LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY (LIGO)

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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 May 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 98.0 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 was used to host the LIGO Scientific Collaboration (LSC) meeting in March. A punch list has been prepared, and the contractor is working to resolve open issues. The punch list is over 80 percent complete.

2.2. Hanford Laboratory Building

The construction of the Laboratory building is going well and is on schedule. The siding is nearly installed. Heating, Ventilation, and Air conditioning (HVAC), plumbing, electrical and insulation work is in progress. The outside areas are being seeded and mulched. We are in the process of selecting a vendor for the audio/visual equipment.

2.3. Safety

Installation of the Livingston Laser Safety system is complete. Safety training and regular safety meetings are in progress. Both observatories now have their card controller laser interlock safety system on line. This includes restricted area access control.

3. DETECTOR

By the end of the quarter we achieved strain sensitivity better than has been achieved with any previous broadband detector, and on two interferometers, the two-kilometer interferometer at Hanford and the four-kilometer interferometer at Livingston. This was the case over the entire gravitational wave band from 100Hz to higher frequencies. Two interferometers at separated sites support coincidence techniques for the gravitational wave searches.

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[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

The Detector Group is focused on commissioning and operating the interferometers in preparation for the first Science Run (S1). We continue to concentrate on reducing noise and improving the duty cycle. We are refining the design based on our growing operational experience.

3.1. Engineering Runs

The eighth Engineering Run (E8) is scheduled for early June 2002.

Analysis of E7 Engineering Run data and continued interferometer commissioning and modification, based partly on the E7 experience, are in progress. The E7 run was covered in the progress report for the quarter ending February 2002. Our current focus is the first Science Run (S1) scheduled in August 2002.

We are seeking commitments from LIGO Scientific Collaboration (LSC) organizations to augment the LIGO resident scientific and operator staff for the science runs.

3.2. Science Runs

Our mission is to accomplish the scientific reach planned for the LIGO interferometer system and to exploit the system, with the LSC, to accomplish the science. Given these goals, we have planned a progression of three science runs with increased scientific reach for each. The first of the three Science Runs planned (S1) will be initiated at the end of August 2002. The timing for S1 is driven by lessons learned from Engineering Runs conducted to date, and the remaining high priority interferometer installation and rework tasks. All three Science Runs will be the joint responsibility of the Laboratory and the LSC.

The sensitivity goals for S1 are a two-site coincidence with all three interferometers running and an achieved scientific reach (volume searched x observation time in coincidence) an order of magnitude better than that achieved in the E7 run. At least one interferometer at each site should be operated in the full-recycled configuration. The S2 run will have a goal of at least an order of magnitude improvement in scientific reach beyond S1, and will follow the completion of the analysis of S1 data.

S2 will complete upper limit running and the orientation of the LIGO-LSC scientific and operations staff. We believe that S1 and S2 running experience should lead to new publishable limits, well beyond what has been previously observed.

S3, scheduled to start in the middle of 2003, will be a true search for gravitational waves with astrophysical significance.

The plan for scientific operation of the LIGO interferometers provides a clear structure for the work involved, interleaving interferometer development and improvement with progressively more ambitious science goals. The three consecutive Science Runs also provide a baseline for LIGO Data Analysis System (LDAS) development, detector modeling and diagnosis, as well as interferometer commissioning, modification, and revision.

3.3. Commissioning the Two-kilometer Interferometer at Hanford

At the end of the last quarter we reported improved sensitivity of the two-kilometer interferometer relative to the noise levels measured during the E7 run. Building upon the enhanced robustness of the interferometer we have been able to run with significantly improved attenuation. Locking is generally robust even at high light levels. We have successfully overcome the dark noise that has been limiting performance at frequencies above approximately 500 Hz. With approximately an order of magnitude less attenuation, we have four to five times better displacement sensitivity at these frequencies and another factor of four to five in margin above the dark noise.

We installed and tested a new configuration for the common mode servo. Software for automating calibrated displacement spectra was also released. The interferometer locked easily in common mode and held for nine hours. We used improved filtering capability to insert resonant gain stages and to quiet a number of control loops. These changes have dramatically improved interferometer behavior.

We installed new Length Sensing and Control (LSC) hardware and software. The ability to dynamically add filtering is an important new feature aiding in noise investigations.

3.4. Commissioning the Four-kilometer Interferometer at Hanford

The commissioning team focused on restoring the interferometer to operation after software changes, and making subsystem adjustments and improvements in preparation for S1. We also focused on subsystem enhancements to improve the interferometer locking. We installed new hardware and software and devoted significant effort to checking the digital suspension controllers after the changes. We continued our one-arm investigations to better understand frequency noise in the light and saturation effects in the control signals. Single arm locks have been obtained on both arms, with sufficient stability on x-arm to get a preliminary single-arm measurement of the frequency noise.

Testing of the common-mode servo amplifier is in progress. We implemented filters that significantly improve frequency noise. We tested "Super Optical Levers" on the end mirrors and found that they work extremely well.

3.5. Commissioning the Four-kilometer Interferometer at Livingston

The interferometer exhibited reasonably short acquisition times, and when seismic noise is light, as at night, robust operation. The strain sensitivity since the Engineering Run E7 has improved by almost a factor of three at frequencies above 700 Hz. We are working on further improvements by operating the recycled interferometer at higher power and delivering more light to the photodetectors.

We installed and upgraded several critical interferometer features. We implemented significantly improved Length Sensing and Control (LSC) software. We modified the mode cleaner board to reduce the crossover frequency. We tuned the micro-seismic feed-forward system to remove some bugs and enhance filtering. We tuned the common mode servo. We are installing a new intensity stabilization servo.

We continued identifying and measuring noise sources. We improved the robustness of the recycled lock. Fine actuators incorporated in a feedback loop at the end test masses reduced the seismic motion of the stack between 1 to 10 Hz. The Q of the stack mode at 1.2 and 2.1 Hz was reduced by a factor of seven. These are key modes that cause the excess test mass motions driven by the seismic motion in Livingston.

We developed software to be used in the control room to make time domain studies of the signals. We can now make histograms of band pass limited signals for many of the interferometer and Physical Environment Monitoring System (PEM) signals.

We are addressing Electro-magnetic Interference (EMI) and Radio Frequency Interference (RFI). We are incorporating shielded ribbon cables in the Alignment Sensing and Control (ASC) System.

We modified hardware and software to allow optical lever damping as well as wavefront sensing. Furthermore, it is now possible to adjust filter coefficients in the ASC signal chain while the ASC is running.

3.6. Seismic Isolation Upgrade

We are designing and building prototypes of a pre-isolator system targeting the excess seismic noise at Livingston. Stanford University has transferred their basic conceptual design for the hydraulic portion of the system to the LIGO-LSC collaboration for continued development. Preliminary designs for Hydraulic External Pre-Isolation (HEPI) and Electro-Magnetic External Pre-Isolator (MEPI) prototypes were completed, and the final design is being developed. We installed and tested Piezoelectric External Pre-Isolation (PEPI), an interim measure to improve performance and duty cycle at Livingston, in the End Test Mass (ETM) chambers. We placed orders to equip the Input Test Mass (ITM) chambers with PEPI as well. We also finalized the design for course actuation/adjustment for the ITM chambers.

In addition to the external pre-isolation approach, we are exploring in-vacuum sensing and actuation (across the isolation 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.

We were able to suppress motion at the first two Beam Splitter Chamber (BSC) stack resonances using the End Test Mass (ETM) fine actuators in the existing seismic isolation system and are looking into the feasibility of installing fine actuators and control systems onto the ITM as well, as an interim measure before the seismic upgrade project is installed.

4. LIGO DATA & COMPUTING

4.1. Simulation and Modeling

The End-to-End simulation group has achieved two major goals this quarter: release of a second-generation LIGO simulation package, and release of a second-generation graphical user front end based on JAVA.

After we successfully used the simulation package to design the lock acquisition procedures, focus shifted to improving the simulation package to enable the simulation of noise sources representative of the as-built LIGO detectors. This is important for providing scientific guidance during commissioning. The second-generation simulation package includes all major physical effects that can influence LIGO performance, including correlation of the seismic motions, digitization in various control systems, sensor and actuator noise, and complex beam profiles. We changed the software to facilitate the addition of new effects using a powerful expression parser. The number of required data links was reduced by orders of magnitude. New macro capabilities allow easy setup of simulation configurations.

The graphical front end of the simulation package has been crucial in the past. However, new features could not be properly implemented in the original design. After a careful evaluation of various possibilities we decided to rewrite using JAVA. A new version is now complete and in use. In addition, the software is more robust and reliable. Distribution of LIGO Laboratory's simulation package to other platforms is easier because of JAVA's universal availability in a variety of different operating systems and platforms.

Southeastern Louisiana University (SLU) proposed to collaborate with LIGO on the development and use of the simulation tool. They will provide necessary measurements at the site and will help with the model validation. In addition, faculty at SLU found the LIGO simulation package to be useful for the education of undergraduate students, and they intend to install the software for educational use. This is an unexpected and welcome outreach opportunity for the Laboratory.

4.2. LIGO Data Analysis System

4.2.1. Software

LIGO Data Analysis System (LDAS) software development focused on applying lessons learned during the E7 Engineering Run to the version of LDAS to be used during the first Science Run (S1). This is being accomplished in two stages, beginning with migration from an alpha code base used in the E7 Run, to a beta version to be released to the observatories in support of S1.

The LDAS staff continued to actively participate in the Grid Computing activities. Interest in LDAS is becoming increasingly apparent at "All Hands Meetings" for this community. The community is beginning to face several design challenges that were addressed in the LDAS design several years ago and are working in the current implementation of LDAS. The LDAS group is also being asked to participate in the planning for showcase demonstrations of Grid Computing at the Super Computing Conference schedule this fall.

4.2.2. Hardware

A primary activity has been upgrading the Storage Area Network (SAN) and the compute clusters at the Hanford and Livingston Observatories in preparation for the first Science Run (S1).

All Engineering Run data generated by the Laboratory continue to be archived at Caltech in the LIGO data archive running HPSS (High Performance Storage System). However, a major effort is continuing to evaluate the suitability of SAM-QFS (a SUN Storage and Archive Management

System) as an alternative mass storage system to HPSS. Initial testing started at Caltech in April, and disaster recovery experiments have gone well.

We successfully tested the recent LIGO Data Analysis System (LDAS) fiber network installed at Caltech to provide Gigabit network speeds for both Ethernet and Fiber Channel. The fiber network will be replicated at the observatories.

4.2.3. Data Analysis Activities

Known Pulsar Search. We began developing code for searching for "known" pulsars. The code is designed to do three things:

1. Generate Short-time Fourier Transforms (SFTs) of the gravity wave channel;
2. Coherently sum the SFTs for a specified frequency band over longer periods of time, accounting for amplitude and phase modulation;
3. Compute statistics for signal-to-noise and confidence of detection to be stored in the LDAS database.

Search for Binary Inspiral Coalescences. We are analyzing the data from LIGO's E7 Engineering Run in preparation for the upcoming LIGO "Science Runs." The goal of this effort will be to place an upper limit on the rate of binary "inspiral" events in the nearby universe. Two signal-detection algorithms (optimal Wiener filtering and "fast chirp transform") have been implemented to search for the gravitational-wave signatures of such events when two neutron stars or black holes orbit each other with ever-increasing velocity and finally coalesce. We have also expended considerable effort in understanding the behavior of the LIGO detectors during the E7 run and the usefulness of various "veto" criteria, using auxiliary data to reduce the number of astrophysical event candidates.

We initiated research on the so-called "Kozai effect," which can drive an initially circular BH-BH binary orbit into a highly eccentric orbit. This work is important because searching for waveforms from highly eccentric orbits increases the parameter space over which a search must be performed. This information is also needed to determine the search efficiency if one only searches for waveforms from circularized orbits.

Search for Transient Bursts. The Burst Group conducted a workshop devoted to the full data analysis pipeline.

Grid Computing and Related Research. LDAS provides, in addition to a complete system for analysis, a true Application Programmers Interface (API). The details are complicated, but one can generalize that the API allows the programmer to pipe LIGO data through a number of executable procedures for pre-conditioning before beginning parallel analysis. We have begun to investigate how the LDAS API can also be used to enable searches on very "generic" Grid resources.

4.3. General Computing

There is a new dedicated LIGO Scientific Collaboration (LSC) web server. We are defining the policy for server access and usage. However, the server is now on line to support the LSC, and a number of presentations and other information have been posted.

The LIGO Data Analysis System (LDAS) group at Livingston Observatory is testing a PIX (CISCO PIX Firewall Series) firewall system. The PIX Firewall Series are state-of-the-art, purpose-built software appliances that deliver unprecedented levels of security, performance and reliability. The LDAS group is also identifying suitable software for a Virtual Private Network (VPN). While originally researched for the LDAS subnets, the solution appears attractive also for the broader General Computing needs of the Laboratory.

We installed several virtual remote control rooms linked to the sites. These rooms are now on line and initial evaluation has proven them to be time saving alternatives. The system at Caltech has been used extensively. Further work remains, including setting up video cameras, introducing improved security, developing better user interfaces, and providing better communications bandwidth.

We are investigating an expansion to a gigabit Ethernet (GigE) network. The need to move large amounts of data among the different servers continues to increase. Both LIGO observatories are considering GigE building-to-building backbones.

5. LIGO SCIENTIFIC COLLABORATION (LSC) MEETING

The March 2002 LSC meeting was held at the Livingston Observatory. In conjunction, Louisiana State University (LSU) hosted a symposium honoring Bill Hamilton. Numerical relativists with an interest in coupling to LIGO and LISA made presentations and participated throughout the LSC meeting. Collaboration with LIGO-LSC was initiated to formulate plans for useful activities, on the part of Numerical relativists, in support of LIGO observational programs and to guide theoretical research.

6. PROJECT MANAGEMENT

All milestones identified in the LIGO Project Management Plan[2] have been completed.

6.1. Financial Status

Table 1 summarizes costs and commitments as of the end of May 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 98.0 percent complete.

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

WBS	Description	Budget	Actual Costs (May 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

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

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

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 (May 2002)**	**Open Encum-brances**	**Estimate-to-Complete**	**Total**
Open Tasks						
1.1.4	Livingston Construction	2,562	2,312	138	112	2,562
1.1.4	Hanford Building	2,760	1,470	1,190	100	2,760
1.2	Detector	59,415	58,598	301	516	59,415
1.4	Data Analysis System	15,463	12,362	294	2,565	15,222
	Contingency	240			481	481
Total		**292,100**	**286,402**	**1,923**	**3,775**	**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.

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 in progress. The Storage and Staging Building at Livingston is complete, and the contractor is addressing 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 $58,900,069. 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 now planned to begin in August 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

The following construction project change request was approved this quarter. The total budget baseline is $291,859,516 leaving a management contingency of $240,484.

Change Request	Description	Submitted	Amount
CR-020004	WBS 1.2.1—Reduced estimate for Interferometer Sensing and Controls Staffing	April 15, 2002	($171,000)