LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY (LIGO)

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LIGO Construction Project Quarterly Progress Report
February 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 February 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 97.6 percent complete.

2. FACILITIES

We have completed the construction of the vacuum systems, beam tubes, and the initial complement of buildings. Construction of an Office Support building at Hanford is in progress, and the Storage and Staging building at Livingston is nearing completion.

2.1. Livingston Storage and Staging Building

The Storage and Staging building at Livingston is nearly complete and efforts will be made to use parts of the new facility, including the auditorium, during the LIGO Scientific Collaboration (LSC) meeting in March. A punch list has been prepared, and we are meeting with the contractor to resolve open issues.

2.2. Hanford East Office Support Building

The construction of the building is on schedule. Electricity has been installed. The steel framing is complete and so is the roof decking. Currently the wall studs are being installed. In its current state, it is apparent that the structure is unique and will create a good impression for visitors arriving at the Hanford site. Visual impact provided by different wings and roof angles, while simple architecturally, work to make the building attractive.

2.3. Safety

Installation of the Livingston Laser Safety System is complete. A safety audit has not yet been scheduled but will be sometime in May.

3. DETECTOR

The Detector Group is focused on commissioning and operating the interferometers. We continue to focus on reducing noise and improving duty cycle. We are refining the design based

[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

on our growing operational experience. A very successful engineering run (E7) was conducted at the end of December continuing into January.

3.1. Engineering Runs

The seventh engineering run started on December 28, 2001, and data collection was completed January 15, 2002. Lock statistics for the run are summarized in Table 1.

Table 1: Interferometer Lock Statistics for Engineering Run (E7).

Single Interferometer Statistics		**Hours**	**Duty Cycle (Percent)**
L1	Total Locked Time	284	71
	Locked Time for Periods Longer than 15 Minutes	249	62
H1	Total Locked Time	294	72
	Locked Time for Periods Longer than 15 Minutes	231	57
H2	Total Locked Time	214	53
	Locked Time for Periods Longer than 15 Minutes	157	39
Three Interferometer Coincidence Statistics			
	Total Locked Time	140	35
	Locked Time for Periods Longer than 15 Minutes	72	18

The Livingston four-kilometer interferometer (L1) was operated at a sensitivity of 2.5×10^{-19} strain/$\sqrt{(Hz)}$ or better from 250 to 3000 Hz and 8×10^{-20} strain/$\sqrt{(Hz)}$ between 400 to 1000 Hz. The combined duty cycle with the two-kilometer at Hanford, which has comparable sensitivity, was about 40 percent. The overlap is primarily at night when the seismic conditions at Livingston are relatively quiet. Combined observations with the bar detector at Louisiana State University (LSU) began on Wednesday, January 9. Concurrently, GEO operated a power-recycled Michelson. These coincidence runs may set new observational limits on the gravitational wave strengths incident on the Earth, although they do not yet test theorists' predictions of signal strengths.

The next engineering run is scheduled in May.

3.2. Commissioning the Two-kilometer Interferometer at Hanford

After the E7 run the noise-equivalent displacement of the two-kilometer interferometer was improved across a broad band of frequencies. The commissioning team also boosted the laser power into the interferometer to near-design levels, with only a little reserve to assure constant operating conditions. The recycling-cavity components run "hot," closer to the self-focusing levels for which we selected mirror curvatures.

We show the improved sensitivity of the two-kilometer interferometer as a calibrated spectrum of the present displacement sensitivity in Figure 1. Compared to the noise levels measured during the E7 run, the spectrum is about a factor of five better in the 100 Hz to 1 kHz band, and a factor of seven better at higher frequencies. The displacement sensitivity goal for the two-kilometer interferometer is included on the same plot.

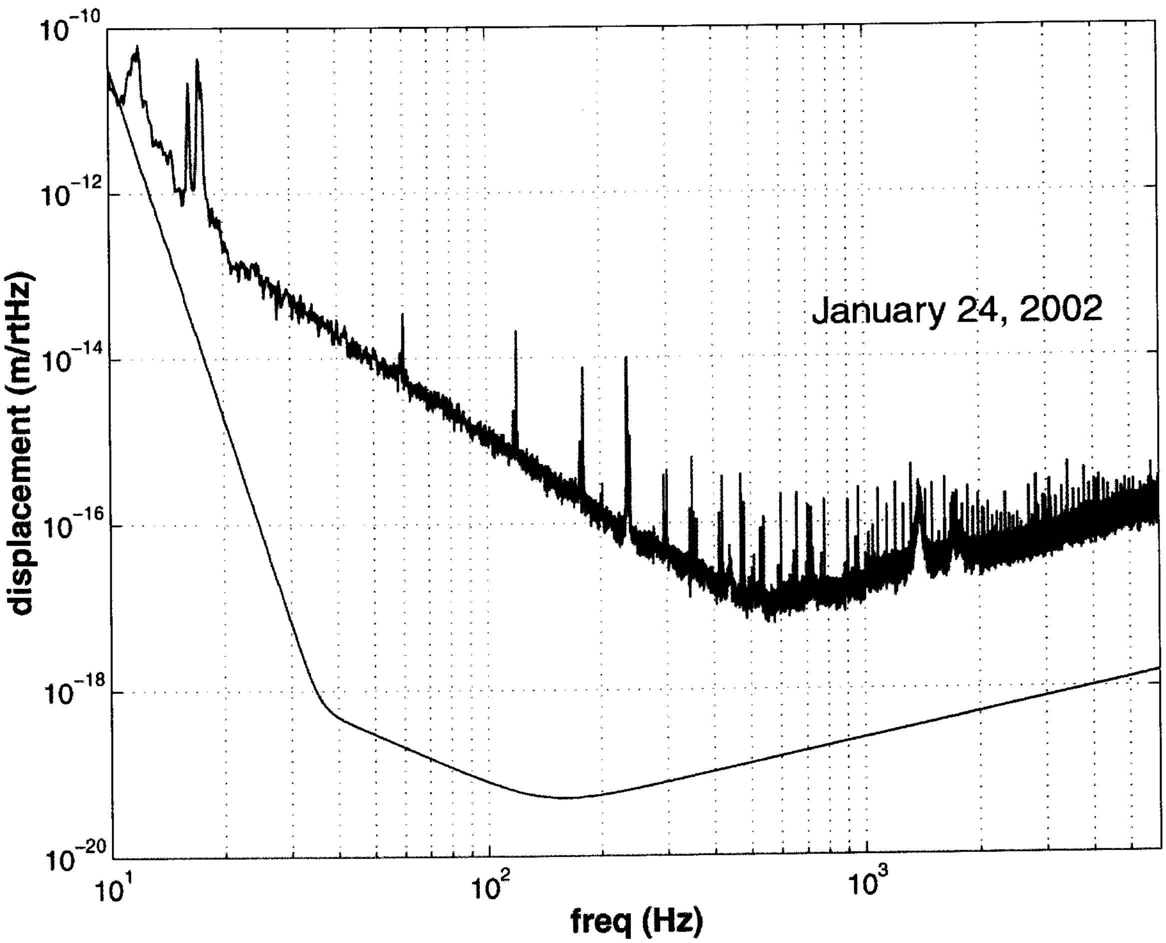

Figure 1 Calibrated Spectrum Showing the Displacement Sensitivity of the Two-Kilometer Interferometer at Hanford (January 24, 2002).

At the end of the quarter we were able to operate the two-kilometer interferometer for extended periods up to a record setting lock of 14 hours and 45 minutes with five Watts of laser input power to the mode cleaner and with the common mode servo running.

3.3. Commissioning the Four-kilometer Interferometer at Hanford

The commissioning team successfully locked the four-kilometer interferometer in its power-recycled configuration in January. By the end of the quarter we had achieved a number of locked periods of 20 to 40 minutes. The tidal correction servo was not running, which limited lock duration, and improvements are expected once that system is reactivated.

Arm cavity buildup of 1200 has been observed and the spots are very stable on the optics.

3.4. Commissioning the Four-kilometer Interferometer at Livingston

The interferometer has been locked in the full-recycled configuration. The maximum power build up is typically between 1000 and 1200. Locked periods have been sufficiently long that lock is only lost as a result of tides and trains.

We incorporated the common-mode arm motion servo into the recycled interferometer. The effects on the spectrum and the robustness of the overall lock are significant.

We, with our LSC collaborators at LSU, incorporated the fine actuators at the end masses in a feedback loop to reduce the seismic motion of the stacks between 1 and 10 Hz. These actuators remove the differential motion due to the tides and feed-forward to reduce the microseism. Using the four longitudinal actuators at the corners of the support beams and two geophones as inertial sensors mounted on the beams, the Q's of the stack mode at 1.2 and 2.1 Hz were reduced by a factor of seven. These are the key modes that cause the excess test mass excursions driven by seismic motion at Livingston. The technique looks promising as part of the solution to reduce the influence of the seismic disturbance. A Change Request to the Operations budget has been prepared to consider installing fine actuators on the input test mass isolation stages.

3.5. Seismic Isolation Upgrade

A design and prototyping effort is underway to develop a pre-isolator targeted at the excess seismic noise at Livingston. Stanford University completed testing the performance of the prototype hydraulic actuator. They achieved a single degree-of-freedom isolation factor of 10, limited by the displacement sensing in this prototype, over a bandwidth greater than 10 Hz. A second generation of hydraulic actuator has now been installed into the test stand at Stanford and is being tested.

In addition to the external pre-isolation approach, we are exploring in-vacuum sensing and actuation (across the stack from the support structure to the table). This approach has the potential to actively damp stack modes in combination with the active isolation from the external pre-isolator.

4. LIGO DATA & COMPUTING

4.1. Simulation and Modeling

We are investigating the effect of the thermal lensing on the ability to acquire and maintain interferometer lock. Preliminary results indicate that the current lock acquisition code can be used without re-tuning as laser power is increased. The noise introduced by the slight mode mismatch remains tolerable.

We are revising the LIGO simulation package to allow us to simulate realistic LIGO noise in the time domain. The new package includes the simulation of: three dimensional mirrors including four voice coil actuators; a realistic length sensing and control servo model including digitization in analog-to-digital converters, digital-to-analog converters, and other electronic noise sources; digital suspension controllers; mirror aberrations based on as-built phase map measurements; and realistic seismic motion and correlation among the suspended masses. We also introduced a number of subsidiary improvements.

Southeastern Louisiana University (SLU) adopted the end-to-end package as a simulation laboratory for an undergraduate physical optics course. The software is being installed at SLU, and a weekly telephone conference between Caltech and SLU has been instituted.

4.2. LIGO Data Analysis System

4.2.1. Software

LIGO Data Analysis System (LDAS) software successfully supported the two-and-a-half week Engineering Run (E7) from December 28, 2001 to January 14, 2002. During the run approximately 130,000 jobs were submitted to the Hanford, Livingston, MIT, and Caltech LDAS systems. The jobs generated roughly 7,000,000 database entries. These entries were derived from software real-time triggers monitoring interferometer performance and astrophysics searches performed with LIGO and LIGO Scientific Collaboration (LSC) analysis and search codes. Data analysis continued through the quarter using LDAS systems at all Laboratory sites as well as more recently installed LDAS systems at LSC institutions such as the University of Wisconsin at Milwaukee.

The software team also focused on developing and implementing the first beta release of the LDAS package. This will be the first release to have a *diskCacheAPI* that can manage raw data on the large RAID[2] storage systems now on-line at Hanford and Livingston. For this release we overhauled the rules for compiling and running the LDAS software to eliminate version crossing and enhance reliability. We expect this release will be reliable to the 99 percent level, up from the approximately 90 percent level for the release used during E7. This release will also produce reduced frame data files. Experience with the more than 10 terabytes of data produced during E7 has underscored the fact that we will need this capability for longer data runs.

4.2.2. Hardware

Our primary activity related to the LDAS computational hardware has been the integration of SunFire880 servers into the existing LDAS systems to operate as the main data servers. The large disk storage systems at the observatories still need to be moved to the new servers, but initial testing has been positive. In addition, the production analysis system at Caltech is now partially operational with all of the servers integrated but with no Beowulf cluster yet.

[2] RAID - Redundant Array of Independent Disks

All Engineering Run data continue to be archived at Caltech in the LIGO data archive running HPSS (High Performance Storage System). The current archive contains 36 terabytes, http://www.ldas-sw.ligo.caltech.edu/archive/hpss. However, we are evaluating the suitability of SAM-QFS[3] as an alternative to HPSS. Among the important reasons to consider this change are: simplicity and reliability; the ability to move media between systems without having to copy the data; sufficiently low licensing fees to allow for the possibility of running at the observatories as well as Caltech; disaster recovery; metadata performance; and minimizing the number of vendors involved. We will begin initial performance testing at Caltech during the next quarter.

We installed a new fiber network at Caltech to provide Gigabit network speeds for both Ethernet and Fiber Channel between the various LDAS systems. This network also demonstrates the technology for similar installations at the observatories that will connect the main buildings, which house the data acquisition equipment, to the new science buildings, which will house the LDAS equipment. The new science buildings will be completed later this year.

4.2.3. Data Analysis Activities

LIGO Laboratory personnel continue to have an active role in the LIGO Scientific Collaboration (LSC) working groups formed to analyze data from the E7 Engineering Run. LDAS computer hardware and software is being extensively used to store and retrieve data and to examine the data for signals of possible astrophysical origin. We are developing statistical analysis procedures to evaluate the significance of the recorded signal candidates, aided by software tools created and maintained by LIGO Laboratory and LSC members.

4.3. General Computing

High-speed WAN options for the observatories are still being explored. Higher bandwidth connection will soon be needed for the anticipated data and database imaging traffic and also for the proposed virtual remote control rooms for LIGO Laboratory staff at Caltech and MIT.

5. LIGO SCIENTIFIC COLLABORATION (LSC) MEETING

The Livingston Observatory is preparing for the March LSC meeting. Louisiana State University (LSU) will host a symposium honoring Bill Hamilton on March 19. On March 20 there will be two LSC sessions: the LIGO I collaborators will meet in closed session, while numerical relativists with an interest in coupling to LIGO and LISA will meet separately at LSU to formulate plans for activities useful for the observational programs and to guide the theoretical research. The formal LSC meeting begins March 21. The numerical relativists will make presentations in the afternoon plenary session and will be welcome to stay throughout the LSC meeting.

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[3] SUN high-performance file management software.

6. PROJECT MANAGEMENT

All milestones identified in the LIGO Project Management Plan[4] have been completed.

6.1. Financial Status

Table 2 summarizes costs and commitments as of the end of February 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 97.6 percent complete.

Table 2: Costs and Commitments vs. Budget as of the End of February 2002 ($K).

WBS	Description	Budget	Actual Costs (Feb 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 (Feb 2002)**	**Open Encum-brances**	**Estimate-to-Complete**	**Total**
Open Tasks						
1.1.4	Livingston Construction	2,562	2,070	333	159	2,562
1.1.4	Hanford Building	2,760	644	2,080	36	2,760
1.2	Detector	59,586	58,412	667	507	59,586
1.4	Data Analysis System	15,463	12,329	172	2,962	15,463
	Contingency	69			69	69
Total		**292,100**	**285,115**	**3,253**	**3,732**	**292,100**

We have 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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[4] 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 scope has been budgeted for scope originally removed from the plan to reduce risk and manage contingency. Contracts are in progress for the Storage and Staging Building at the Livingston site and for an Operations and Science Building at Hanford.

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 $59,586,293 we have accrued and committed a total of $59,079,160. In spite of encouraging progress, the Detector continues to be behind schedule. Efforts to improve the schedule position were set back by the Washington earthquake last year and higher than expected seismic noise in Livingston. The net effect is that Detector commissioning is estimated to be three months behind schedule. We continue to adjust priorities to optimize progress towards the Science Runs. The first Science Run is scheduled to begin in June 2002.

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 are proceeding.

6.2. Change Control and Contingency Analysis

There were no construction project change requests approved this quarter. The total budget baseline is $292,030,516 leaving a management contingency of $69,484.