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Date: April 28, 1998
Refer to: LIGO-L980169-00-P

Ms. Carol A. Langguth
Grants Officer
Division of Grants and Agreements
National Science Foundation
4201 Wilson Blvd.
Arlington, VA 22230

Subject: LIGO Project Quarterly Progress Report, LIGO-M980088-00-P

Reference: NSF Award No. PHY-9210038

Dear Ms. Langguth:

Four copies of the LIGO Project Quarterly Progress Report providing status information as of the end of February 1998 are enclosed in accordance with the requirements of the award referenced above. Please forward three (3) copies to Dr. Berley.

Sincerely,

Philip E. Lindquist
LIGO Project Controls Manager

Concurrence for Caltech:

____
Richard Seligman
Director, Sponsored Research

PEL:pel

cc:

G. Sanders
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Document Control Center

Quarterly Progress Report

(Period Ending February 1998)

The Construction, Operation and Supporting Research and Development of a Laser Interferometer Gravitational-Wave Observatory (LIGO)

NSF Cooperative Agreement No. PHY-9210038

LIGO-M980088-00-P

Quarterly Progress Report

(End of February 1998)

THE CONSTRUCTION, OPERATION AND SUPPORTING RESEARCH AND DEVELOPMENT OF A LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY (LIGO)

NSF COOPERATIVE AGREEMENT No. PHY-9210038

LIGO-M980088-00-P

CALIFORNIA INSTITUTE OF TECHNOLOGY

1.0 Introduction

This Quarterly Progress Report is submitted under NSF Cooperative Agreement PHY-9210038[1]. The report summarizes Laser Interferometer Gravitational-Wave Observatory (LIGO) Project status for the period ending February 1998.

2.0 Recent Progress and Status

The project continues to make excellent progress and is 78 percent complete as of the end of February 1998.

Vacuum Equipment (WBS 1.1.1). As of the end of February 1998, fabrication and testing activities are complete. Installation in Washington is six weeks behind schedule partly due to differences in the floor elevation from nominal in the corner station and partly due to weather that delayed access to buildings. Installation in the Y-arm buildings and the X-arm mid-station has been completed, and installation in the corner station is in progress. Vacuum Bake of the Y-arm mid-station components has started. All Washington components have been shipped to the site. The Washington site is expected to be mechanically complete by the end of April. Acceptance testing commenced in Washington late in January and will finish in July. Fabrication and testing of all Louisiana components were completed during the period. The vacuum equipment contractor, Process Systems International (PSI), has held the bidder's conference for the subcontract for installation of the Louisiana components. Completion in Louisiana is expected this year.

Beam Tube (WBS 1.1.2). Beam Tube installation at Hanford is complete. The vacuum acceptance testing of modules 'Y1' and 'Y2' has been completed, and all four modules have been accepted. Alignment checks of the Hanford Y-arm by an independent contractor are now complete, and results are being evaluated. Chicago Bridge & Iron (CB&I), the Beam Tube contractor, has completed all work at the Hanford site and has moved out all equipment and personnel.

All stainless steel material has been received, and all but five coils have been processed for fabrication. Fabrication quality continues at a high level. Hydrogen outgassing screening tests con-

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

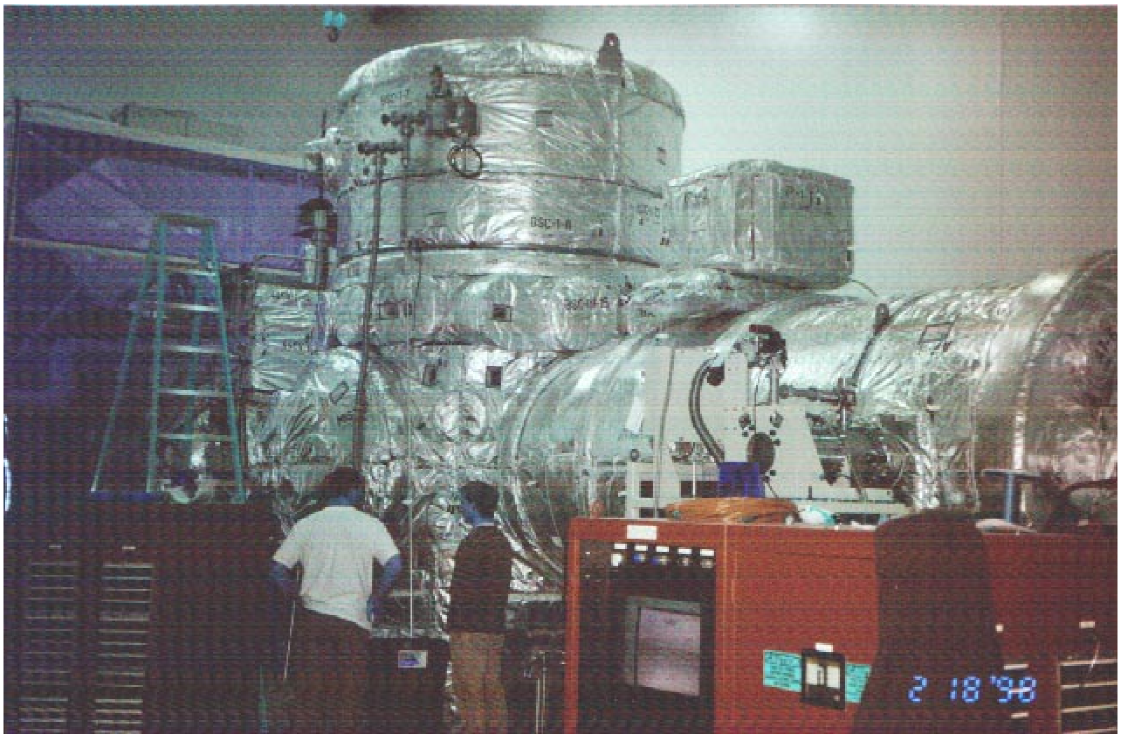

FIGURE 1. Beam Splitter Chamber (BSC) Bake at Hanford

tinue to demonstrate the effectiveness of the coil degassing bake operation. The Magnolia Beach fabrication shop has formed 288 tube sections and checked 266 for leaks, all with acceptable results. Cleanliness checks confirm good tube section cleaning performance. Although the tube section field installation rate now exceeds the shop fabrication rate, the shop's early start on fabrication and the presence of in-shop storage compensates.

CB&I has completed installation of the Beam Tube modules on the X-arm at Livingston, with 200 tube sections installed, including baffle installation (See Figure 2). Installation equipment is now being moved to the Y-arm, and final alignment of the X-arm continues. After that, the modules will be pumped down and acceptance tested.

Beam Tube installation efficiency is surprisingly high at Livingston, and quality continues to be very good. All 202 girth seam leak checks showed acceptable leak results. In spite of the additional rain in comparison with the Hanford site, the rate of installation meets and exceeds that developed at Hanford. One day of work was lost due to a high water level on the site access road, and nearly a day was lost due to a weather-caused power outage on the X-arm.

Installation of the Livingston Y-arm will be completed by mid-June, and all CB&I work will be completed by the end of the year.

Beam Tube Enclosures (WBS 1.1.3). Two thousand Beam Tube Enclosure segments have been cast for the Livingston site representing 77 percent of the total required. Of these, 1300 have been installed, and the X-arm is complete. High voltage power distribution along both arms is complete.

FIGURE 2. Beam Tube Termination Valve at Livingston X-arm End-Station

Washington Civil Construction (WBS 1.1.4). Construction activities have focused on punch list items associated with the completion of all facilities. All remaining items concern fit and finish and are pending the receipt of replacement parts. Beneficial Occupancy has been reached for all facilities. Not all of the subsystems have been accepted--HVAC vibration testing remains to be completed. LIGO staff have occupied the Operations Support Building since September 1997. Roads, parking lots, and landscaping have been installed. Tasks remaining concern re-engineering the potable water system to integrate the pumps and holding tanks, and completing the HVAC remote control for the mid- and end-stations. Also a clean storage and staging building is being designed with an expected completion date in March 1999.

Louisiana Civil Construction (WBS 1.1.4). The site experienced extremely wet weather during January (28 inches). Since most facilities are now under roof, construction progress is being maintained. Beneficial Occupancy has been reached for the Arm 1 End-Station and Joint Occupancy for all buildings. LIGO staff moved into the Operations Support Building on February 17, 1998. A punch list has been established and the contractor has addressed 31 percent of the items. Roads, parking lots, and erosion control are in place, and landscaping is in progress. Work remaining includes completion of the staging and storage building, completion of the overpass, modification of the water system, and close-out of the punch list. It is expected that this work will be completed by June 1998.

Beam Tube Vacuum Bake (WBS 1.1.5). The insulation contractor completed installation of the insulation on all four modules at Hanford. A review of the electrical design was held and the bid package issued. Procurement and installation of control and monitoring instrumentation is in progress. Power supplies and chillers are on hand, and the power distribution cable has been ordered. The vacuum bake at Hanford is planned to start in June 1998 and to complete by April 1999. Vacuum bake of the Beam Tubes in Livingston will follow.

Detector (WBS 1.2). The Detector is making the transition from design into full fabrication. First Detector component deliveries to Hanford are beginning. Installation will start as soon as Process Systems International (PSI) completes the section of the Vacuum Equipment in the Laser and Vacuum Equipment Area (LVEA) required for installation of the two kilometer Interferometer.

Prestabilized Laser. A complete LIGO Nd:YAG prestabilized 'test-bed' laser subsystem is being developed based on the earlier 700mW laser prototype but using the 'Alpha' 10 W laser from Lightwave, Inc. (see Figure 3 on page 5). This 'testbed' will be transferred to Hanford to serve as the light source for the first on-site tests of the laser and Input Optics subsystems. A variety of technical issues have been resolved. The 700 mW NPRO laser continues to operate in the Phase Noise Interferometer (see Section 8.0 on R&D), and experience from that effort is being incorporated into the 10W design.

Lightwave, Inc., continued fabrication of the production 10W lasers. The acceptance review for the first deliverable laser took place at Lightwave's facility in Mountain View, California on February 26, and work on the second laser is in progress. The deliverable laser will replace the 'Alpha' laser in the 'brassboard' Pre-Stabilized laser, and 'Alpha' will be returned to Lightwave. A long-term service contract has been negotiated for support of the on-site lasers by Lightwave.

Optical tables will be delivered to Hanford during March, and the delivery of table enclosures is scheduled in April 1998.

Input Optics. The University of Florida group is responsible for the design of the Input Optics. The Final Design Review for the Input Optics is scheduled in March. The mode cleaner and mode matching optics are being polished. The fabrication of the small optic suspensions for the Input Optics in the first interferometer (two kilometer) was completed during January (See Figure 4 on page 6.) These have been shipped to Caltech for cleaning and baking prior to being shipped to Hanford.

Laboratory testing of components has been an important activity this quarter. For example, the Faraday Isolator must meet isolation performance requirements, have limited optical backscatter, and be vacuum compatible in the strict sense of not inducing additional losses in the mirrors due to contamination. In addition, the external magnetic field must not induce motion in the nearby

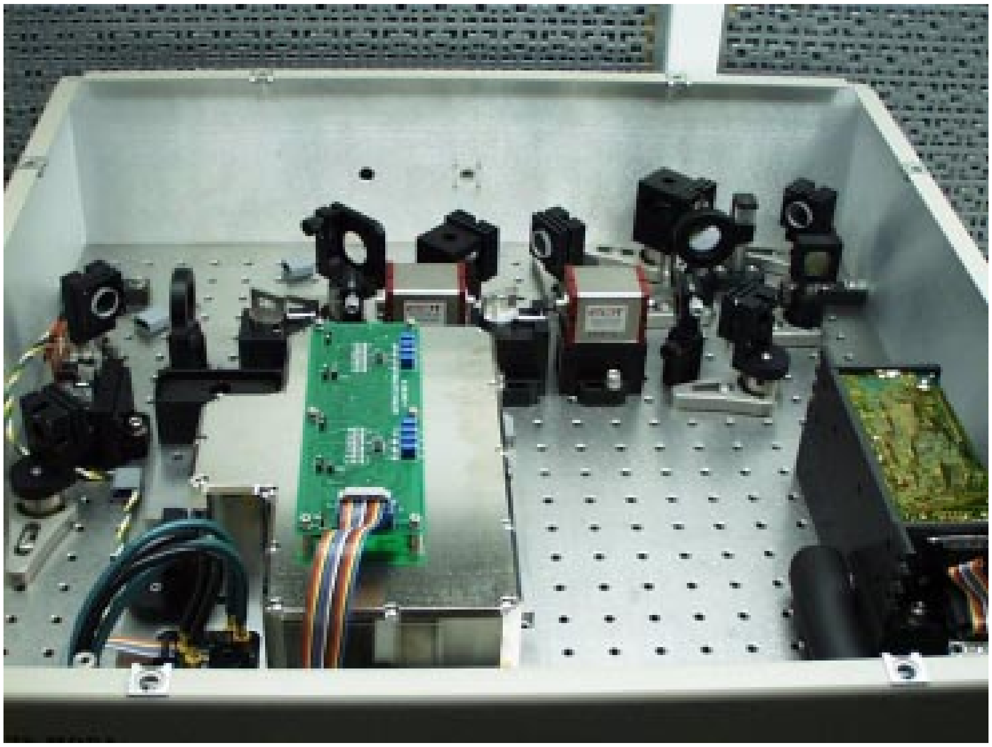

FIGURE 3. View of the 10W Laser Source with the Cover Removed

suspended test masses. The candidate isolator from Electro-Optics Technology appeared to meet the requirements in a series of tests.

Core Optics Components. The last fused silica blanks were received from Heraeus. Polishing continues at our vendors, CSIRO and GO. A number of smaller issues have been addressed during the quarter. The coatings which are designed for 1064 nm must also have a reasonable reflectivity at the wavelengths used for auxiliary lever-arm beams, which are preferably in the visible red (to aid in alignment). The optimal wavelengths were determined from models of the coating response. CSIRO is polishing the optics for our metrology interferometer, and the requirements for and scheduling of this task were defined. There is a change in the radius of curvature of the optics after coating due to the different temperature coefficients of expansion of the coating and substrate materials and the elevated temperature of the coating when applied; this change is anticipated through modeling, and measurements were made to confirm the model.

Trial coatings on full-size pathfinder test masses were carried out (for the HeNe 632 nm wavelength to simplify testing), and the initial characterization is very encouraging.

Core Optics Support. Preliminary design is nearly complete for this subsystem responsible for handling light leaving the interferometer. The principal challenge has been the design of the telescope used to reduce the size of the output beams. Several different designs were pursued in sufficient detail to find the one best suited to address the combination of requirements for wavefront flatness (to ensure that the alignment system receives an unambiguous signal), size, weight, and cost. The solution selected (see Figure 5 on page 7) uses a stock off-axis parabola for the larger

FIGURE 4. Production Small Optics Suspension Fabricated at the University of Florida for the Input Optics System

optic, and while somewhat longer than ideal, fits within our physical and cost envelopes. A detailed model of the optical system has been developed which is fully integrated with the overall optical layout.

The Core Optics Support Preliminary Design Review will be held early in March. Detailed design is in progress.

Seismic Isolation. Production of the first lot of damped metal springs for the seismic isolation system started in January at Pegasus. The approach for manufacturing the coil springs is now established including welding of the end-caps (which must be UHV leak-free). Pegasus is approaching a 30 springs per week production rate.

Fabrication of the other in-vacuum seismic isolation hardware for the first article test continued at Allied Engineering. Allied has revised their procedures to reduce the risk of trapped gasses or cleaning difficulties. Samples of the vertical actuator (a scissors table) in aluminum and stainless steel are in test for stiffness and actuation.

Preparations are underway for first article tests of the Horizontal Access Module (HAM) and Beam Splitter Chamber (BSC) isolation systems, to start during the next quarter. The HAM test will be conducted at the LIGO Hanford Observatory, in one of the production HAM chambers on

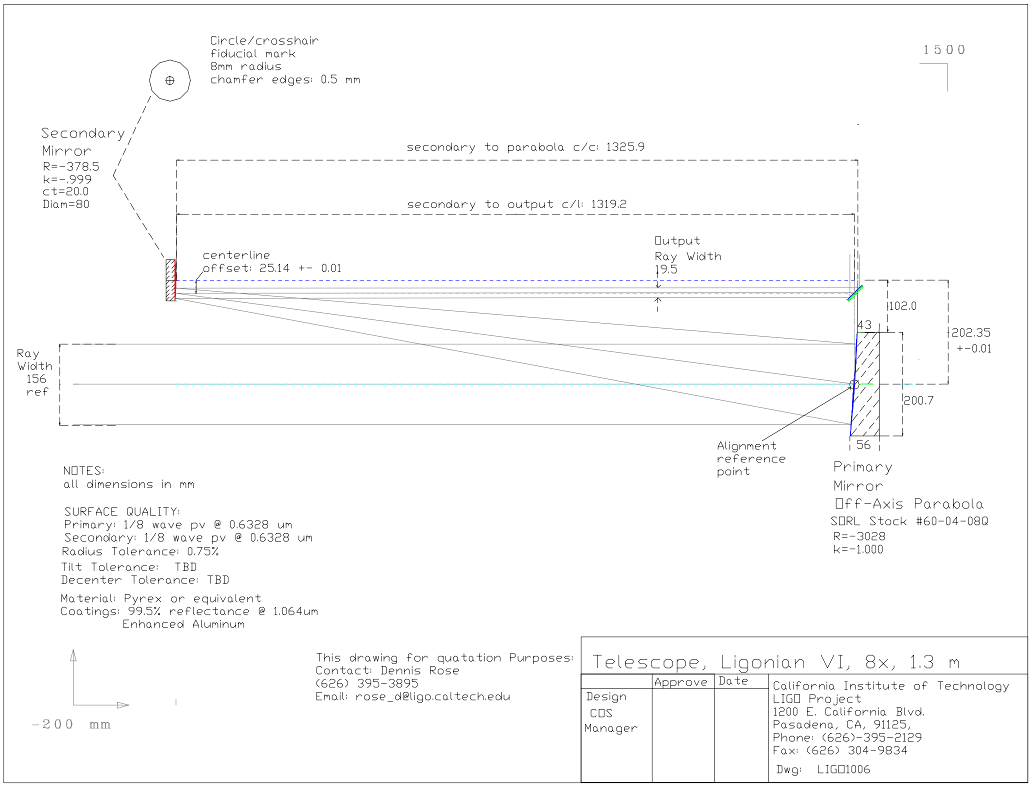

FIGURE 5. Layout of the Core Optics Support Off-axis Output Coupling Telescope

site; the BSC test will take place at the Hytec, Los Alamos facility using a mock-up which allows the critical fit and installation questions to be resolved (see Figure 6).

Suspension Design. The Small Optics Suspensions are being fabricated at the University of Florida as part of the subcontract for the Input Optics subsystem (See Figure 4 on page 6.) Nine have been completed or are being fabricated, and seven have been shipped to Caltech for vacuum-compatibility cleaning.

A contract was awarded to Brookfield Machining of Massachusetts for fabrication of the large optic suspension mechanical components. A second Request for Proposal (RFP) for suspension components and fixtures was prepared for release. The first article controller is being tested.

Alignment Sensing/Control. Final design continued this quarter. Tests of the optical lever prototype for the initial alignment subsystem were completed. The design was modified to integrate the mount into the Seismic support piers, a simple and very stable solution. The initial alignment will be among the first of the on-site activities and is critical to the commissioning of the Input Optics and the Core Optics system.

Some minor changes of the alignment system wavefront sensors were made to integrate an improved photodiode into the design. A prototype will become the basis for the Input Optics alignment system. There was progress in the mechanical and electronic design effort (choice of remote controlled mirror mount actuators), as well as with the development of the software.

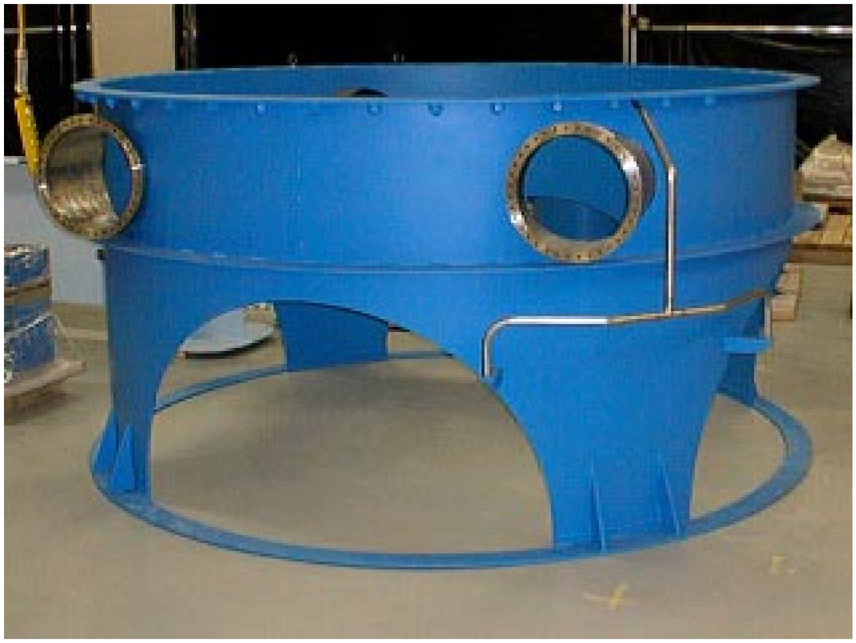

FIGURE 6. Mock-up of the Beam Splitter Chamber (BSC) for First Article Fit Check

Length Sensing/Control. Final design continued with progress to report in the control systems, photodetectors, and lock acquisition. The length control model was elaborated to include the vertical ‘bounce’ mode of the test masses, a realistic seismic isolation stack transfer function, and laser frequency noise. The design work on the Input Optics length control was also integrated. Necessary modifications in the overall control system, including the implementation of a full multi-input, multi-output (MIMO) controller, provided a workable design.

Measurements of backscatter from several candidate photodiodes was compared with calculations of the expected scatter based on atomic force microscope measurements of the surfaces, and agreement was satisfactory. Two photodiodes have now been qualified (from EG&G and Hamamatsu) with the EG&G model demonstrating superior electrical characteristics.

Lock acquisition modeling tools have been exercised to study the test-mass velocity threshold for acquisition of the linear control regime. One approach to a higher threshold is to increase the gain in the servo systems during the acquisition sequence above the point where stable closed-loop operation is possible, with a quick automated reduction after linear operation is achieved (and before any oscillation can be significantly excited). The acquisition software is being interfaced to the operational mode control to allow an integrated model to be used for the final design adjustments.

Time spent in acquiring additional staff has delayed Interferometer Sensing and Control and the related Control and Data Systems design effort. Available resources have focused on two schedule critical areas: the initial alignment system (viewports, optical levers, alignment tooling, etc.) and the Input Optics length and alignment control. This will permit LIGO to meet delivery and installation requirements although the current schedule is tight. Prototype tests will be completed before the Final Design Review to reduce technical risk. Staffing needs have been addressed (see Section 7.0).

Control and Data System (WBS 1.2.2). The Final Design Review for the Control and Monitoring System was held on December 17, 1997. Figure 7 shows the proposed layout of the LIGO Interferometer Control Room.

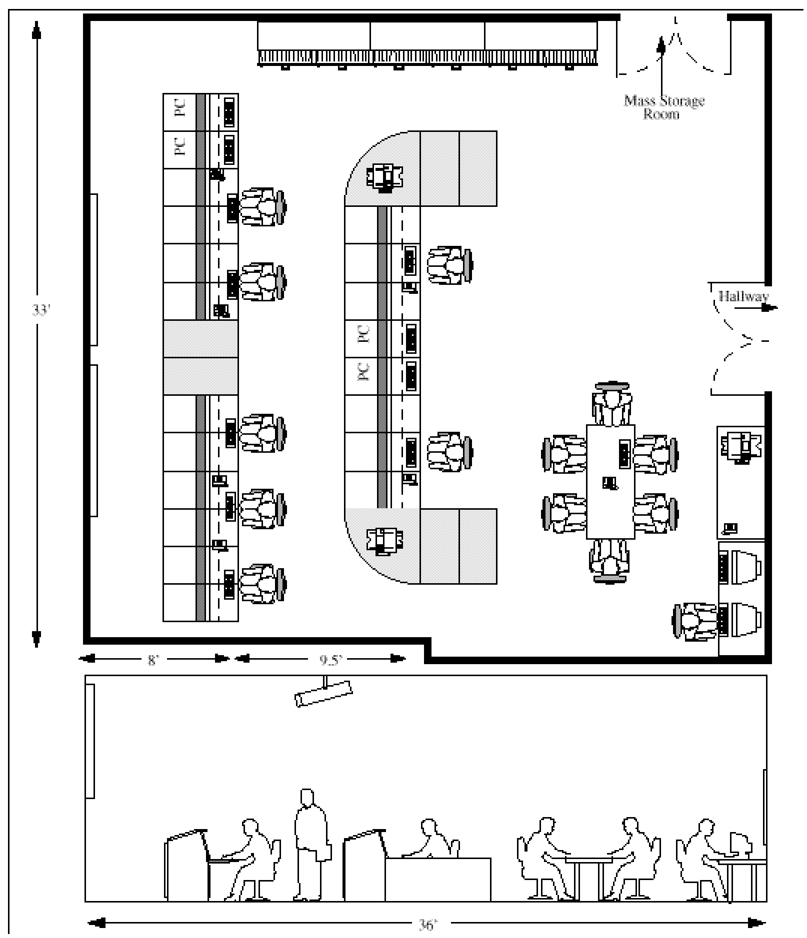

FIGURE 7. Layout of the LIGO Interferometer Control Room

Vacuum controls integration progresses in Hanford. This is the first Detector hardware at the site. The software and hardware were qualified, and the system is now being used to characterize the Vacuum Equipment. The staff involved are moving to Livingston for a parallel effort planned there.

The first article Large Optic Suspension controller and the prestabilized laser prototype are being tested, and the prototype control system for the Input Optics is being fabricated.

The control filters are a challenge with large attenuations required in a narrow frequency band, without introducing excess phase in-band. The analog-to-digital and digital-to-analog conversion for the length controls require a combination of precision (16 bits) and low-latency (tens of microseconds maximum) which are difficult to find in standard commercial equipment. Characterization and coding are in progress. The Input Optics controls will be among the first to be implemented at the sites, and these also received attention.

A prototype data acquisition system has been installed and tested on the 40 Meter Interferometer. The Final Design Review is scheduled in May.

Control and Data System (CDS) network installation has started in Hanford, Washington and is scheduled to begin in Livingston, Louisiana in April.

Detector System Engineering and Integration. The interferometer integration effort made important progress this quarter. The integration plan for the two kilometer Hanford interferometer (the first to be installed) has been developed (See Figure 8 on page 10.) This plan includes estimates for the duration and manpower required for each of the hundreds of tasks leading up to the commissioning of the two kilometer interferometer, as well as the contingencies and required precedents. Teams to execute the plan are being formed.

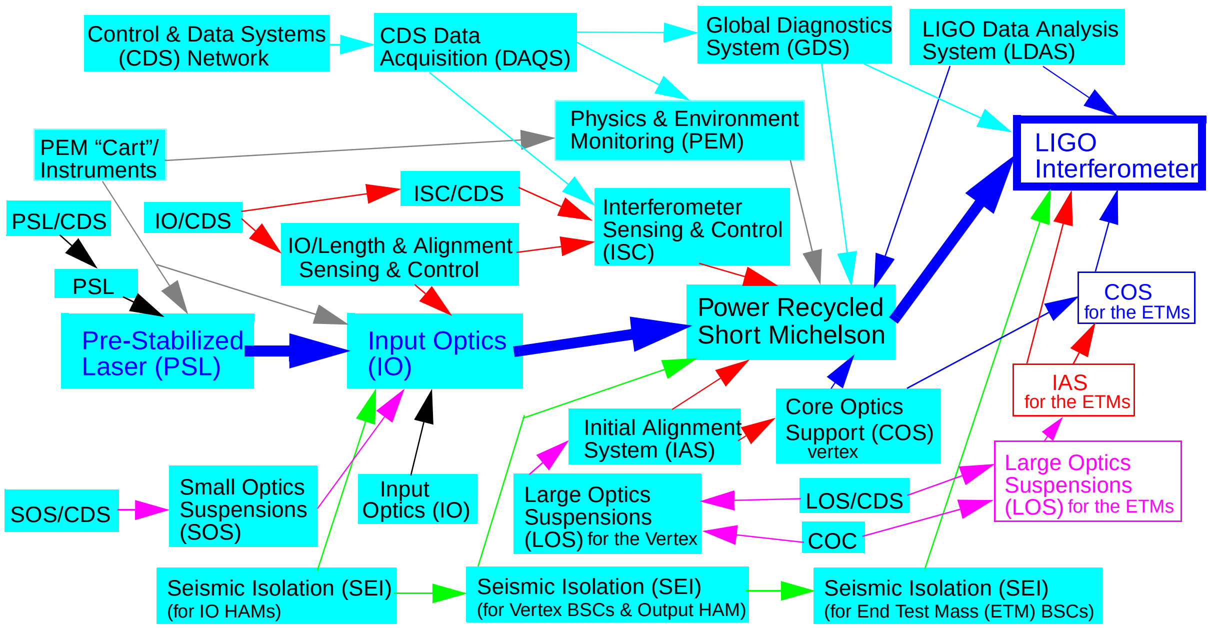

FIGURE 8. Graphical Summary of the Final Stages of Integration of the Two Kilometer LIGO Interferometer

Interferometer Diagnostics. The Global Diagnostics System is responsible for establishing inter-subsystem tests to be performed, and to enable them through software and hardware. A preliminary design has been prepared and will be reviewed early next quarter. It is integrated with the data acquisition and control software and hardware design. The design allows real-time monitoring of the state of the interferometer, invasive and non-invasive diagnostics, and sophisticated triggering and searching mechanisms for reducing the large amount of data for viewing and archiving.

Contamination Qualification. The effort to qualify in-vacuum materials and processes for their optical contamination properties progressed this quarter. A system was qualified for direct optical measurement using high-finesse Fabry-Perot cavities in initially very clean vacuum chambers, with a precision measurement of the change in the storage time or the shift in higher-order spatial modes (due to direct absorption). An example of data is shown in Figure 9 on page 12. The accrued losses (Cavity 1-loaded with suspension sensor components: absorption: 0.7 +/- 0.5 ppm/year, absorption plus scatter: 4 +/- 1 ppm/year; Cavity 2-empty: absorption: 0.9 +/- 0.5 ppm/year absorption plus scatter: -6 +/- 4 ppm/year) are those expected in one year, extrapolated from measurements over 45 days of cavity running time, with a stored intensity of 200 kW/cm^2.

The values listed for absorption were obtained from the resonant mode frequency spacing technique, and the values listed for absorption + scatter were obtained from ringdown measurements. Scaling these rates to LIGO is based on the fact that the contamination cavities are pumped by 10 liter/sec ion pumps, compared to 1000 liter/sec pumps to be used in the LIGO chambers, and a stored intensity of 100 kW/cm^2 in the mode cleaner and 1 kW/cm^2 in the LIGO arms. The only statistically significant effect seems to be the increase in scatter loss for cavity 1, containing the light emitting diodes (LED's) and photodiodes. However, given the larger pumping speed for LIGO relative to the test cavities mentioned above, which would reduce the hydrocarbon pressures by a factor of 100, the components are deemed qualified for use in LIGO. Cavity 2 (empty) has now been qualified, and is being loaded with Teflon-coated wire used to form suspension drive coils.

Physics Environment Monitoring System (WBS 1.2.3). The Physics Environment Monitoring System, which is responsible for surveying and reporting the environment to the operators and data system, entered the fabrication phase. Most of the equipment is commercial, and first articles of all critical components were ordered and tested. The planning for installation proceeded and was integrated with the top-level interferometer plan.

The first on-site measurements involved an effort to characterize several parameters of interest at the two sites simultaneously and with Global Positioning Satellite (GPS) time stamps. Undergraduates at Whitman College and Louisiana State University helped to record the magnetometer and seismometer signals, and the data is now being reduced. Correlated events, which appear to be lightning, have been observed; comparison with independent measurements of lightning pulses is in progress.

Support Equipment (WBS 1.2.4). The Support Equipment plan for the Hanford site was reviewed and approved. Equipment is now being acquired to aid during installation and shakedown of the first detector components at the Hanford site.

Research and Development (WBS 1.3). Investigation of the locking challenges in the power-recycled Michelson configuration continued on the 40 Meter Interferometer. Comparisons with the dynamic model allowed corrections and refinements to both the model and the experiment. The addition of wavefront sensors to give alignment information has shown correlations with the ease of locking, as anticipated, and closed-loop servo-control of those degrees of freedom is being installed.

Reliability problems again limited progress this quarter. The Argon Ion laser required the replacement of a plasma tube. Electro-optic modulators suffered transmission losses in the vacuum system. An alternate modulator has been ordered.

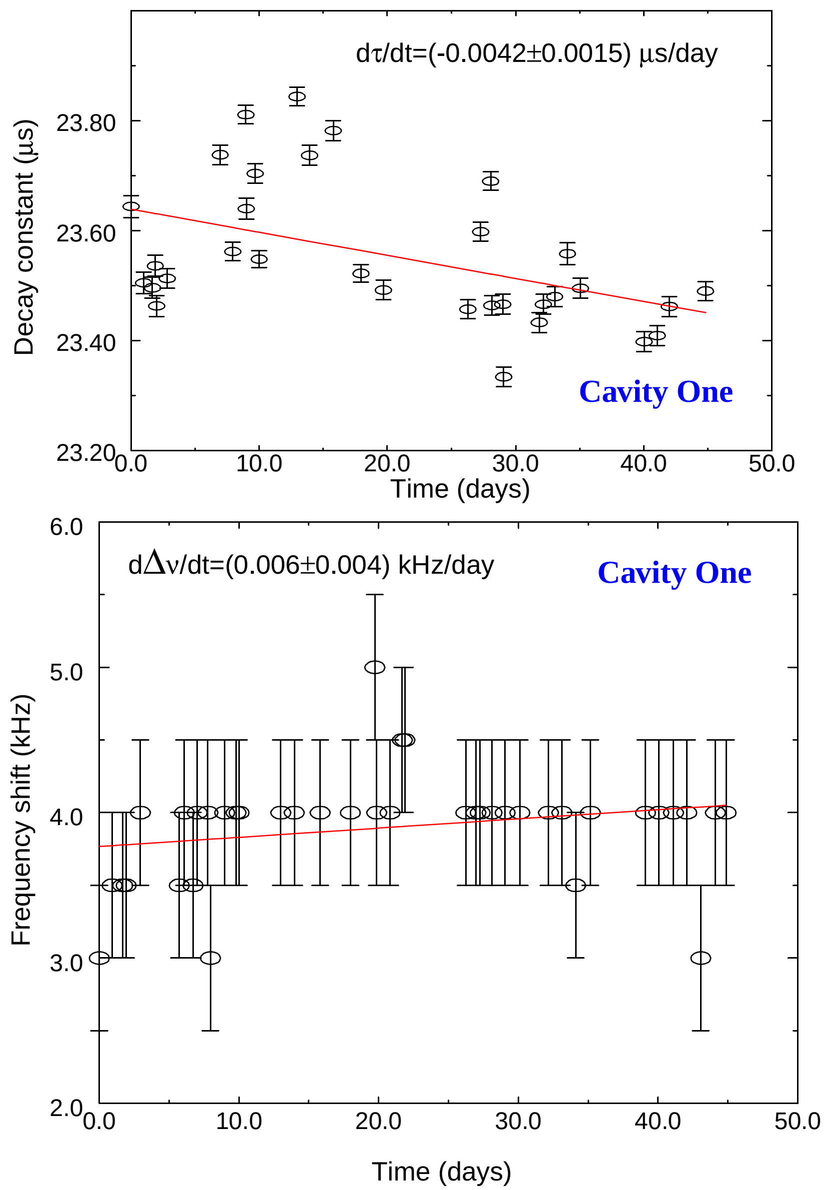

FIGURE 9. Qualification of an Empty Test Chamber to be Used to Determine Contamination from In-vacuum Materials.

The Phase Noise Interferometer research effort at the five meter facility at MIT is intended to develop and demonstrate the technology for shot-noise limited interferometer operation at initial LIGO power levels to achieve the required phase sensitivity. During this quarter the final phase of this research was conducted. Low-frequency noise sources were specifically targeted. Contributions from parasitic interferometers (formed between the isolated, suspended in-vacuum components and the much seismically noisier input and output optics) were identified and reduced by improvements in optical surfaces and the addition of acoustic shields. Radio-frequency amplitude noise was also a contributor, and the optical layout was changed to reduce the out-of-phase noise level and the significance of this noise source. The final spectrum shows a shot noise sensitivity in excellent agreement with the calculated value and with a much improved low-frequency spectrum. There is an intermediate frequency range, from 120 to500 Hz, which is not explained; analysis is continuing. This phase of the research was completed in February 1998. Figure 10 on page 13 shows the Phase Noise Interferometer spectrum. The upper curve represents the best results with the Argon laser; bottom, with the Nd:YAG. The solid line is the calculated shot noise value.

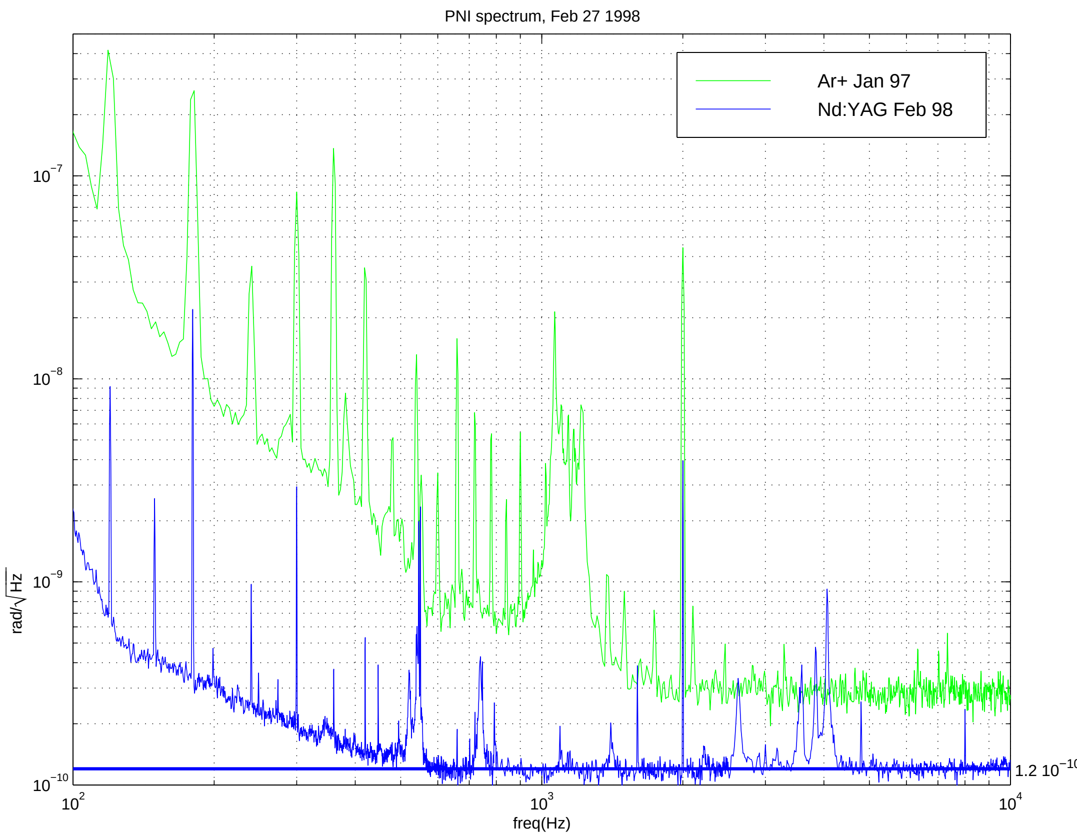

FIGURE 10. Phase Noise Interferometer Spectrum (Argon Laser vs. Nd:YAG vs. Calculated Shot Noise)

Aspen Winter Conference. The Aspen Winter Conference on Gravitational Waves and their Detection was held January 4 - 10, 1998. The focus of the scientific program was on advanced interferometer topologies and advanced concepts in suspensions and noise. There were also several tutorial sessions that provided newer members of the community an opportunity to learn about the field of gravitational-wave detection.

David McClelland (Australian National University) gave three tutorial lectures on Advanced Interferometer Topologies. Peter Saulson gave two tutorial lectures on Thermal Noise, and also gave a very well attended and well received public lecture on “The Quest for Gravitational Waves: Fulfilling Einstein's Vision.” Tuck Stebbins (JILA) also gave a tutorial lecture on Advanced Concepts in Suspensions and Noise. Jim Hough (Glasgow) organized a session on Advanced Detectors that addressed Interferometry and Suspension issues as well as possible Space Experiments. The current plan is to alternate the Aspen Conference with an analogous conference at Moriond, where the conference will be held next year.

Collaborative Research by Visitors. The following individuals are performing collaborative research under the auspices of the LIGO Visitor’s Program which is separately funded by the NSF.

A group led by Sam Finn of Northwestern University joined LIGO in September 1997. Its members will be at Caltech for approximately one year. Sam Finn is focused primarily on the use of Kalman filters for tracking wandering oscillators, violin mode resonances, and other narrow line features in the LIGO output data. He has also worked on related projects including detection strategies for gravitational-wave receivers consisting of heterogeneous and geographically separated detectors. Soumya Mohanty is focused on the LIGO End-To-End Model. Mohanty's particular responsibilities involve integrating the Hytec model of the seismic isolation system into the End-To-End model, and developing a complete set of equations that describe the motion and resonances of the suspension system. Soma Mukherjee is studying the noise characteristics of the September 1994 40 Meter Interferometer. The goal is to develop tools which may prove useful to the instrumental team in diagnosing instrument misbehavior, and in later data analysis. Joseph Romano, working with Finn, is examining in detail statistical tests appropriate for the identification of a stochastic gravitational-wave signal in several gravitational-wave detectors. Optimal filters previously derived for this problem, while appropriate for continuous time data streams, are inappropriate for the analysis of discretely sampled time series data. Romano found the appropriate filters for time series data and developed Matlab code to generate them.

Janet Houser of the Smithsonian Astrophysical Observatory/MIT joined the LIGO effort at MIT in September 1997 and will be working part time for two years. She is currently using a three-dimensional hydrodynamic code to investigate the dynamics and gravitational radiation emitted by non-axisymetric instabilities in rapidly rotating stars as the equation of state, angular momentum distribution, and rotation rate are varied. She has recently included the General Relativistic back reaction, and is now beginning production runs of secular unstable stellar cores and inspiralling neutron star binaries.

Keith Riles of the University of Michigan is working at the 40 Meter Interferometer where he is developing analytical tools for “on-line” and “off-line” software diagnostics for the rapid detection of noise sources including correlations in servo control signals. In collaboration with Richard Gustafson, an early participant in the Visitor Program, he has started the development of electronics for use in LIGO diagnostics. He started at Caltech in January and expects to remain here through December 1998.

Shaoul Ezekiel of MIT visited Caltech for two weeks and will return next quarter. He worked with the staff of the 40 Meter Interferometer to assist with commissioning the recycled configuration. He provided recommendations regarding the servo control system. In addition, he participated in a series of meetings with various LIGO staff to provide input relevant to a wide range of topics including lasers, optics, atomic clocks, and control systems.

3.0 Project Milestones

The status of the project milestones identified in the Project Management Plan (PMP) for the LIGO Facilities is summarized in Table 1.

LIGO has assumed "Joint Occupancy" of all buildings. Levernier, the prime construction contractor in Hanford, continues to address "punch list" items in the buildings. Beneficial Occupancy is typically following Joint Occupancy by 90 days. The final Beneficial Occupancy in Hanford--of the X-arm end-station--is currently projected for March 1998.

The milestone "Accept Vacuum Equipment (WA)" was slipped four weeks during the summer of 1997 to reflect the expected late completion of the X-arm buildings at Hanford. The NSF milestone was not changed because it was anticipated that Process Systems International (PSI) would not require the entire four weeks to finish. The additional six weeks, delaying the milestone to July 1998, are due to a recent floor elevation change order. The floors in the Laser and Vacuum Equipment Area (LVEA) and Vacuum Equipment Area (VEA) at Hanford were discovered to be more than an inch too low. As a result the subcontractor, PSI, had to order new anchor bolts. Delivery required approximately nine weeks. During this time PSI was only able to work effectively in one building (Y-arm mid-station).

TABLE 1. Status of Significant Facility Milestones

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

a. Project Management Plan, Revision C, LIGO-M950001-C-M submitted to NSF in November 1997

The milestone "Accept Vacuum Equipment (LA)" slipped to reflect the delays in Hanford. The two installations are serially linked because common subcontractor staffing is planned for accomplishing the work. However, the subcontractor is still targeting a Louisiana completion date of December 1998. The "Initiate Facility Shakedown" milestones are tied to the vacuum equipment acceptance milestones.

Table 2 shows the actual and projected status of the significant Project Management Plan (PMP) milestones for the Detector. Every effort has been made to prioritize critical-path tasks as required to support Detector installation.

The Seismic Isolation (BSC and HAM) Final Design Review is scheduled for June 12, 1998. This review will focus on the structural components with an update for the actuation system to be held at a future date.

The projected completion date for the Core Optics Support Final Design Review is now August 1998. Significant scope originally in this task has been moved to the suspension task (Final Design Review already completed), deferring some "need" dates for the Core Optics Support. The delay leaves unaffected the target date for first operation of the LIGO interferometers. A better understanding of the requirements and design for the Core Optics Support has reduced the expected fabrication time, and all critical components are expected to be ready in time to avoid installation delays.

The Core Optics Components Final Design Review has also been delayed by approximately three months. In this case, an aggressive procurement strategy has been instituted which permits initial fabrication steps to begin prior to the Final Design Review without incurring significant risk and, in fact, reduces costs by allowing time for rework of any parts damaged as opposed to requiring additional spares.

TABLE 2. Status of Significant Detector Milestones

Milestone Description	Project Management Plan Date		Actual (A)/Projected (P) Completion Date	
	Washington	Louisiana	Washington	Louisiana
BSC Stack Final Design Review	04/98		06/98 (P)	
Core Optics Support Final Design Review	02/98		08/98 (P)	
HAM Seismic Isolation Final Design Review	04/98		06/98 (P)	
Core Optics Components Final Design Review	12/97		04/98 (P)	
Detector System Preliminary Design Review	12/97		07/98 (P)	
I/O Optics Final Design Review	04/98		03/98 (P)	
Prestabilized Laser Final Design Review	08/98		10/98 (P)	
CDS Networking Systems Ready for Installation	04/98		03/98 (P)	
Alignment (Wavefront) Final Design Review	04/98		07/98 (P)	
CDS DAQ Final Design Review	04/98		04/98 (P)	
Length Sensing/Control Final Design Review	05/98		07/98 (P)	

TABLE 2. Status of Significant Detector Milestones

Milestone Description	Project Management Plan Date		Actual (A)/Projected (P) Completion Date	
	Washington	Louisiana	Washington	Louisiana
Physics Environment Monitoring Final Design Review	06/98		10/97 (A)	
Initiate Interferometer Installation	07/98	01/99	07/98 (P)	01/99 (P)
Begin Coincidence Tests	12/00		12/00 (P)	

The initial alignment component (for which site deliveries are required late in 1998) has been uncoupled from the other Alignment Sensing and Control tasks, and the final design for initial alignment, now substantially complete, will be reviewed ahead of the original schedule. The remaining Alignment Sensing and Control and Length Sensing and Control components are not required for integration until May 1999. The revised Final Design Review dates are thus consistent with timely fabrication and integration, and are not expected to affect site operations.

Delaying reviews of the Length Sensing and Control and the remaining components of the Alignment Sensing and Control until summer 1998 allows us to complete extensive closed-loop testing at Caltech and the Phase Noise Interferometer at MIT. These tests are in progress and should be essentially complete by June, with required modifications incorporated into the designs before the Final Design Review. Finally, due to the loss of key personnel late last year, additional time is required to complete the Length Sensing and Control lock acquisition final design. New staff has been assigned and the activity is back on track with a delay of approximately two months.

The Physics Environment Monitoring FDR was completed ahead of schedule in October 1997.

4.0 Financial Status

Table 3 on page 19 summarizes costs and commitments as of the end of February 1998.

5.0 Performance Status (Comparison to Project Baseline)

Figure 11 on page 20 is the Cost Schedule Status Report (CSSR) for the end of February 1998. The CSSR shows the time-phased budget to date, the earned value and the actual costs through the end of the month for the NSF reporting levels of the WBS. The schedule variance is equal to the difference between the budget-to-date and the earned value, and represents a “dollar” measure of the ahead (positive) or behind (negative) schedule position. The cost variance is equal to the difference between the earned value and the actual costs. In this case a negative result indicates an overrun. Figure 12 on page 21 shows the same information as a function of time for the LIGO Project.

Vacuum Equipment (WBS 1.1.1). The favorable schedule variance is due to being ahead of schedule with fabricating the hardware for the Louisiana site. Installation is actually somewhat behind schedule in Hanford. However, the contractor plans to complete the contract early.

The favorable cost variance reflects normal delays in processing invoices. Some overruns have been incurred for supporting activities including Quality Assurance and travel. These overruns have been reflected in the Estimate-at-Completion on the CSSR. Change Requests have been submitted to address some of the added scope.

Beam Tube (WBS 1.1.2). There has been significant improvement in the schedule variance due to the acceptance of all four modules at Hanford and credit taken for completing fabrication of the first 266 Beam Tube sections in Livingston (seven weeks ahead of schedule), and installation of the first 200 Beam Tube sections in Livingston (nine weeks ahead of schedule).

The favorable cost variance reflects normal delays in processing invoices. Some overruns have been incurred for labor rate variances as well as supporting activities including Quality Assurance. These overruns have been reflected in the Estimate-at-Completion on the CSSR. Change Requests have been submitted to address this added scope.

Beam Tube Enclosures (WBS 1.1.3). The contract for the Hanford site is complete with the exception of "punch list" items. A number of enclosures have been cast for the Livingston site, but acceptance is behind schedule, and installation will be delayed since enclosure installation follows installation of the Beam Tube.

The favorable cost variance reflects normal delays in processing invoices.

Civil Construction (WBS 1.1.4). Civil Construction is ahead of schedule. The facilities in Hanford are nearly complete. The subcontractor in Livingston is also pushing to complete ahead of schedule.

Detector (WBS 1.2). The Detector is behind schedule and under cost. LIGO has been hiring additional staff, but this was not accomplished quickly enough to avoid some delays. The Detector plan has been reviewed and adjusted to reflect the current status and a reassessment of the work remaining. Priorities have been adjusted to assure that critical milestones are met.

Laser and Optics - Most of the glass has been received for the optics.

Seismic Isolation - The Seismic Isolation effort is two to three months behind schedule. The procurement process has proved to be more time consuming than anticipated. The award of contracts for first article fabrication was scheduled to have been accomplished by August 1997, but contracts were still being issued in November and December. Essentially everything is now under contract. The NSF has been very supportive during the review and approval cycle for many of these procurements.

Alignment Sensing and Control - The Alignment Sensing and Control (ASC) effort is behind schedule because resources have been shared to accomplish R&D tasks supporting interferometer development as well as the design of the input optics.

Control and Data Systems - There are minor behind schedule positions reported for the controls for the Pre-stabilized Laser (one month), the Alignment Sensing and Control System (PDR is one month late), the Length Sensing and Control System (PDR is two months late), and the Input Optics (DRR is three months late).

TABLE 3. Costs and Commitments as of the end of February 1998

(all values are $Thousands)

WBS		*Costs Thru Nov 1996*	*FY 1997 Costs*	*Dec-97*	*Jan-98*	*Feb-98*	*Cumulative Actual Costs*	*Open Commitments*	*Total Cost Plus Commitments*
1.1.1	**Vacuum Equipment**	21,254	9,263	1,990	700	698	33,905	12,439	46,345
1.1.2	**Beam Tube**	17,262	15,717	2,036	702	2,965	38,681	9,979	48,661
1.1.3	**Beam Tube Enclosure**	6,237	7,036	1,504	304	179	15,261	6,657	21,918
1.1.4	**Civil Construction**	14,117	30,564	2,827	1,790	(368)	48,930	6,676	55,606
1.1.5	**Beam Tube Bake**		75	288	50	367	779	961	1,740
1.2	**Detector**	6,270	8,069	1,249	1,740	1,374	18,703	7,529	26,232
1.3	**Research & Development**	16,816	2,865	360	15	295	20,351	1,019	21,371
1.4	**Project Management**	16,288	6,362	611	320	528	24,108	1,733	25,841
7LIGO	**Unassigned**	2	(0)	1	8	(3)	7	31	38
	Installation and Commissioning		330	72	103	551	1,055	60	1,115
TOTAL		98,246	80,280	10,939	5,731	6,586	201,781	47,085	248,866
Cumulative Actual Costs		98,246	178,526	189,464	195,196	201,781			
Open Commitments		91,492	62,510	55,236	51,446	47,085			
Total Costs plus Commitments		189,738	241,036	244,700	246,642	248,866			
NSF Funding		*$ 208,468*	*$ 265,389*	*$ 265,389*	*$ 265,389*	*$ 265,389*			

Note: “Unassigned” Costs have not been assigned to a specific LIGO Construction WBS but are continually reviewed to assure proper allocation

LIGO Project

Cost Schedule Status Report (CSSR)

End of February 1998

(All values are $Thousands)

Reporting Level	Cumulative To Date					At Completion		
Work Breakdown Structure	Budgeted Cost of Work Scheduled (BCWS)	Budgeted Cost of Work Performed (BCWP)	Actual Cost of Work Performed (ACWP)	Schedule Variance (2-1)	Cost Variance (2-3)	Budget-at-Completion (BAC)	Estimate-at-Completion (EAC)	Variance-at-Completion (6-7)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1.1.1 Vacuum Equipment	35,607	36,610	33,905	1,003	2,705	42,739	43,617	(878)
1.1.2 Beam Tubes	37,378	39,815	38,681	2,437	1,134	47,050	47,147	(97)
1.1.3 Beam Tube Enclosure	16,663	17,565	15,261	902	2,304	19,796	19,244	552
1.1.4 Facility Design & Construction	48,025	48,964	48,930	939	34	50,605	51,774	(1,169)
1.1.5 Beam Tube Bake	999	999	779	-	220	3,564	3,744	(180)
1.2 Detector	27,352	21,397	18,698	(5,955)	2,699	54,200	53,499	701
1.3 Research & Development	22,211	22,144	20,351	(67)	1,793	23,490	23,490	-
1.4 Project Office	23,603	23,603	24,100	-	(497)	27,574	28,570	(996)
Subtotal	211,838	211,097	200,705	(741)	10,392	269,018	271,085	(2,067)
Contingency						-	21,015	(21,015)
Management Reserve						23,082	-	23,082
Total	204,536	202,094	194,499	(2,442)	7,595	292,100	292,100	-

FIGURE 11. Cost Schedule Status Report (CSSR) for the End of February 1998

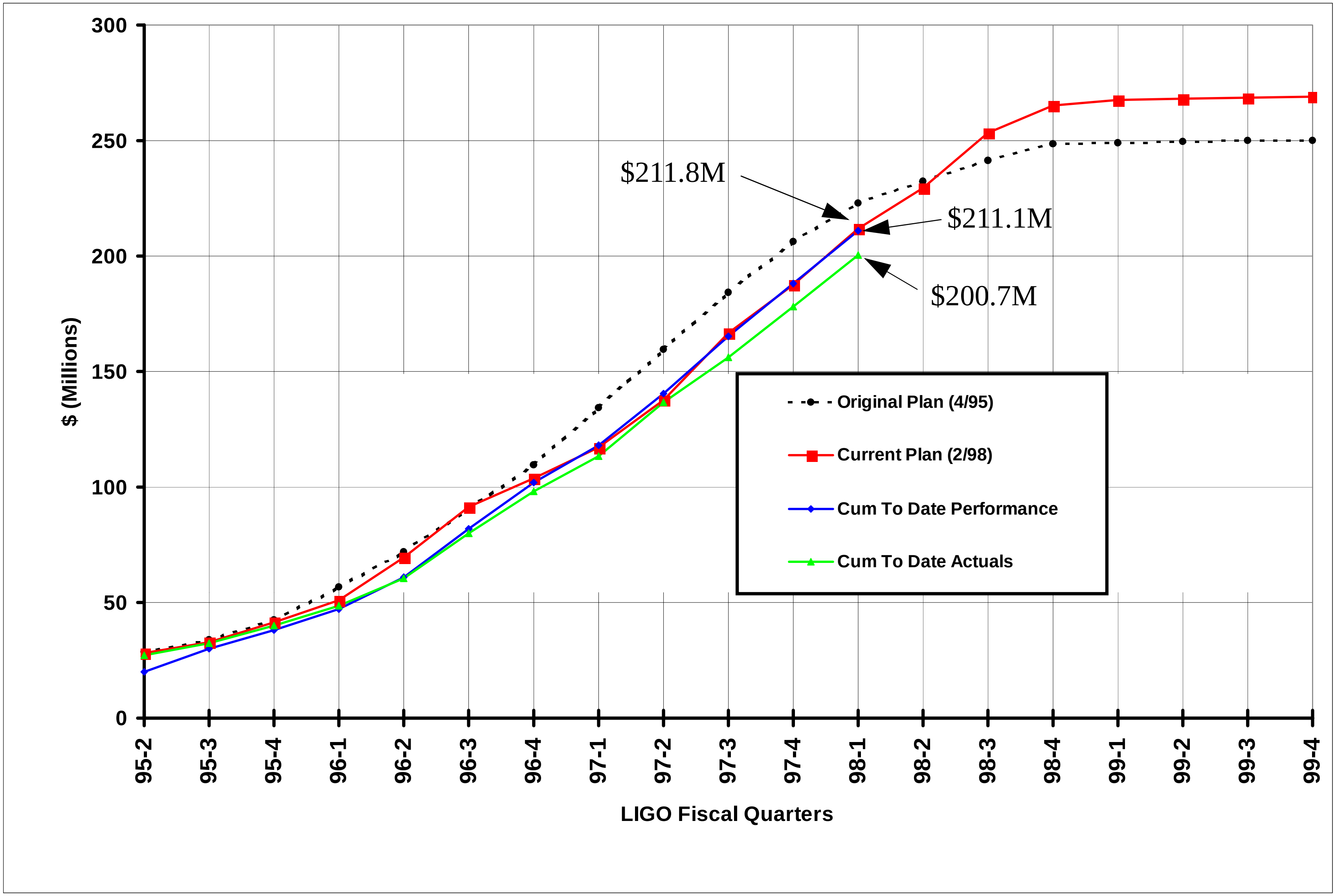

FIGURE 12. LIGO Construction Performance Status as of the End of February 1998

Project Office (WBS 1.4). The Project Office is reporting an unfavorable cost variance. The added costs have been incurred to support property management, scheduling and integration activities, and general computing. The overrun is being reflected in the Estimate-at-Completion, and change requests are being prepared to address the added scope.

6.0 Change Control and Contingency Analysis

The change requests in Table 4 were approved during this reporting period. These change requests allocated $1.5 million from the contingency pool and with corresponding additions to the budget baseline used for preparing the end-of-February reports. The current contingency pool is $23.1 million (relative to the budget-at-completion). One change request for the LIGO Data Analysis System (LDAS) was held. However, a planning package has been set aside from the contingency for LDAS equipment and software.

TABLE 4. Change Requests Approved during the First Quarter LIGO FY 1998

Change Request Number	WBS	Description	Amount
CR-970042	1.1.4	Civil Construction - Levernier Field Work Directives	324,328
CR-970043	1.1.2	Beam Tube In-House Miscellaneous	1,088,000
CR-980001	1.1.4	Hensel Phelps Field Work Directives	38,331
CR-980002	1.1.4	Civil Construction Added Scope - Hanford	104,115
CR-980003	1.1.4	5000 Square Foot Building at Hanford	510,000
CR-980004	1.2.3	Physics Environment Monitoring Effort Replan	(757,000)
CR-980005	1.1.4	Extending Parsons Support at Hanford	68,000
CR-980006	1.2.1	Seismic Isolation - Spring Cleaning and Bellows Fabricatio	147,052
		Total	1,522,826

7.0 Staffing

The LIGO staff currently numbers 125 (full time equivalent). Of these, 38 are contract employees. Eighty-seven LIGO staff are located at CIT including seven graduate students. Eighteen are located at MIT including four graduate students. Fourteen are now located at the Hanford, Washington site, and six have relocated to Livingston, Louisiana.

In addition, there are ten visitors currently at LIGO under the auspices of the LIGO Visitor's Program separately funded by the NSF.

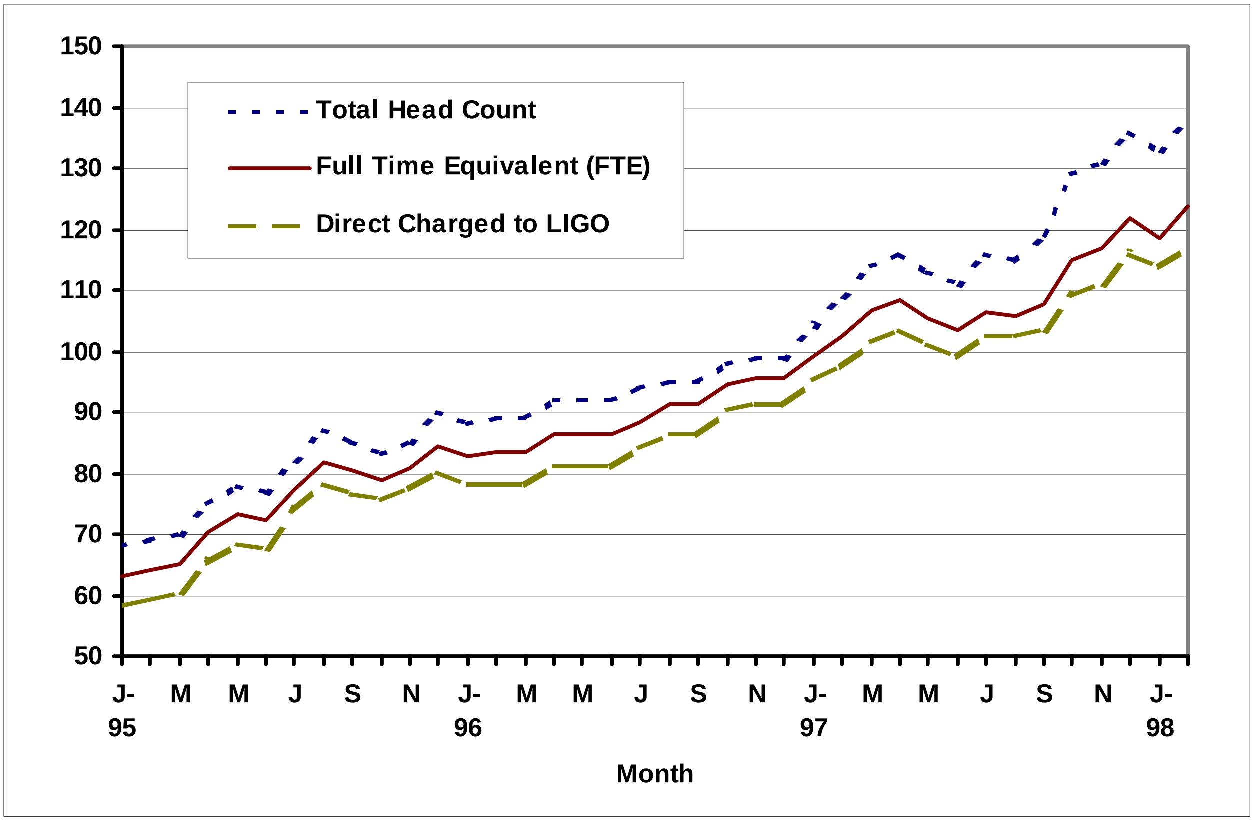

FIGURE 13. LIGO Staffing History since January 1995