Quarterly Progress Report

(December 1995 through February 1996)

The Construction, Operation, and Supporting Research and Development of a Laser Interferometer Gravitational-Wave Observatory (LIGO)
NSF Cooperative Agreement No. PHY-9210038

March 1996

Quarterly Report

(December 1995 - February 1996)

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

NSF COOPERATIVE AGREEMENT No. PHY-9210038

March 1996

CALIFORNIA INSTITUTE OF TECHNOLOGY

This Quarterly Report is submitted under NSF Cooperative Agreement PHY-9210038[1]. The report summarizes Laser Interferometer Gravitational-Wave Observatory (LIGO) Project activities from December 1, 1995 through February 29, 1996.

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

Table of Contents

List of Figures

LIST OF TABLES

1.0 Executive Summary

During the report quarter, the LIGO Beam Tube Fabrication/Installation contract was awarded and rough grading at the Livingston site and Beam Tube Enclosure/Slab construction at Hanford commenced. The Beam Tube, Vacuum Equipment and Facilities are all in Final design. The LIGO Detector advanced with solicitation for the first required solid state laser, and work on the critical core optics has resolved many technical issues. LIGO is progressing well along its baseline plan with only Livingston rough grading experiencing weather-related delays.

The $39.5 million contract for fabricating and installing the Beam Tube was issued to Chicago Bridge and Iron (CB&I) on December 11, 1995. The contract kick-off meeting was held on January 8, 1996. The scheduled date for the design review is March 27, 1996.

The bids for the Beam Tube Enclosure contract were opened January 4, 1996. A total of 13 bids were received. The low bidder was ACME Materials and Construction Company of Richland, WA. The contract was awarded for $7,200,000 and construction started (see Figure 1.)

FIGURE 1. The first concrete is poured at LIGO. Dr. Barry Barish (Caltech) and Dr. Dave Berley (NSF) watch as concrete is poured for the Termination Valve Anchor Foundation on the southwest arm Mid-station at Hanford. (March 1996)

Construction power was installed at the Livingston, LA site on January 11. A cost proposal (one of two) for permanent power installation has been received.

The Livingston rough grading work is behind schedule due to rain. Parsons (the A&E contractor), Stranco (the rough grading contractor), and Professional Service Industries (our QC contractor) revised the undercut and backfill procedure which is more adaptable to the wet weather that is being experienced, will allow Stranco to make up lost time, and will result in cost savings. Stranco has submitted a proposed contract modification. Stranco will also install concrete slabs over the Pipe Line crossings at Livingston.

Three prototype Beam Tube baffles have been constructed and evaluated for mechanical design and the development of a coating process. A Request For Quotation (RFQ) has been issued for procurement of the uncoated baffles.

There has been progress in both the implementation and research aspects of the Detector effort. Design Requirements reviews signaled the start of Preliminary Design for two subsystems (Core Optics and the Control and Data System). A Request For Proposal (RFP) has been sent to prospective bidders for the Nd:YAG high-power lasers. Many technical issues in the production of the Core Optics Components have been resolved through in-house and contracted effort. The change to a longer wavelength has also been incorporated in the optics design. The initial configuration of the Phase Noise Interferometer (PNI) has been concluded and documented. Work on both the PNI and the 40 meter facility is progressing more slowly than planned, as unexpected research questions are resolved.

In preparation for the NSF Review scheduled April 9-11, 1996, LIGO has completed a “replanning” exercise, which involved developing a new schedule and cost estimate for the entire project. The new schedule uses the scheduling information we now have from our major facilities contractors. The replan for the detector includes new strategies to accommodate the switch to the Nd:YAG laser and to take into account the actual progress to date on the detector and the rate at which we have staffed the group. The new baseline has been used to prepare the performance measurement data in Section 5.1.

The Aspen Winter Conference on Gravitational Waves and their Detection was held during the week of January 14-20, 1996. This was a very successful meeting. In addition to the many interesting technical presentations, the first meeting of the LIGO Research Community and of its Executive Committee took place. An informal meeting between members of LIGO and VIRGO resulted in a proposed set of near term collaborative actions related to vacuum compatibility testing, optics, thermal noise, beam tube, baffles and data formatting. Minutes of the meeting have been circulated

2.0 Facilities and Vacuum System (WBS 1.1)

2.1 Vacuum Equipment (WBS 1.1.1)

Significant accomplishments during this quarter:

- Completed the BSC Vessel design.
- Placed the order for the prototype BSC material.
- Placed the purchase order for rough pumps, turbomolecular pumps.
- Placed the purchase order for 44 and 48 inch gate valves.
- Placed the purchase order for ion pumps.

In December 1995 the LIGO Vacuum Equipment subcontractor, Process Systems International (PSI) finalized the BSC chamber design and proceeded to initiate procurement of stainless steel head and shell material. Also in December, the specifications for the "Beam Tube Deliverables" were approved. This allowed PSI to place purchase orders for rough pumps, turbomolecular pumps, and the 44 and 48 inch gate valves. These items are required at the Washington site in August of 1996 in support of beam tube activities. The pump order was placed with Edwards Vacuum Products; the gate valve order with GNB. In January PSI completed negotiations with ion pump vendors and in February placed a purchase order for a prototype 2500 liter/second ion pump with Varian. Other procurement activities are taking place in preparation for the final design review in May. PSI will be placing purchase orders for purge air compressors, portable clean rooms, and some miscellaneous items. The intent is to obtain final vendor drawings and incorporate these into the final design package.

Work planned for the next quarter:

- Finalize interface details of the rough pumps and turbomolecular pumps with the beam tube and beam tube enclosure.
- Place purchase orders for the remaining items required for the prototype activities.
- Perform a preliminary "Hazard Analysis" prior to FDR.
- Complete the HAM chamber design.
- Submit the Final Design package and hold a Final Design Review in May of 1996.

No significant milestones have been missed. However, the purchase order placement for the ion pumps was delayed for roughly two weeks to allow for additional vendor negotiations. This should have no impact on other milestones. The scheduled dates for the Final Design Review are May 22 and 23, 1996.

2.2 Beam Tube (WBS 1.1.2)

Significant accomplishments during this quarter:

- Signed contract with CB&I Services, Inc. for the fabrication, installation, and acceptance testing of the beam tube modules at the two LIGO sites.
- Initiated development of the management plans and implementation plans for the new contract.
- Initiated design updates for beam tube features not covered or completed during the design and qualification test contract.
- Developed the mechanical design for the beam tube baffles and issued a Request For Quotation (RFQ) to secure quotes for procurement of the uncoated baffles.

The signing of the beam tube contract was accompanied with some concern regarding rumors of a hostile takeover of CB&I Industries, Inc. (parent of CB&I Services, Inc.), by a competitor in the industrial gas market, Praxair. Praxair did purchase CB&I within a month, and plans to sell CB&I's fabrication and construction business as a unit. This is not expected to affect CB&I's successful performance under this contract.

CB&I is completing negotiations for lease of the buildings to be used as the temporary fabrication facility near the Hanford site, and has developed an effective plan for fabrication. The size of the buildings will allow for all tube storage to be indoors, with just in time delivery at the installation site.

Contracts have been issued for long lead items, such as the custom spiral tube mill and the tube end expander and cutoff machine. The spiral mill will use laser controls for weld joint fitup and arc length, and a video monitor may be effective in full-time monitoring of full depth penetration of the inside weld. CB&I is developing a weld procedure for more effective penetration with a high current, 10K Hz pulsing frequency welding system. We will measure hydrogen outgassing of the weld for assurance that this has not been degraded. A full-circumference vacuum box design has been developed which will permit effective, efficient leak testing of girth weld seams between tube sections in the field.

The baffle mechanical design now includes tabs for spot welding the baffle in an expanded configuration to lock it into position. A wet application process of the glass frit, followed by a bake, has been qualified for the baffle coating, having acceptable optical and outgassing performances.

Work planned for the next quarter:

- Review and approve management plans and implementation plans for the new beam tube contract.
- Conduct a review of the design updates and determine whether the design is acceptable for proceeding with procurement and mobilization.
- Develop plan for LIGO monitoring of the beam tube contractor's and subcontractors' activities; mobilize initial field staff at the Hanford site.
- Install model of beam tube and beam tube enclosure at the Caltech campus.
- Receive quotations for uncoated baffles, select a supplier, and award the contract.
- Develop the specification for glass coating the baffles, issue RFQ for coating, receive quotations, select a supplier, and award the contract.

2.3 Beam Tube Enclosure (WBS 1.1.3)

Significant accomplishments during this quarter:

- Signed contract with ACME Material and Construction Company for the site work and precast fabrication of the enclosure for the Hanford site.
- Initiated the construction work on the beam tube enclosure at the Hanford site.
- Started the development of the beam tube installation bid package for the Hanford site.

The Invitation for Bid (IFB) for the Sitework and Precast Fabrication of the enclosure for the Hanford site was sent to 34 potential bidders on November 22, 1995. Thirteen bids were received on the public bid opening day, January 4, 1996. All thirteen bids were responsive and responsible. The lowest bidder was ACME Material and Construction Company from Richland WA. ACME's bid was within the LIGO budget for the scope of the bid. After obtaining NSF approval, ACME was awarded the contract and the Notice to Proceed was issued on January 25, 1996. The contractor has mobilized and initiated the construction work. Construction of the beam tube enclosure is proceeding on schedule at the Hanford site.

Parsons, the A-E contractor, is in process of developing the beam tube enclosure installation bid package for the Hanford site. The Parsons Construction Manager has moved to the site to oversee the construction activities.

Work planned for the next quarter:

- Complete the beam tube enclosure installation bid package for the Hanford site.
- Initiate the bid process for the beam tube enclosure installation for the Hanford site.
- Complete the site work and precast fabrication of the enclosure for the Livingston site.

2.4 Civil Construction (WBS 1.1.4)

Significant accomplishments during this quarter:

- Developed the detail design package for the facility (buildings) for the Hanford site.
- Conducted a series of reviews of the detailed design for various areas of the facility.
- Signed a contract with Public Utility District for providing electric power to the Hanford site.
- Signed a contract with Westinghouse Hanford Company for providing the telecommunication services to the Hanford site.
- Signed a contract with Stranco Inc. for construction of rough-grading and drainage work for the Livingston site.

The Parsons has continued to work on the development of the detailed design for the Hanford site. A review of Parsons' performance indicates that the design team is slightly behind schedule in the completion of the specifications and the production of design details for the corner station. However, they are slightly ahead of schedule with activities associated with the rework of the mid/end stations and the initiation of design for the Hanford three Interferometers alternate design package.

A series of reviews of the detailed design for various areas of the facility have been conducted. The purpose of these activities are to identify any concerns regrading the design approach and to agree upon modifications, as well as to resolve any interface issues effectively and efficiently. This will help minimize comments during the Final Design Review and thereby help accelerate the project schedule. The Final Design Review is scheduled for April 25, 1996.

Hanford Site. The Public Utility District (PUD) was awarded the contract for providing electric power to the Hanford site. PUD has mobilized at the site and started installing the 13.8 KV underground power cables from 400 Area to the LIGO site. The Westinghouse Hanford Company was contracted for the installation of a 50 pair telephone cable and a 12 fiber single mode fiber optics cable from the 400 Area to the construction site.Underground telephone wire conduits have been installed.

Livingston Site.The rough-grading and drainage work at the site started by Stranco Inc., at the beginning of this period. Parsons' construction manager has been assigned to the site. The construction of drainage culverts have been completed. The construction of the berm is behind schedule due inclement weather. However, Stranco has added additional equipment and manpower in an attempt to recover some lost schedule days.

Work planned for the next quarter:

- Complete the detailed design package for the facility (buildings) at the Hanford site.
- Perform the final design review and approval process for facility at the Hanford site.
- Prepare the bid package for the facility (buildings) for the Hanford site.
- Initiate the bid process for the facility (buildings) for the Hanford site.
- Develop the detailed design package for the facility (buildings) for the Livingston site.

3.0 Detector (WBS 1.2)

Detector activities are defined and described in the Detector Implementation Plan (LIGO-M940005-C-D), which is incorporated into the Project Management Baseline. The accomplishments and work planned which is outlined below are consistent with the Implementation Plan.

Detector activities are organized according to the LIGO WBS as follows:

- WBS 1.2.1 Interferometer (IFO) System, which is organized into subsystems:
  - Seismic Isolation (SEI)
  - Suspension Design (SUS)
  - Prestabilized Laser (PSL)
  - Input/Output Optics (IOO)
  - Core Optics Components (COC)
  - Core Optics Support (COS)
  - Alignment Sensing/Control (ASC)
  - Length Sensing/Control (LSC)
- WBS 1.2.1.9 Detector System Engineering/Integration (SYS)
- WBS 1.2.2 Control and Data Systems (CDS)
- WBS 1.2.3 Physical Environment Monitor (PEM) System
- WBS 1.2.4 Support Equipment.

Detector activities started in December 1994, and made significant progress in 1995. A re-baselining was performed during the first quarter of 1996 to account for design changes (e.g., switch in laser type) and organization changes, and to reflect our improved knowledge of the problems. The plans given below reflect that new baseline.

Four task groups have been formed: Lasers and Optics (working on PSL, IOO, COC, and COS subsystems); Suspensions and Isolation (including the SUS and SEI subsystems); Interferometer Sensing and Control (including LSC and ASC subsystems); and Control and Data Systems (the CDS subsystem). While we continue report progress separately for R&D activities and Detector activities, the task groups enumerated above include the relevant R&D (most laboratory activities, exploratory modeling) with the objective of concentrating the activity on a given domain in a tightly-knit effort. In addition, the Detector Site Implementation and Operations task group collects activities focussed on these topics and also the activities in the 40m interferometer lab, which is a primary tool for tests of operations and integration for the Detector group.

There were no activities planned during 1996 first quarter for WBS 1.2.3 and 1.2.4.

3.1 Interferometer (IFO) Activities (WBS 1.2.1)

Significant accomplishments during this quarter:

- The requirements, interfaces, and the conceptual design of the Core Optics Components subsystem were documented in a Design Requirements Document (DRD), and successfully reviewed. This allowed the Preliminary Design phase to commence.
- A Request for Proposal for Nd:YAG lasers was sent to six prospective bidders.
- There has been significant activity in the Core Optics Pathfinder program. Test masses have been polished and measured, there has been progress in the uniformity of coating, and a contract has been placed with NIST for independent metrology.

Seismic Isolation (SEI). HYTEK, an independent subcontractor, has been engaged to refine the passive seismic isolation design. The goals are to improve the performance (by reducing the cutoff frequency) and to reduce the weight of the system (simplifying the support structure design and reducing costs). A finite element model of the present system has been completed, and favorably compared against measurements. Alternative lossy springs, either using different forms for the elastomer or using a combination of metal and elastomers, are now under study.

Suspension Design (SUS). The Preliminary Design of the subsystem has continued, with a Preliminary Design Review planned for early in the second quarter of 1996 and tests of a small-scale suspension in the 40m interferometer on the same time scale. Measurements of the Q of Pathfinder (full-size) test masses are underway to refine the suspension design details.

Prestabilized Laser (PSL). A plan for the development of Nd:YAG lasers suitable for LIGO has been developed and put into motion. A Request for Proposal has been sent to prospective bidders, with visits to the firms to explore approaches in technical detail. Several medium-power Nd:YAG lasers have been ordered and received and programs to convert the control systems previously developed for Argon lasers started; to the maximum extent, the well-developed system for Argon will be adapted to the Nd:YAG. A laboratory test of the Argon PSL subsystem performance was completed, providing information concerning the functioning of the PSL and its control systems under conditions expected in the LIGO implementation. It is now installed in the 40m interferometer as an integration and operations test.

Input/Output Optics (IOO). Due to the change in laser wavelength, the IOO subsystem development has been pushed forward in time (without impacting any higher-level activities); this allows the parameters of the input and output of the system to be determined by the PSL and COC subsystems, which is the correct hierarchical approach. IOO design requirements and conceptual design are now scheduled for review in the third quarter of 1996.

Core Optics Components (COC). The focus of COC work has been in the area of the full size LIGO optics “pathfinder” effort. A metrology program to verify the mirror surface quality has been developed and a vendor (NIST) selected. The ground and polished Pathfinder optics will be delivered to the metrology vendor in mid-March. Collaborative interaction with the coating vendor (REO) has led to improvements in the uniformity of the coatings, with complementary measurements performed by REO and LIGO. The Design Requirements Review of the COC took place in late February, after a strong and very successful effort in modeling and design, kicking off the Preliminary Design phase for this subsystem.

Alignment Sensing/Control (ASC). Progress has been made in the understanding of the Wavefront sensing system through the joint R&D-Detector modeling effort using the Modal Decomposition model. With this, better estimates of the maximum angles that can be sensed, and the influence of misalignment on the length control system, have been achieved. The Preliminary Design of the Optical Lever has progressed, with selection of specific components and layouts for the prototype effort.

Length Sensing/Control (LSC). A complete small-signal length control system was finished in this quarter, with seismic and shot noise correctly incorporated. The propagation of frequency and intensity noise through the interferometer was worked in detail, aiding both the model above as well as the development of requirements for the PSL subsystem.

There was continued work on the model for acquisition of length and angle lock from an initial start-up state. Documentation of the work to date was completed, and plans for the work for FY 1996 were made and started.

System Engineering/Integration (SYS). The Systems Engineering Design Requirements Document (DRR) was started in earnest, with the flowdown for the primary limiting noise sources (Seismic, Thermal, Shot) delineated. The DRRs in COC and CDS, and preparations for upcoming DRRs in LSC and ASC, have been used to resolve systems-level questions of interfaces and flowdown. A DRR for the Detector System is planned for the second quarter of 1995.

Work planned for the next quarter:

- Seismic Isolation (SEI). Complete and document the design requirements for the BSC and HAM seismic isolation with a formal review (Design Requirements Review, DRR); start the preliminary design. Continue the trade study.
- Suspension Design (SUS). Complete and document the preliminary design phase and review it in a preliminary design review. Start the final design and prototype phases of the Large and Small Optics Suspensions (LOS and SOS).
- Prestabilized Laser (PSL). Select vendors for the Phase A SSPSL (Solid-State PSL) effort. Stabilize the master oscillator Nd:YAG, and convert the 12m mode cleaner to 1064 nm optics.
- Input/Output Optics (IOO). As noted above, activity on the IOO is waiting definition of the SSPSL and Core optics. Work on an as-needed basis to support interfaces with other subsystems.
- Core Optics Components (COC). Continue the preliminary design phase. Guide Pathfinder coating and metrology efforts.
- Core Optics Support (COS). Complete and document the design requirements for the optical and mechanical design for the support of core optics, with a formal review (DRR). Start the preliminary design.
- Alignment Sensing/Control (ASC). Continue with the conceptual design, working toward the ASC DRR II planned for late June. Continue with the optical and mechanical design, start prototype fabrication and testing for the Optical Lever subsystem.

- Length Sensing/Control (LSC). Complete and document the design requirements for the length sensing and control system with a formal review (DRR). Start the preliminary design.
- Systems Engineering (SYS). Complete and document the design requirements for the detector system with a formal review (DRR). Coordinate designs among Detector elements and with LIGO Facilities/Equipment and Systems Engineering and Integration Groups.

3.2 Control and Data Systems (CDS) Activities (WBS 1.2.2)

Significant accomplishments during the first quarter:

- The requirements, interfaces, and the conceptual design of the Control and Monitoring, Software Design, and Vacuum Cabling Requirements were documented in Design Requirements Documents (DRD), and successfully reviewed.

Requirements and Conceptual Design. The requirements for the 'global' CDS system, forming the backbone of communication in hardware and software, were refined and brought to review in this last quarter. Some options are left open to account for the evolution of the technology, but the basic system Conceptual Design is established and can now continue into the Preliminary Design phase. The Software Development plan and the in-Vacuum cabling were also reviewed, being key elements in the overall CDS system.

Prototyping and R&D support. CDS has developed prototype electronic and software systems for several efforts in the last quarter. Among them are a Beam Pointing Control Unit for steering beams, a demodulator board for the alignment Wavefront Sensing system, the skeleton of a data acquisition program for the Wavefront Sensing demonstration, and support to the installation of the Argon PSL in the 40m interferometer. The test of a prototype suspension in the 40m has also been supported with control electronics and wiring. These activities give the CDS a jump-start on the later formal design of the LIGO Detector subsystems.

Work planned for the second quarter:

- Interferometer Controls. Complete electronics fabrication for the prototype suspensions; document the requirements and conceptual design for the LIGO suspension electronics; support R&D efforts on wavefront sensing.
- CDS integration and global systems. Continue preliminary designs of timing, networking, and support systems.
- Data acquisition. Continue with requirements and conceptual design.
- Vacuum system controls. Develop requirements and conceptual design.
- Remote diagnostics. Start to develop requirements and conceptual design.

3.3 Physical Environment Monitoring (WBS 1.2.3)

Development of requirements and conceptual design for the PEM started this quarter, and will lead to a DRR in the second quarter.

3.4 Support Equipment (WBS 1.2.4)

The definition of the required support Equipment started this quarter, will continue through the second quarter, and lead to a DRR in the third quarter.

4.0 Research and Development (WBS 1.3)

Significant accomplishments during this quarter:

- The first step of the Phase Noise Research, a non-recycled Michelson, was successfully completed and documented. The installation was prepared for the next phase (a recycled Michelson interferometer).
- Work has continued on the characterization of the recombined 40m configuration
- The prototype Argon Pre-Stabilized Laser, with a LIGO control system, was installed in the 40m lab for systems tests.

The primary aim of the LIGO R&D program is to understand the noise sources which affect interferometer gravitational wave detectors and to develop means to control them. We have instituted a wide variety of research efforts which include experimental investigations using interferometers with suspended mirrors, development of new interferometer techniques starting with tabletop interferometers, and R&D in vacuum science, materials properties, seismic isolation, and optics. At the current stage of the project, the majority of these investigations are directed at achieving the initial LIGO interferometer sensitivity goals. However, an important goal of the R&D program is to lay the groundwork for more advanced interferometers by developing a fundamental understanding of noise mechanisms which can serve as a starting point for advanced developments as soon as the initial LIGO performance is assured.

A second goal of the R&D program is to develop technology needed for the operation of large interferometers by building and testing LIGO-scale models of interferometer subsystems. While many of the aspects of the full-scale LIGO interferometers cannot be demonstrated on a laboratory scale it is possible to develop subsystem requirements and evaluate full-scale (or near full-scale) subsystems against those requirements. The results of these development activities are interpreted through an on-going program of modeling, including optical, control, and system modeling. Highlights of this quarter's activities are given below.

4.1 40 m Interferometer Investigations

- The 40 m interferometer research on optical recombination continued.
- The prototype Argon Pre-Stabilized Laser, CDS electronics and control system, was installed.

Optical Recombination. The major effort on the 40 m was research on the recombined non-recycled Fabry-Perot Michelson configuration. This is the first step toward bringing the 40 m optical configuration to that planned for LIGO, and will permit higher power operation. Effort has focused on a complete characterization of the operation of the interferometer in its new configuration and on developing an understanding of the sources of noise. Detailed studies of the shot noise (agreement with predictions) and measurements of the matrix of the interferometer's optical response to displacements have continued, with some as-yet unexplained excess noise localized to the beamsplitter sensing-servo system.

Preparations for Recycling. The next phase of the 40m research will be to complete the conversion to the LIGO optical configuration by adding power recycling to the recombined interferometer. The critical optical and electronic hardware for the addition of a recycling mirror has been designed and is in construction. In particular, the local oscillator used to drive the synchronous modulation-demodulation systems has been designed to be compatible with LIGO needs, and so will act as a prototype test of that CDS system.

Integration of LIGO Argon PSL. The 40m interferometer carries the role of integration testbed for interferometer subsystems. The Argon Pre-Stabilized Laser (PSL), completed and characterized in 1995, has been installed on the 40m to allow training of personnel with the user interface, as a shake-down of the control electronics, and to improve the reliability of the present laser source. Operation with this new laser was resumed just one week after physical installation, leading to a short down-time of the 40m interferometer.

Development of Data Acquisition and Analysis Techniques. An automated system for recording data tapes on off-hours (nights) has been put in place, and routines developed for handling the data transfer and translation.

4.2 Suspended-Mirror Mode Cleaner Development

A 12 meter long mode cleaner using separately suspended mirrors was developed in ‘94-’95 and was characterized and reviewed in 1995. Some final experiments on the transmission of phase-modulated light were performed in this quarter. With the change to a Nd:YAG laser system, a new need has arisen for a precision frequency reference for the development of frequency-stabilization techniques on the new laser source, and the mode cleaner is ideal for this role. In addition, the exhaustive independent characterization of the mode cleaner and the present research on the 40m (for which a suspended mode cleaner is not needed) have reduced the urgency of a combined test. Thus, the move of the suspended mode cleaner to the 40m interferometer has been delayed and the conversion of the optics to 1064 nm has been started in this quarter.

4.3 Suspension Development

An effort to install a new design for test mass suspensions for the 40 m interferometer is underway. This new design, which was reviewed internally mid-’95, incorporates the key elements planned for the LIGO detector suspensions. Fabrication of a prototype of this suspension is nearly complete, and preparations for installation in the 40 m interferometer have been started. Once installed, its performance will be characterized and feedback will be given to the LIGO detector suspension design.

4.4 Phase Noise Research

To attain the high sensitivity to gravitational wave strains in the frequency range of interest, the LIGO interferometers must make a very precise measurement of the optical phase of the light ($\sim 10^{-10}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$). This research effort is designed to develop and demonstrate the technology for the shot-noise limited interferometer operation at initial LIGO power levels to achieve the required phase sensitivity using the 5-m facility at MIT, configured as a Phase Noise Interferometer (PNI).

Non-recycled Michelson research. The first phase of the research with the PNI employed a Michelson without recycling, with the objective of getting the newly-commissioned 5m system shaken down. This phase was finished in the first quarter 96, with some incremental improvements due to several changes:

- The Input Optics were re-worked to improve the mechanical and acoustic coupling to beam motion. This eliminated several peaks in the spectrum, which were due to a coupling between beam motion and interferometer phase induced by the intentional asymmetry used for the phase detection system.
- Some additional mirrors and beam dumps were installed to aid in diagnostic tests.
- A second Barry Controls, Inc. active isolation system was installed in the vacuum tank planned for the recycling mirror. This reduced the RMS motion of the beam steering components in that tank, and thus reduced the low-frequency noise due to upconversion of interference from scattered light.
- Improvements in the efficiency of the input optics allowed a somewhat higher input light level, leading to a better shot-noise limited sensitivity at high frequencies.

The spectrum before (top curve) and after these changes (bottom curve) is shown in Figure 2. With these improvements, the objectives for the initial phase were achieved.

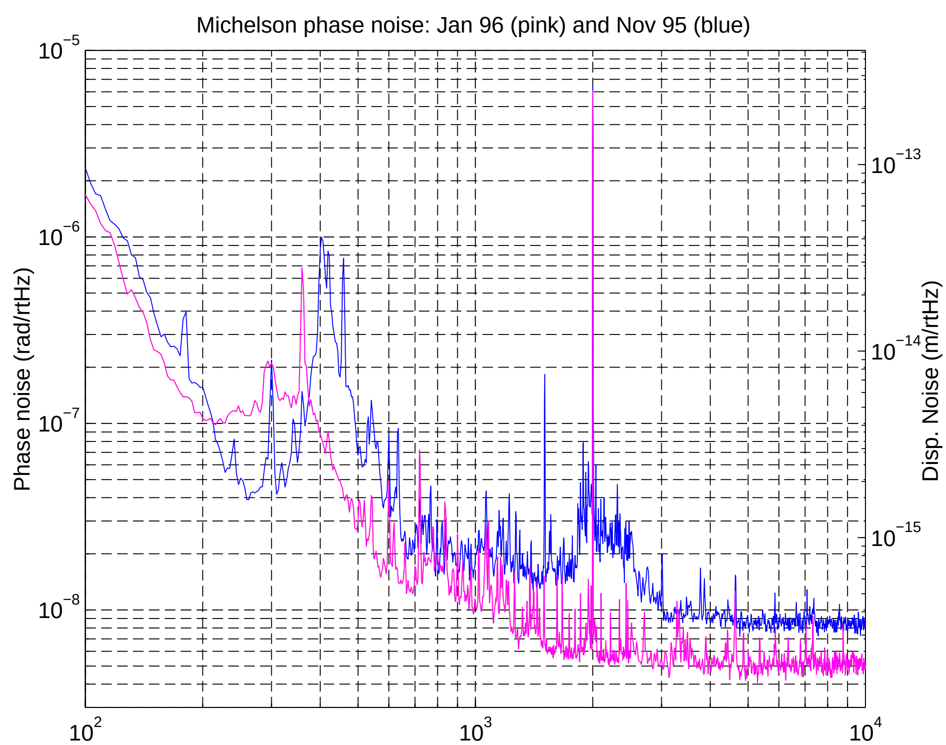


FIGURE 2. Phase Noise Interferometer spectrum, showing improvements due to Input Optics modifications

Recycled Michelson. The modifications for recycling were made this quarter. This involved preparation of a suspension controller, attaching control magnets and sensor vanes to the recycling mirror, and vacuum cleaning of all parts; and development of the length control system including the recycling mirror degree-of-freedom. The recycling mirror was installed, and some adjustments to the seismic isolation system (to account for the changed load and settling of the passive stack) made. At the close of the quarter, initial tests with the complete recycled Michelson were starting.

4.5 Interferometer Alignment Investigations

This research effort is directed toward providing the operational system of alignment for the LIGO initial interferometer. A test of the target wavefront sensing system is underway on the MIT Fixed Mass Interferometer (FMI), where the discriminants at all interferometer ports will be measured and compared with a semi-analytical model.

The construction of the experiment was finished in the last quarter of ‘95. In this quarter, the length control system has been shaken down, with some changes in the servo compensator identified and implemented. The efforts to date have been with incremental parts of the interferometer (recycled simple Michelson, each arm cavity independently, non-recycled Fabry-Perot Michelson). The complete system is being exercised as the quarter closes.

Construction of the Wavefront Sensors and demodulators has started this quarter; printed circuit boards have been fabricated and parts are in-house.

R&D Work planned for the next quarter:

- Completion of the 40m non-recycled recombination research
- Installation of one new prototype suspension in 40m interferometer
- Shakedown and measurements of the Recycled Phase Noise Interferometer; installation of a wavefront sensor for alignment diagnostics and for active control if indicated
- Shakedown of the length control system on the Alignment Fixed Mass Interferometer; fabrication, testing, and installation of the wavefront sensors; completion of the programming for the real-time data acquisition system for this experiment.

5.0 Project Office

5.1 Project Management (WBS 1.4.1)

Staffing. The LIGO staff currently consists of 83 equivalent employees. Of these, eleven are contract employees. During the quarter LIGO added the following personnel:

TABLE 1. New LIGO Employees (December 1995 - February 1996)

Dave Beckett	Document Control Specialist, Project Controls, CIT
Tina Lowenthal	Subcontracts Administrator, Project Controls Group, CIT
Paul Russell	Electronics Technician, Detector Group, CIT
Ching Shih	Computer Support, General Computing, CIT

Sixty-eight and one-half LIGO staff are located at CIT including four graduate students. Fourteen and one-half are located at MIT including five graduate students. In addition there are four undergraduate students working part-time at Caltech.

Schedule Status. As of February 1996, all significant milestones can be achieved. The milestone for Initiating Slab Construction in Washington slipped from October 1995 to February 1996 to combine the Slab Construction effort, Finish Grading, and construction of the Tube Enclosure. This milestone has been completed. The contract for Beam Tube Fabrication and Installation was placed with CB&I in December 1995.

The Performance Measurement Baseline (PMB) including the Integrated Project Schedule (IPS) and the time phased budget have been adjusted 1) to reflect the major contracts for the vacuum equipment and the beam tube that were recently definitized, 2) to implement the conversion to the Nd:YAG Laser, 3) to reflect the new organization of the Detector and R&D Groups, and 4) to incorporate the experience gained over the past year which will in turn be reflected in the updated cost estimate to be presented at the NSF Management Review scheduled in April 1996. The revised baseline is in place and was used for reporting progress as of the end of February.

The status of the significant milestones identified in the Project Management Plan for the LIGO Facilities is summarized in Table 2. The milestone dates projected in this table have been updated

TABLE 2. Status of Significant Facility Milestones

Milestone Description	Project Management Plan Date		Projected Completion Date	
	Washington	Louisiana	Washington	Louisiana
Initiate Site Development	03/94	08/95	Complete	Complete
Beam Tube Final Design Review	04/94		Complete	
Select A/E Contractor	11/94		Complete	
Complete Beam Tube Qualification Test	02/95		Complete	
Select Vacuum Equipment Contractor	03/95		Complete	

TABLE 2. Status of Significant Facility Milestones

Milestone Description	Project Management Plan Date		Projected Completion Date	
	Washington	Louisiana	Washington	Louisiana
Complete Performance Measurement Baseline	04/95		Complete	
Initiate Beam Tube Fabrication	10/95		12/95 Complete	
Initiate Slab Construction	10/95	01/97	02/96 Complete	
Initiate Building Construction	06/96	01/97		
Accept Tube and Cover	03/98	09/98		03/99
Joint Occupancy	09/97	03/98		
Beneficial Occupancy (Accept Buildings)	03/98	09/98		
Accept Vacuum Equipment	03/98	09/98		
Initiate Facility Shakedown	03/98	09/98		03/99

to reflect delivery dates negotiated with vacuum equipment, beam tube, and beam tube enclosure subcontractors as well as the efforts to integrate these schedules with the plans for constructing the buildings. This schedule will be presented in detail during the NSF review scheduled in April. Table 3 is the status for the significant milestones for the Detector. This schedule has been revised to reflect the change to the Nd:YAG laser.

TABLE 3. Status of Significant Detector Milestones

Milestone Description	Project Management Plan Date		Projected Completion Date	
	Washington	Louisiana	Washington	Louisiana
BSC/TMC Seismic Isolation Final Design Review	11/96		7/97	
Core Optics Support Final Design Review	11/96		4/97	
HAM Seismic Isolation Final Design Review	12/96		7/97	
Core Optics Components Final Design Review	01/97		7/97	
Detector System Preliminary Design Review	01/97		12/97	
I/O Optics Final Design Review	06/97		04/98	
Prestabilized Laser Final Design Review	08/97		08/98	
CDS Networking Systems Ready for Installation	09/97			

TABLE 3. Status of Significant Detector Milestones

Milestone Description	Project Management Plan Date		Projected Completion Date	
	Washington	Louisiana	Washington	Louisiana
Alignment Final Design Review	11/97		4/98	
CDS DAQ Final Design Review	04/98			
Length Sensing/Control Final Design Review	05/98			
Physical Environment Monitor Final Design Review	06/98			
Initiate Interferometer Installation	07/98	01/99		
Begin Coincidence Tests	07/00		12/00	

Financial Status Report. Table 4 on page 19 summarizes costs for the first quarter and commitments as of the end of February 1996.

Performance Status. Table 5 on page 20 is a Cost Schedule Status Report (CSSR) for the end of February. 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.

In addition Figure 3 on page 21 shows the same data graphically as a function of time. The revised baseline is in place and was used for reporting progress as of the end of February.

Facility Design and Construction (WBS 1.1.4) is behind schedule. The Rough Grading Contract in Louisiana was scheduled to begin in August, while the notice to proceed was issued early in November. In addition, recent weather conditions in Louisiana have further delayed the contractor. However, ‘work-around’ schedules have been developed and are reflected in the new baseline.

The primary contributors to the R&D schedule variance include the effort on Recombination/ Recycling, the Phase Noise Research, and the Interferometer Alignment Investigations.

The Project Office (WBS 1.4) is level-of-effort and, therefore, shows no schedule variance. However, there is an unfavorable cost variance for unplanned management personnel and computer support. Change Board actions have been initiated to allocate the needed resources

Change Control and Contingency Allocation. A The Change Requests in Table 6 on page 22 have been approved. $3,825K has been <u>allocated from</u> the contingency pool.

TABLE 4. Actual Costs and Commitments through February 1996

WBS	Description	Allocation of Costs through Nov 1994	LFY 1995 (Dec. 1 - Nov. 30)	December 1995	January 1996	February 1996	Cumulative Costs	Open Commitments	Total Costs Plus Commitments
1.1.1	Vacuum Equipment	$487,273	$3,593,563	$2,775,108	$406,653	$60,104	$7,322,701	$33,473,767	$40,796,468
1.1.2	Beam Tubes	$1,339,077	$1,396,960	$52,858	$1,533,855	$32,807	$4,355,587	$38,195,883	$42,551,470
1.1.3	Beam Tube Enclosures	$8,149	$459,408	$9,712	$6,217	$8,806	$492,293	$7,615,257	$8,107,550
1.1.4	Facility Design and Construction	$3,238,405	$3,438,684	$544,111	$343,580	$477,532	$8,042,313	$6,150,625	$14,192,938
1.2	Detector	--	$2,429,521	$172,425	$218,599	$398,028	$3,218,572	$895,302	$4,113,874
1.3	R&D	$10,407,161	$2,914,107	$105,788	$115,733	$302,550	$13,845,339	$2,220,883	$16,066,222
1.4	Project Office	$4,716,180	$5,435,300	$484,504	$396,503	$473,529	$11,506,016	$1,299,390	$12,805,406
	Unassigned[a]	$1,670	$77,160	$5,432	($8,215)	($120,922)	($44,845)	$82,739	$37,894
1.0	Total Project Costs	$20,197,916	$19,744,702	$4,149,939	$3,012,957	$1,632,434	$48,737,976	$89,933,846	$138,671,822
Cumulative Project Costs		$20,197,916	$39,942,647	$44,092,587	$47,105,543	$48,737,977			
Open Commitments		$3,531,398	$44,992,602	$44,350,451	$82,584,663	$89,933,846			
Costs Plus Commit-ments		$23,729,314	$84,935,250	$88,443,038	$129,690,206	$138,671,822			
NSF Funding		$47,088,935	$136,088,935	$136,088,935	$149,888,935	$149,888,935			

a. These costs have not been assigned to any LIGO account by CIT Finance but are continually reviewed to assure proper allocation.

TABLE 5. Cost Schedule Status Report (CSSR) End of February 1996

COBRA (R) WST Corp. — COST/SCHEDULE STATUS REPORT — Page 1

CONTRACTOR: Caltech LOCATION: Pasadena, CA	CONTRACT TYPE/NO: PHY-9210038	PROJECT NAME/NO: LIGO Master Merged PMB - WBS 1.0	REPORT PERIOD: 31JAN96-29FEB96	SIGNATURE: TITLE / DATE:

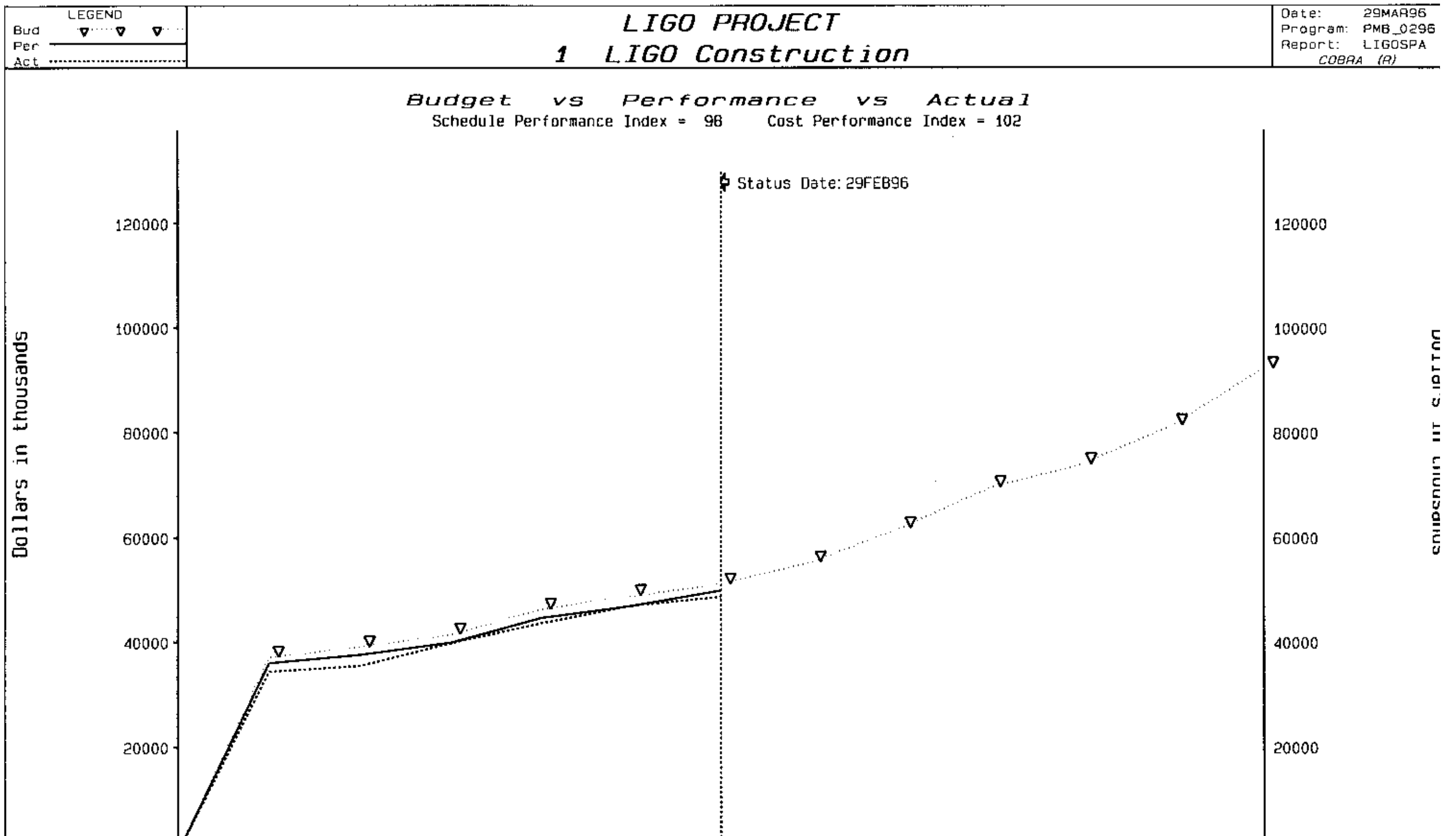
CONTRACT DATA

ORIGINAL CONTRACT TARGET COST	NEGOTIATED CONTRACT CHANGES	CURRENT TARGET COST	ESTIMATED COST OF AUTHORIZED UNPRICED WORK	CONTRACT BUDGET BASELINE
	292,100,000	292,100,000		292,100,000

PERFORMANCE DATA

	CUMULATIVE TO DATE					AT COMPLETION		
MPR Level	BUDGETED COST		(3) ACTUAL COST WORK PERFORMED	VARIANCE		(6) BUDGETED	(7) ESTIMATE AT COMPLETE	(8) VARIANCE (6-7)
	(1) WORK SCHEDULED	(2) WORK PERFORMED		(4) SCHEDULE (2-1)	(5) COST (2-3)			
1.1.1 : Vacuum Equipment	7925	7935	7323	10	612	42210	42210	0
1.1.2 : Beam Tubes	4334	4326	4356	(7)	(29)	48653	48653	0
1.1.3 : Beam Tube Enclosur	608	528	492	(80)	36	19687	19687	0
1.1.4 : Facility Design &	9602	9390	8042	(211)	1348	49100	49100	0
1.2 : Detector	2607	2759	3219	152	(460)	50946	51714	(769)
1.3 : Research & Developme	15346	14298	13840	(1048)	458	23490	23490	0
1.4 : Project Office	10725	10725	11506	0	(781)	22791	22791	0
SUBTOTAL	51147	49962	48777	(1185)	1184	256877	257646	(769)
CONTINGENCY						0	34452	(34452)
MANAGEMENT RESERVE						35221	0	35221
TOTAL	51147	49962	48777	(1185)	1184	292098	292098	0

29MAR96 11:29:45 — Thousands of $ — COBRA (R) by WST Corp.



	SEP95	OCT95	NOV95	DEC95	JAN96	FEB96	MAR96	APR96	MAY96	JUN96	JUL96	AUG96	SCALE
Planned Budget	37, 167	39, 115	41, 556	46, 342	49, 016	51, 147	55, 402	61, 926	69, 727	74, 049	81, 486	92, 337	K$
Performance	*36, 056*	*37, 640*	*40, 003*	*44, 706*	*47, 046*	*49, 962*							*K$*
Actuals	34, 402	35, 509	39, 863	43, 730	47, 029	48, 777							K$
Schedule Variance	-1, 111	-1, 475	-1, 553	-1, 636	-1, 970	-1, 185							K$
Cost Variance	1, 654	2, 131	140	976	17	1, 185							K$

Schedule Variance = Perf-Budg   Cost Variance = Perf-Actual   Schedule Performance Index = Perf/Budg   Cost Performance Index = Perf/Actual

FIGURE 3. LIGO Project Performance Measurement Status as of the end of February 1996

TABLE 6. Approved Change Requests

Change Request No.	Description	Date Approved	Amount
CR-950027	1.1.4 - Observation Deck above LVEA (Design Package)	December 1995	$15,731
CR-950028	1.1.4 - Increase LVEA area at Hanford to accommodate three interferometers (Design Package)	December 1995	$150,067
CR-960002	1.1.1 - Vacuum Equipment, WA Beam Manifold	January 1996	$200,557
CR-960003	1.1.1 - Vacuum Equipment, Corner Station Pipe Bridges	January 1996	
CR-960004	1.1.1 -Vacuum Equipment, Roughing Pump Fail-safe Valves	January 1996	
CR-960005	1.1.1 - Vacuum Equipment, Main Ion Pump Auxiliary Ports	January 1996	$9,854
CR-960006	1.1.2 - Beam Tube and Beam Tube Enclosure Model	February 1996	$40,600
CR-960007	1.2 - Detector, Increases Due to Conversion to Nd:YAG Laser	February 1996	$3,390,000
CR-960008	1.1.1 Vacuum Equipment - Gate Valve Weld Stubs	February 1996	$17,953

5.2 Support Services

Arrangements have been made with the Jet Propulsion Laboratory's (JPL) Office of Engineering and Mission Assurance (OEMA) to staff positions supporting quality assurance, reliability, product assurance, and ES&H.

Quality Assurance (QA). During this past quarter, LIGO QA Engineering has focused on supporting the Facilities Group in the preparation of contracts and new procurements packages. This QA support has also included a QA audit of the on-site geotechnic QA/QC support contractor at Livingston, La. and participation in meetings with Livingston community leaders.

LIGO QA participated in the civil construction Preliminary Design Review [PDR] and provided review comments for the PDR documents submitted to LIGO. Proposal evaluation support was also provided. The QA Engineer coordinated JPL technical support for a beam tube expansion joint QA acceptance test, arranged for JPL NDE technical consulting support for beam tube spiral weld inspection, and set up and coordinated discussions with JPL weld engineers to work reliability issues for the proposed beam tube baffle spot welding. This effort lead to a successful welding demonstration with baffle samples and the loan of a weld machine to support weld and assembly tooling design development.

LIGO QA supported discussions with CB&I personnel regarding their QA, Configuration, Fabrication and Installation plans for the Beam Tube effort. A visit was also conducted to the porcelain vendor with a JPL materials engineer to observe and become familiar with processes involved in coating and handling baffles.

QA planning discussions were initiated with the LIGO Detector Optics personnel for the Core Optics in-house, on-going, and future contracted efforts. The QA plan will include a matrix of issues, concerns and remedial tasks. The responsible person or agency and how the task will be documented will be identified.

Safety Office. Safety has reviewed the preliminary design for the buildings and associated site development that the LIGO Architect/Engineering contractor (Ralph M. Parsons Co.) accomplished. As the final design effort and preparation of the bid packages for the construction contracts continued, the LIGO Safety Office assured that requirements were included to prevent mishaps during site construction.

Safety also supported the achievement of significant milestones in other major elements of the LIGO facilities. A contract for the construction of the Beam Tubes was signed with Chicago Bridge and Iron (CB&I). CB&I is preparing for full production of the LIGO beam tubes and plans to begin installation by fall of this year. CB&I has provided a safety plan for review. They also have an outstanding method for controlling mishaps during the construction and installation phase by requiring the workers to develop the safety procedures thereby assuring that safety has top priority.

The contract for the final design, fabrication and installation of the vacuum system was signed with Process Systems International (PSI), and they have begun intensive design work. This design work is scheduled to be complete by summer and will be followed by fabrication of the hardware to be delivered to the sites. PSI is required as a part of the design work to perform a vacuum safety hazards analysis. This analysis has started and will be completed by next quarter.

The Laser Safety Program is in the signature phase and baseline eye checks are in progress. Training materials and plans have been reviewed and are in the final phase for laser training presentations during the next quarter. The primary hazard control will be the Safety/Standard Operating Procedure that will be defined and established by the laser operators with a review and acceptance by the LIGO Safety Steering Committee.

Preparations have begun to hold a safety review of the LIGO design this summer. The intent is to invite experts in potentially hazardous systems (i.e. vacuum systems) to help assure that major safety risks or unrecognized hazards have not been overlooked. Additional information will be provided in the next quarterly report.

6.0 Systems Engineering (WBS 1.4.3)

6.1 Integration (WBS 1.4.3.1)

Significant accomplishments during the first quarter:

Trade Studies and Analyses

- Determined the heat loads and power usage for VE and the Detector in the Operations Support Building (OSB), LVEA, VEA and Mechanical Rooms

Requirements Definition

- Defined the logistics relating to BT pump usage and availability
- Prepared the baffle science performance requirements document
- Resolved the LVEA/VEA slab thickness requirements
- Resolved the Facility Monitoring and Control System (FMCS) requirements

Meetings and Documentation

- Held a Quarterly Science and Integration Meeting
- Issued a draft Configuration Management Plan for internal review

Vacuum tube manifold and gate valve aperture requirements. SA quick study of the integration of the laser light baffling and the infrared shielding in the region around the short cryopumps in the mid- and end-stations (i.e. the locations where it is most difficult to baffle the laser light due to their proximity to the test masses) was performed. The "graphical study" looks at the approximate number of baffles required, their approximate locations and the approximate "view factors" of the "dark" (high emissivity) surface to the infrared shield

The recommendation from the study was to proceed with 44" gate valves and vacuum tube. Although this will increase the complexity of the integrated baffle-infrared shield design, there appear to be no significant problems.

Characterization and selection of the BT baffle material. LIGO has completed the specification for the Beam Tube baffles material and is now in the process of procuring baffles. This procurement is a two-step process: mechanical fabrication and surface treatment. This represents the culmination of a year-long trade and design study which was initiated when the decision was made to modify the simpler baseline design.

The baffle material selected is identical to that used in the Beam Tube: 304L stainless steel (unoxidized, roughened), approximately 1mm in thickness. The baffle form is similar to the VIRGO design: a cylindrical band approximately 15 cm wide which conforms to the inner diameter of the beam tube. To this band, a truncated conical section of material is welded. The conical section protrudes 9 cm radially into the beam tube aperture an makes a 35 degree angle with the band. The conical baffle is inclined away from the reflecting surface of the nearest test mass.

To mitigate diffraction effects, the inner edge of the conical section is randomly serrated. The conical section surface is roughened (bead blasted) and then glazed with a black glass frit formulation. The decision to use an enameling process followed an exhaustive evaluation of the vacuum and optical properties of the glazed enamel. The optical properties of the glazed material were studied for backscatter, reflectivity, and the potential for glint-producing features.

These optical and vacuum properties are adequate to meet the LIGO light scattering control requirements. We are now concentrating on process control of the glaze application to ensure that a quality product can be produced in the quantities required for LIGO.

Refined estimates of the BT bellows fatigue life. A revision to the ASME piping code (C. Becht, "B31.3 Appendix X Rules for Expansion Joints", Journal of Pressure Vessel Tech., volume 177, Aug 1995.), "supersedes" the EJMA standards, which have been used by Hyspan, Chicago Bridge and Iron's bellows supplier. In particular, the fatigue calculations of the EJMA were called into question and revised in the ASME code. Although the magnitude of the difference between the EJMA and ASME codes is large, the bottom line is that we have sufficient fatigue life. Concern regarding the variation in localized plastic deformation during forming has prompted the suggestion of additional quality assurance tests for the bellows. These tests would add considerable cost. An effort to evaluate the feasibility and advisability of such testing is planned.

Space Allocation for Vacuum Support Equipment in the Mid- and End-Stations. The preliminary design of the mid- and end-stations did not allow space for Vacuum Equipment in the Mechanical Room (space is provided in the corner station). The support equipment consists of an air compressor (for purge air and venting), backing pumps for the main turbo pumps, ion pump controllers and power supplies, etc. This issue was resolved by assembling the parties involved for discussions of alternative arrangements. Three arrangements were examined for suitability in meeting requirements, cost and impact to the design schedule. The selected configuration required the addition of a 18' x 20' room.

LIGO Global Site Alignment Requirements. LIGO is required to provide a means by which centerlines can be located at five (5) positions along each of the two arms. One of these points, the vertex, will be common to both arms. The alignment accuracies and precision required at these nine points has been established and documented.

Operations Support Building (OSB) Architectural Requirements. A set of architectural room layout requirements were proposed for the Operations Support Building (OSB), Mid Stations and End Stations. The requirements included flooring type, ceilings, electrical, plumbing, cooling and heating temperature requirements, fume hoods, floor drains, and lighting types. The requirements and facility layouts of the OSB, Mid Stations, and the End Stations from the Ralph M. Parsons design drawings were not complete. After meeting with each of LIGO technical groups, a set of requirements were collected from the Control and Data System (CDS), Detectors and Vacuum Equipment groups. The collected requirements were circulated for review and comments before being incorporated in the final architectural requirements. The requirements were provided to Ralph M. Parsons to be incorporated into the architectural design.

Major Interface Definition and Control Documents. Three Interface Control Documents

(ICD) were issued in this quarter:

- Vacuum Equipment (VE) - Civil Construction (CC) ICD
- Beam Tube (BT) - Civil Construction (CC) ICD
- Beam Tube (BT) - Vacuum Equipment (VE) ICD

The BT-CC Interface Control Document (ICD) has been released as a signed document under configuration control, with a few items to be resolved. The BT-VE and VE-CC ICDs have been released (after two internal review cycles) for review, comment, and input by PSI, CB&I and Parsons. Completion of the balance of the ICDs (Detector-CC, Detector-BT and Detector-VE) is an on-going activity with high priority.

EMI/EMC Plan Development. The EMI/EMC plan will define an approach to grounding, shielding, bonding and electrical design for the program by calling out relevant design standards and guidelines and defining the basic approach for distributing power and grounds. The EMI/EMC plan will also scope design and test activities. Although we are using the DoD EMC process as a guide, we are tailoring it to suit LIGO needs and ensuring that only essential analyses and tests are performed.

Reliability Plan Development. LIGO Systems Engineering is also developing a Reliability Plan. This effort will be performed by the Jet Propulsion Laboratory Reliability Group. To begin the LIGO Science Requirements Document are being revised as the source of reliability requirements (from a facilities availability perspective). Once the reliability requirements are defined, a plan will be written showing how the reliability of the LIGO subsystems will be designed, assessed, and verified to meet LIGO top level requirements. As part of this effort, LIGO will develop a fault tree analysis, needed to identify failure modes and risks. These data are also required to support a parallel effort to prepare a LIGO safety plan. Ultimately a failure modes and effects analysis (FMEA/FMECA) will be developed. From this analysis, sensitivity of overall system availability to the reliability of various LIGO subsystems will be quantified. The results of this analysis will be used to develop spares strategies, maintenance strategies, and to perform trade studies for reliability improvement.

Vacuum Compatibility, Cleaning Methods and Procedures for LIGO Instrumentation Materials Specification Document. The potential for outgassing and contamination must be considered and factored into every aspect of interferometer construction, from design and choice of materials through preparation, bakeout, storage and installation as well as during subsequent handling or adjustment. To assure a uniform application of the criteria, a list of vacuum compatibility, cleaning methods and procedures for LIGO instrumentation materials were collected in a draft specification. All instrumentation for installation inside LIGO vacuum vessels or tubes are to conform to this policy.

Work planned for the next quarter:

- Complete the Interface Control Documents
- Assess the merit of Beam Tube bellows QA tests based upon permanent deflection variation
- Issue the Reliability Plan

- Issue the EMI/EMC Plan
- Issue the Configuration Management Plan
- Issue the System Design Requirements Document
- Issue a (first draft) Detector Integration Plan
- Draft an outline of the Internal Interface Control Document for the Detector subsystems
- Prepare the System Design Requirements Document for the Detector system

6.2 Modeling and Analysis (WBS 1.4.3.3)

Significant accomplishments during this quarter:

- Compared and exchanged models with the VIRGO Group.

AVS modeling environment code maintenance & development. In LIGO, two packages, AVS/Express - developer edition, and the end-user version called “AVS/Express - the Visualization Edition” will be used. Two licenses have already been upgraded to Express. We have installed and are beginning to work with these upgraded packages to identify any potential incompatibilities with the previous AVS code releases

Thermal noise modeling software. An existing fortran program for calculating the thermal noise associated with the internal modes of the test mass was rewritten in C. The program calculates the modal frequencies and the effective mass coefficients used in the determination of the thermal noise. The new code predicts a slightly higher(~10%) overall thermal noise from the internal modes of the test masses. This code was made into an AVS/5 module and added to the end-to-end noise model.

Four new thermal noise source modules were added to the LIGO end-to-end noise model during this quarter. Three of these modules characterize thermal noise sources found in the suspension system. The fourth is the thermal noise from the internal modes of the test masses discussed above.

The results of these modules, along with the modules developed specifically for the 40 meter noise sources were compared with the displacement sensitivity measured in the 40 meter interferometer in the fall of 1994. Agreement between the measurements and theory is demonstrated in Figure 4 on page 29.

Seismic noise model for LIGO and implemented the model as an AVS/5 end-to-end noise module. A seismic noise module was developed to calculate the displacement noise sensitivity and was added to the end-to-end noise modeling environment. The model for this noise source uses piece-wise continuous fits to the measured ground motion at the Louisiana and Hanford sites, measured two dimensional isolation stack transfer functions and theoretical calculations for the suspension transfer function. The model also includes a transfer function for the pitch mode of the stack. Together these noise models along with the models developed during the past year provide an envelope for the dominant noise sources expected in the LIGO interferometer.

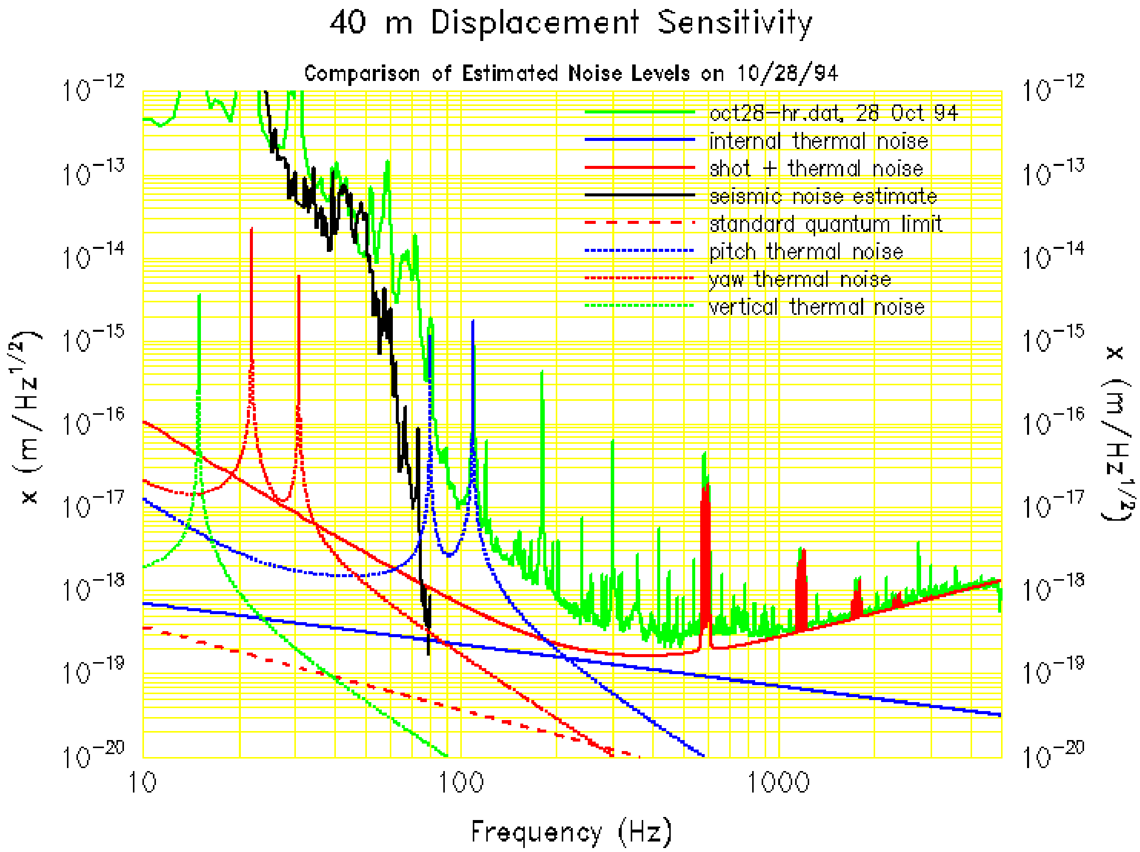


FIGURE 4. 40 Meter Displacement Sensitivity - Comparison of Model Results with Previous Measurements

Work Planned for the next quarter

- Continue to develop noise models for LIGO and implement those models in the end-to-end noise model for inclusion in the full LIGO end-to-end modeling environment. The noise sources to be modeled in the next quarter will primarily be noises that effect sensing such as amplitude and frequency noise in the laser, residual gas noise, etc.
- Convert the existing modeling software based on the AVS/5 environment over to the newer object oriented AVS/Express environment.