Safety

We completed the annual Safety Audit of the Livingston site with no significant safety problems or issues identified. We installed the new laser safety interlock system, and it is fully operational. The interlock system is "robust," and includes many features beyond the primary safety functions.

For additional site security, the laser safety interlock system connects with various remotely operated video cameras and sensors for observing controlled access areas, locating system users, notifying users and operators concerning alarms, and monitoring laser status.

3. DETECTOR

The Detector Group has been commissioning and operating the interferometers in preparation for the first science run (S1). We continue to focus on reducing noise and improving duty cycle. We

[1] Cooperative Agreement No PHY-9210038 between the National Science Foundation, Washington, D.C. 20550 and the California Institute of Technology, Pasadena, CA 91125, May 1992

are also improving seismic isolation systems at both LIGO sites. Refinements are based on growing operational experience.

3.1. Engineering Runs

We conducted an engineering run (E8) June 8 to June 10, 2002 at the LIGO Hanford Observatory. The objective was to evaluate the Data Monitoring Tool (DMT) software developed by the LIGO Scientific Collaboration (LSC) in preparation for the first science run (S1). We tested sixteen monitoring programs under real operating conditions. Useful recommendations for needed modifications were provided to software authors. As a result, DMT programs ran reliably and usefully during S1.

DMT is an elaborate and useful suite of programs that continuously review the interferometer data streams, watch for various potential problems, and record summary information for later use concerning the three interferometers and their environments. DMT also supports interactive exploration of the data in the gravitational-wave channel and of non-linear noise processes.

3.2. Science Runs

Our mission is to achieve the scientific reach planned for LIGO and, with the LSC, to accomplish the science. With these goals, we have planned a progression of three science runs, interleaving interferometer development and improvement with increased scientific reach for each run. The three consecutive runs will provide a baseline for LIGO Data Analysis System (LDAS) development, detector modeling and diagnosis, as well as interferometer commissioning, modification, and revision. All three science runs are the joint responsibility of the Laboratory and the LSC.

The first of the three science runs (S1) was held from August 23 to September 9. The four-kilometer (H1) and two-kilometer (H2) interferometers at Hanford observatory operated at comparable sensitivities throughout. A key performance measurement for these machines is the science duty factor, namely the fraction of the run that each interferometer was available for uncompromised detection of a gravitational-wave event. H1 achieved a science duty factor of 58 percent and H2 achieved a duty factor of 73 percent. The interferometer typically held lock for many hours at a time, with one continuous locked stretch for H1 exceeding 21 hours. Together with the Livingston interferometer (L1), we recorded nearly 100 hours of triple coincidence data.

S1 was a showcase for a variety of new and improved DMT monitors. The experience gained will also help us to be better prepared for the second science run (S2), tentatively scheduled for February 2003, after the completion of the analysis of the S1 data.

The goal for S2 is at least an order of magnitude improvement in scientific reach. S2 will complete upper-limit operation and orientation of the LIGO-LSC scientific and operations staff. We expect that S1 and S2 data will provide new publishable limits, well beyond what has been previously reported.

S3, scheduled for mid 2003, will be a true search for gravitational waves with astrophysical significance.

3.3. Commissioning of Interferometers at Hanford

Based upon experience with the prototype Pre-stabilized Laser (PSL) Intensity Stabilization Servo (ISS), we designed, tested, and installed a new ISS. This was completed in time for the science run (S1). The new ISS is fully integrated with the control infrastructure and provides good visibility and control directly from the control room.

We developed a revised timing module and the associated software with variable delay to eliminate noise generated by the Pentek analog-to-digital converter (ADC) modules. We are considering converting to a programmable timing module with an ASIC[2] for post-S1 installation and commissioning.

Cross-coupling to the sensitive input and output signals for the suspension controls exceeds requirements. To meet the original noise targets for the suspension drivers, we designed and bench tested a prototype of an improved input and output signal-conditioning channel design. We will select a final design after the completion of the first science run (S1).

Observatory personnel are required to make repeated and time-consuming re-alignments because of beam drift to the wavefront sensors (and other photodiodes) on the Interferometer Sensing and Control (ISC) optics tables. We are considering an optomechanical system to automatically center the beams on the ISC tables. We initiated the design work and are defining the associated system requirements.

3.4. Commissioning of Interferometer at Livingston

We operated the LIGO Livingston four-kilometer interferometer during the first science run (S1) at sensitivities at least equal to that of the Hanford interferometers. Low frequency ground motion was especially high during the daylight hours as trees were harvested on the property adjacent to the Livingston corner station. At nighttime, the interferometer performed reliably with locks maintained continuously for as long as eight hours. Over the entire S1, the interferometer operated in a high sensitivity mode about 43 percent of the time.

We are upgrading and testing the servo control electronics with new hardware and software, which will allow us to readily implement digital filtering techniques that will further improve the noise performance of the interferometer. The hardware and software is identical to that successfully implemented on the Hanford four-kilometer interferometer.

3.5. Seismic Isolation Upgrade

We reduced the micro-seismic peak (at about 0.15 Hz) using “feed-forward” to control the fine actuation systems located on the end-test-mass chambers. Precision seismometers were used as inertial sensors for the control signal. The feed-forward system was first implemented at Livingston. Now that the design has been successfully demonstrated, we are replicating it at Hanford. We are re-designing and testing the interface and signal conditioning electronics for the Hanford seismometers based on experience at Livingston.

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[2] ASIC: Application Specific Integrated Circuit.

4. LIGO DATA & COMPUTING

4.1. Simulation and Modeling

4.1.1. Second Generation LIGO Simulation Package

We used a LIGO simulation package, *Han2k*, running on top of the LIGO end-to-end (e2e) simulation framework, to design the LIGO lock acquisition approach. To simulate the details of the locked state, a more realistic and more sophisticated simulation was needed. This quarter we released the first version of this second-generation simulation package, *SimLIGO*, which includes most of the major LIGO hardware components and measured noise sources. The sensitivity curve simulated by *SimLIGO* demonstrates all major characteristics of the measured noise curve.

4.1.2. Graphical User Interface – *alfi5*

We rewrote this front-end software using JAVA, and all simulation work has switched to the new version, *alfi5*. Several major improvements were added to facilitate development activity.

4.1.3. Outreach

Faculty and students of Southeastern Louisiana University (SLU) are very interested in LIGO physics and the simulation tools. The simulation tool can be used in the classroom to explain basic physics, like mechanics and optics. A Memorandum of Understanding has been established with SLU to initiate the collaboration. This summer, an SLU student worked as a Caltech summer student at the Livingston site and performed environmental seismic measurements that will be useful for simulation development.

4.1.4. Near Term Plans

- ***SimLIGO*.** Some LIGO interferometer sensing and control designs have been changing rapidly, including those for the wave front sensor and the common mode servo. The models for those systems are obsolete and are now being updated.

- ***alfi5*.** New functionalities are added and existing features are improved based on the user experience. *alfi* is like a text editor, and its capabilities influence user productivity. During the next quarter we expect that *alfi* will become stable and mature.

- **SLU.** A professor in the Physics department at SLU is collecting seismic data at the Livingston site and measuring seismic isolation system characteristics. His student is developing a subsystem model in e2e, which will be used to validate the modeling of mechanical motions. A professor in the Computer Department is interested in participating in the development of the simulation code as a topic in the Computer Department program.

4.2. LIGO Data Analysis System

4.2.1. LDAS Software Development

We released LDAS version 0.4.0 during August in preparation for the first science run. This release provides new support for creating reduced data set frames within the *frameAPI*. Other enhancements included a more fully threaded *frameAPI*, which provides a significant performance increase as measured by the number of jobs that can be processed concurrently. The monitoring features of the *controlMonitorAPI* were also enhanced for better monitoring of system functions and individual job requests.

The LIGO Scientific Collaboration (LSC) upper limits groups used LDAS online during the science run, and there were close to ***230,000*** jobs submitted to the Hanford, Livingston, and MIT systems during the run. This is roughly twice the number of jobs submitted during the E7 engineering run last December and January. These jobs inserted over ***7,000,000*** rows into the databases. This represents roughly the same number of triggers and events as were produced during the E7 engineering run even though the burst group chose not to put their event candidates into the database during this run.

A new version of the frame specification prompted a major rework of the *frameCPP* I/O library for C++ applications. This rework required more time than we would have predicted based on experience. However, thorough testing and the sharing of pre-release frame files with the Virgo Project (Italian-French Laser Interferometer Collaboration) have allowed us to improve the reliability of the code and assure compliance with the specification.

This quarter provided a long window for the development of the next version of LDAS (version 0.5.0) scheduled to be released this fall. The new *frameCPP* library has been integrated into LDAS, there have been significant improvements in processing efficiency, and the interface protocol used by the search codes to support raw sequences in data exchanges, which are used to exchange generic filter information between the *dataConditionAPI* and the *wrapperAPI* (for use in the LALwrapper search codes), has been enhanced.

4.2.2. LDAS Hardware

Integrating a "compute cluster" and large disk cache to the LDAS archive system at Caltech was the primary LDAS hardware activity this quarter. In addition to an initial 16 node Beowulf cluster, we installed a 17-terabyte disk farm holding all of the first science run (S1) data in this system. Furthermore, all of the LDAS servers in five of the six LIGO Laboratory run systems have been upgraded to Gigabit Ethernet networks.

All engineering and science run data generated by the Lab have been archived at Caltech in the LIGO data archive running HPSS[3]. The current archive contains 54 terabytes (http://www.ldas-sw.ligo.caltech.edu/archive/hpss). However, we have decided to use SAM-QFS[4] rather than HPSS for the following reasons: simplicity, reliability, the ability to move media between systems without data replication, sufficiently low licensing fees to allow use at the observatories as well as Caltech, disaster recovery, metadata performance, and minimization of the number of vendors supporting LDAS. Demonstration of these advantages during the science run and the

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[3] The High Performance Storage System™--IBM (HPSS) is a hierarchical storage system software designed to manage and access hundreds of terabytes to petabytes of data. (http://www4.clearlake.ibm.com/hpss/index.jsp)

[4] SUN Storage and Archive Management system

ability to archive and retrieve the 17 terabytes of S1 data without corruption provided a final successful test for SAM-QFS.

4.2.3. Grid Computing and Related Research

During the past quarter, LIGO Laboratory has worked closely with other members of the GriPhyN[5] Project LIGO Applications development group (at the University of Southern California Information Sciences Institute, ISI, and the University of Wisconsin at Milwaukee) to produce a demonstration prototype for the Supercomputing 2002 Convention. With the support of GEO (British/German Cooperation for Gravity Wave Experiment), LIGO has also worked to integrate into the demonstration a subset of the pulsar search codes being used by the LIGO Scientific Collaboration. This will provide a stand-alone analysis of LIGO data on grid computing resources. The demonstration will stage data from LDAS resources under LIGO control to grid computational resources. The data products and analytical results will then be re-ingested into the LDAS databases for subsequent use.

4.3. General Computing

We have conducted preliminary computer security audits at all four sites. More detailed audits are planned.

We have completed the General Computing Policy, and LIGO management is reviewing it.

We met with with NoaNet[6] and PNNL[7], and successfully identified a near term and long term solution to bandwidth and networking for the LIGO Hanford Observatory. The Hanford Observatory did establish an Ethernet connection to ESnet/. There are a few remaining technical issues, but the additional bandwidth has been immediately helpful and is a big improvement over the old T1 connection. Work is continuing on getting additional bandwidth to the Hanford Observatory. PNNL and NoaNet are working logistical details, and once those are resolved LIGO will utilize the new network.

We have discussed the need with Louisiana State University (LSU) to provide greater bandwidth to the Livingston Observatory. Currently LSU is contacting the local cable company to see if they can provide network services to the observatory. We should receive information sometime during the next few months. The Livingston Observatory is also preparing to install a new GbE backbone network.

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[5] GriPhyN - Grid Physics Network, the GriPhyN Project is developing Grid technologies for scientific and engineering projects that must collect and analyze distributed, petabyte-scale datasets. GriPhyN research will enable the development of Petascale Virtual Data Grids (PVDGs) using a Virtual Data Toolkit (VDT). (http://www.griphyn.org/index.php)

[6] The Northwest Open Access Network (NoaNet) is a nonprofit corporation that has licensed fiber optic cables from the Bonneville Power Administration and will license fibers from other sources and make the network available to utilities and communities in the Pacific Northwest. (http://www.noanet.net/about/index.html)

[7] Pacific Northwest National Laboratory

5. LIGO SCIENTIFIC COLLABORATION (LSC) MEETING

The eleventh meeting of the LIGO Scientific Collaboration (LSC) was held at the Hanford Observatory August 19-23, 2002. The significance of the upcoming science run and the organization of the subsequent data analysis effort were discussed. The schedule for Advanced LIGO was also presented.

The first science run (S1) included active participation from not only LIGO Laboratory scientists and staff but also in numerous ways from the broader community of scientists composing the LSC. LSC scientists contribute to real-time monitoring of the interferometer data for detector diagnostics and conduct analyses of the data.

The LSC scientists, as members of “upper limits” groups, pioneer the analysis of LIGO data in the search for gravitational waves. Several of these groups perform real-time searches using computers at the observatories. These searches are useful in providing rapid feedback to the control room on any instrumental pathology that might mimic a true gravitational-wave source.

More that 180 eight-hour shifts were staffed by scientists from Caltech, Carleton College, the University of Florida, Hanford Observatory, Livingston Observatory, Louisiana Tech., the University of Southeastern Louisiana, Loyola University, Louisiana State University, the University of Michigan, Massachusetts Institute of Technology, the University of Oregon, Pennsylvania State University, the University of Rochester, Syracuse University, the University of Texas at Brownsville, Washington State University–Pullman, and the University of Wisconsin-Milwaukee.

Keeping the LIGO interferometers running smoothly and continuously requires a cadre of skilled operators at each site, working in teams on rotating shifts. The operators must bring the interferometers into lock, tune the alignment and gains to optimize sensitivity, and try to preserve those optimum conditions.

LSC scientists have been staffing the scientific monitoring shifts. The scientists or “scimons” focus on ensuring that the interferometer data is of the highest quality. Since scimons start with diverse specialties and backgrounds, formal training was instituted for bringing new participants up to speed. An expert scimon is paired with a “trainee,” a pattern that began back in November 2000. As a result, the pool of scimon experts has steadily increased. This will be essential to support the anticipated periods of steady state, multi-month data runs.

Just prior to the start of S1, several of the upper limits groups verified that an emulated gravitational-wave signal could be detected in the data. They simulated the response of the LIGO mirrors to a variety of gravitational waveforms, allowing downstream confirmation that the signal did indeed appear as expected.

We have scheduled the next LSC meeting at Livingston, March 17-20, 2003.

6. NSF REVIEW

A review of LIGO by an NSF Review Panel is scheduled for October 23-25, 2002 at MIT.

7. PROJECT MANAGEMENT

All milestones identified in the LIGO Project Management Plan for Construction[8] have been completed.

7.1. Financial Status

Table 1 summarizes costs and commitments (encumbrances) as of the end of August 2002 and provides a comparison to budgets for both completed and open construction tasks. Based on actual costs compared to the total budget, the project is 98.6 percent complete.

Table 1: Costs and Commitments vs. Budget as of the End of August 2002 ($K)

WBS	Description	Budget	Actual Costs (Aug 2002)	Open Encum-brances	Estimate-to-Complete	Total
Completed Tasks						
1.1.1	Vacuum Equipment	44,047	44,047			44,047
1.1.2	Beam Tube	47,004	47,004			47,004
1.1.3	Beam Tube Enclosure	19,338	19,338			19,338
1.1.4	Civil Construction	53,493	53,493			53,493
1.1.5	Beam Tube Bake	5,570	5,570			5,570
1.3.1	Lab Operations	6,291	6,291			6,291
1.3.2	Research and Development	15,860	15,860			15,860
1.4.1	Project Management	14,561	14,561			14,561
1.4.2	Support Services	820	820			820
1.4.3	Document Control	830	830			830
1.4.4	Office Operations	3,845	3,845			3,845
Subtotal Completed Tasks		**211,660**	**211,660**			**211,660**
WBS	**Description**	**Budget**	**Actual Costs (Aug 2002)**	**Open Encum-brances**	**Estimate-to-Complete**	**Total**
Open Tasks						
1.1.4	Livingston Construction	2,719	2,445	45	239	2,562
1.1.4	Hanford Building	2,845	2,527	288	280	2,760
1.2	Detector	59,415	58,685	185	575	59,415
1.4	Data Analysis System	15,463	12,689	251	2,221	15,222
	Contingency	-2			10	481
Total		**292,100**	**288,006**	**769**	**3,326**	**292,100**

We requested and received a no-cost extension to the Cooperative Agreement to June 2003, which will be sufficient to complete the construction work discussed below. Our current focus is to manage the remaining funds and risk.

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[8] Project Management Plan, Revision C, LIGO-M950001-C-M submitted to the NSF November 1997.

Vacuum Equipment (WBS 1.1.1). All work is complete.

Beam Tube (WBS 1.1.2). All work is complete.

Beam Tube Enclosures (WBS 1.1.3). All work is complete.

Civil Construction (WBS 1.1.4). The original scope for Civil Construction has been completed. Additional tasks have been budgeted for scope originally removed from the plan to reduce risk and manage contingency. The contract to build a Laboratory Building at Hanford is nearly complete, and the contractor is working on punch list items. The LSC meeting in August was held in the new auditorium. The Storage and Staging Building at Livingston is complete, and the contractor is addressing remaining punch list items.

Beam Tube Bake (WBS 1.1.5). All work is complete.

Detector (WBS 1.2). The Detector is the largest task remaining to be completed, although of a total budget of $59,415,293 we have accrued and committed a total of $58,870,113. We continue to adjust priorities to optimize progress towards the science runs. The first science run started at the end of August and was successfully completed early in September.

Research and Development (WBS 1.3). All LIGO Construction Related Research and Development effort is complete.

Project Office (WBS 1.4). All LIGO Project Office activities are complete with the exception of the procurement of computer hardware associated with the LIGO data analysis and computing systems. These procurements were delayed pending NSF approval of our procurement plan and also to achieve the most favorable performance per dollar ratio. The NSF has approved our plan, and procurements will be completed over the next two quarters.

7.2. Change Control and Contingency Analysis

The following construction project change requests were approved this quarter. The total budget baseline is now $292,101,516 leaving a negative management contingency of $1,516. This is offset by projected returns.

Table 2. Change Requests Approved during Third Quarter FY 2002

Change Request	Description	Submitted	Amount
CR-020007	WBS 1.1.4, Finishing and furnishing the Livingston Staging Building	June 12, 2002	$157,000
CR-020008	WBS 1.1.4, Purchase and install audio/visual equipment in the new Hanford Laboratory Building Auditorium	July 8, 2002	$85,000