# Quarterly Progress Report

## (March 1996 through May 1996)

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

**June 1996**

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

NSF COOPERATIVE AGREEMENT No. PHY-9210038

June 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 March 1, 1996 through May 31, 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.

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# 1.0 Executive Summary

There is considerable progress to report this quarter as the Project approaches full construction activity. The Vacuum Equipment contractor, Process Systems International (PSI) in Massachusetts hosted, a Final Design Review (FDR) in May, and long lead items have been ordered. The final design review for the Beam Tube contract was successfully completed in March. The spiral mill for the fabrication of the beam tubes was acquired and will be moved to Hanford in August. CB&I has occupied factory space in Pasco, Washington. The contract for baffles to be inserted in the Beam Tubes to control noise and false signals from light scattering has been issued as has the contract for the porcelain coating of the baffles. The distribution of the baffles in the beam tube has been calculated. The Beam Tube Fabrication Readiness Review is the next major milestone and is scheduled for September.

ACME, the Beam Tube Enclosure contractor has completed the finish grading and the Beam Tube Enclosure slabs at the Hanford site. The first slab at Hanford was started on May 22. All grading, trimming, preparation has been completed. After months of careful preparations, the first 2-1/2 mile slab was poured in six working days. Quality Assurance is on site as is the Caltech Construction Manager. The batch concrete plant is on site.

ACME prepared forms for sections of the Beam Tube Enclosure. The forms permit fabrication of the main cross-section in sets of four, each ten feet long. More than 150 sections (of 1,400 required for the Hanford site) have been fabricated. Some cracking was encountered in the first ones, and the problem was corrected by modifying the form. The enclosure sections will be fabricated five miles from the site and then transported to the site where they will be set next to the arms for the installation contractor. There will be 700 sections completed by September. Each weighs nine tons. The procurement process for the installation contract will be initiated early in the third quarter.

The bid package for building construction at Hanford (3 interferometer version) has been issued. The bids are scheduled to be opened on June 18. The building planned for the Livingston, Louisiana site will house two interferometers. This configuration preserves the opportunity for one interferometer additional at each site (one complete new detector).

Louisiana site Rough Grading has suffered due to rain. A total of 68 days have been lost due to inclement weather through the end of the reporting period. The current estimate of completion for the rough grading is mid August which will support the construction schedule.

The Detector Implementation effort made advances in developing requirements, designs, and in developing commercial sources for detector components. The requirements, interfaces, and the conceptual design of the Seismic Isolation subsystem were successfully reviewed, and an outside contractor (HYTEC Inc.) has refined the conceptual design and performed trade studies for performance and cost and weight reduction. An important step in the implementation of solid-state lasers was made in the award of a contract to Lightwave Electronics for the LIGO 10 W laser development and production. The Pathfinder process to develop interferometer test mass optics saw the delivery of polished substrates (from CSIRO and Hughes-Danbury), some of which significantly exceeded our stringent requirements; the metrology contractor (NIST) and the coating contractor (REO) also made strides forward in preparing for their tasks.

Reviews of the requirements for the Length Sensing and Seismic Isolation Subsystems were held, launching the preliminary design phase of those subsystems. The preliminary design for the structure and backbone of the Control and Data System continued, and a review of the requirements for the Vacuum Control and Monitoring was performed.

Research and Development accomplishments centered on the 40m and 5m interferometers. The Phase Noise research moved into its second phase, a recycled Michelson configuration. Due to a very small contrast defect and refinement of the length and angular control systems, a high recycling gain (as high as 450) was achieved, which gives LIGO-like circulating power; measurements of the noise performance are just starting. The Recombination/Recycling of the 40m interferometer continued with a better understanding of the locking of the system and integration of LIGO prototype control hardware and software. There was progress on the mission of the 40m interferometer to develop techniques for achieving the very high availability planned for LIGO, accomplished through the implementation of a monitoring and scheduling plan. Other significant activities included alignment research and the development of moderate-power Nd:YAG lasers for lab use.

The regular semi-annual review of LIGO was conducted by a review committee of experts on behalf of NSF on April 9-11, 1996 at Caltech. The focus of this review was on the cost, schedule, and management aspects of the LIGO Construction Project and the supporting R&D. The committee’s report has been issued.

During a review conducted at MIT in March, there was a second meeting of the Pre-Program Advisory Committee. The committee having completed its function then self-annihilated. The committee:

- proposed the elimination of the External Advisory Committee (this function is to be performed by the Program Advisory Committee),
- proposed the expansion of the charter of the Program Advisory Committee,
- provided recommendations as to how the PAC should start and function,
- recommended membership of the PAC and recommended that the PAC should start by the Fall of 1996.

An active visitors program is being developed, roughly equivalent to three FTE's each year (more during later years) with people involved in research for periods of time six months or longer. Professor Kris Sliwa of Tufts University is at MIT this year.

Active collaborations are being sought with Stanford and the University of Florida. Stanford can provide good technical input especially in the domain of lasers. The University of Florida is looking to assume tasks for which they can be responsible.

# 2.0 Facilities and Vacuum System (WBS 1.1)

## 2.1 Vacuum Equipment (WBS 1.1.1)

**Significant accomplishments in the last quarter:**

- Began fabrication of prototype BSC vessel at Ranor.
- First test of a main turbomolecular pump cart at Edwards.
- Began fabrication of main rough pump carts by Edwards.
- Begin fabrication of first large gate valve at GNB.
- Begin fabrication of prototype main ion pump by Varian.
- Placed order for purge and vent compressor systems.
- Placed order for BSC prototype bakeout blankets and control cart.
- Placed order for LN2 tanks.
- Placed order for main project stainless steel plate, heads, and flange forgings.
- Completed setup of Flander’s Road test facility (PSI clean space).
- Completed fabrication of 10 inch vessel and test system.
- Complete and submit final design review package CDRL 03.
- Complete the Final Design Review.

**Discussion of accomplishments**

In March 1996 Process Systems International (PSI) awarded a contract to Ranor Inc. (Westminster, MA) for the fabrication of the prototype Beam Splitter Chamber (BSC). Actual fabrication of this chamber began in April with PSI supplying the stainless steel material to Ranor. Clean work space was set up within the fabrication shop to accommodate the assembly and welding with PSI welders moving to the Ranor facilities to facilitate the plasma welding. The photos show the clean room structure (Figure 1 on page 4), fabrication of a 60 inch BSC cover (Figure 2 and Figure 3 on page 5) and the main BSC shell being readied for stress relieving (Figure 4 and Figure 5 on page 6),.

Also in March, the main turbomolecular pumps were being assembled by Edwards Vacuum. A preliminary test of the first turbomolecular pump cart was witnessed by PSI in April at Edwards facilities in New York State. The assembly of the main roughing pump carts began in May. Both of these pump carts are part of the Beam Tube deliverables. The other main deliverable component of the Beam Tube is the large gate valves, the first of which entered fabrication in April with the first cycle and shock tests now scheduled for late June. The Beam Tube deliverables are required to be at the Washington site by mid August.

Main ion pumps are being fabricated in Italy by Varian Vacuum. The first of the 2500 liter/second pumps should be ready for testing this summer.

**FIGURE 1. Clean room at RANOR.**

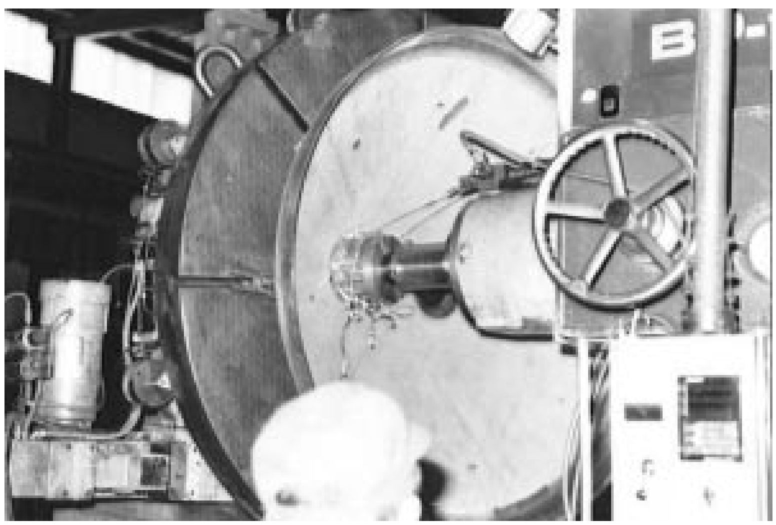


**FIGURE 2. BSC cover being machined.**

A number of procurements took place in this period as well; purge and vent compressors were ordered, bakeout equipment for prototype BSC testing was ordered, and the large LN2 storage Dewars were ordered to allow definition of the concrete slabs which will support them.

The main engineering activity (for both PSI and LIGO) in this period was the preparation for and execution of the Final Design Review which was successfully held on May 22 in Marlborough, MA.

**The work to be done in the next quarter includes:**

- Approval of the Final Design and go-ahead for remaining fabrication and procurement.

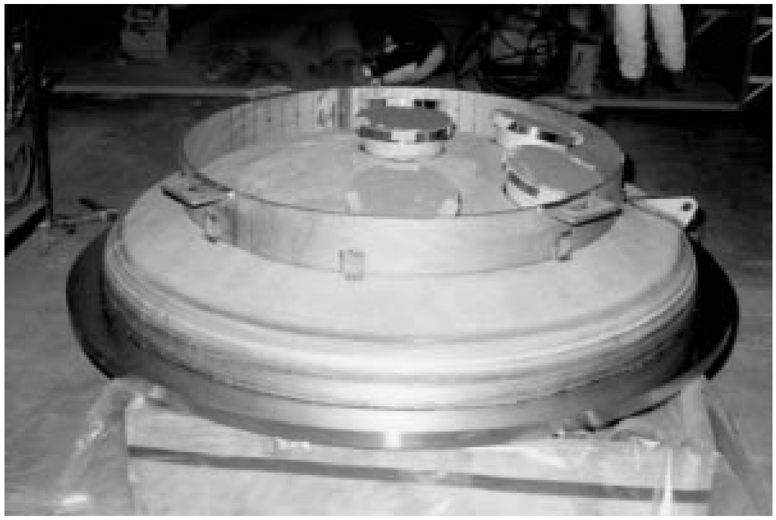


**FIGURE 3. Completed BSC cover.**

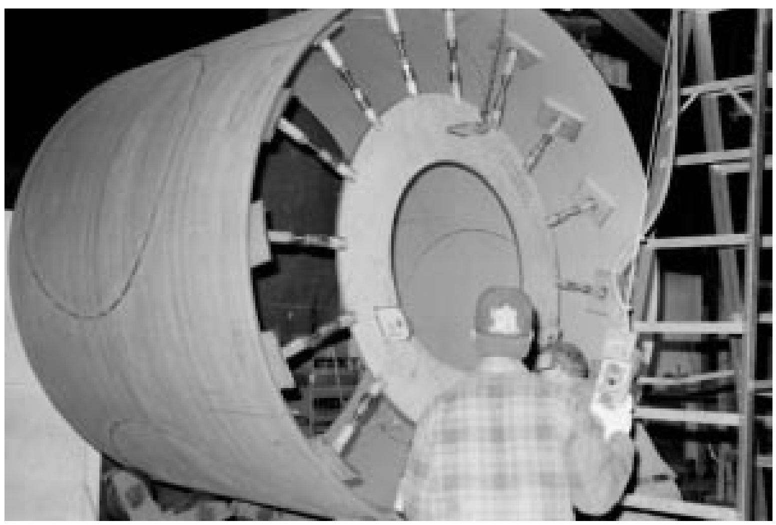


**FIGURE 4. BSC main shell with spider.**

- Complete the fabrication and delivery of the Beam Tube Deliverables - the main rough pumps, the main turbomolecular pumps, and eight of the large gate valves. These are required at the Washington site by August 19.
- Witness performance tests of the prototype main ion pump begin fabricated by Varian.
- Complete the fabrication of the prototype BSC vessel and begin the prototype testing program.
- Begin fabrication of the prototype 80K pump. This pump is scheduled for testing (vibration measurements included) in the fall of 1996.
- Begin fabrication of the prototype HAM chamber.
- Complete the HAM chamber design.

No significant milestones have been missed. The Final Design Review was very successful with

**FIGURE 5. BSC main shell.**

only minor action items resulting. In June PSI will proceed with the full fabrication and procurement activities.

## 2.2 Beam Tube (WBS 1.1.2)

**Significant accomplishments during last quarter:**

- Management plans and implementation plans were submitted by Chicago Bridge and Iron (CB&I); these plans have been reviewed and approved.
- The updated design review was held on March 27, and approval has been given to proceed with the design.
- A plan has been developed for monitoring the activities at CB&I and their subcontractors; monitoring has begun on: stainless steel coil annealing and pickling, baking, slitting and shearing; coupon outgas testing; weld wire cleaning.
- CB&I has mobilized their field staff (including team management) at the Hanford site.
- A model of the beam tube and beam tube enclosure has been installed at the Caltech campus.
- Contracts were awarded to two contractors for the baffles fabrication.
- A contract was awarded for glass coating the baffles.

**Discussion of accomplishments**

The updated design review was successfully completed. Quoting the design review board report, “The overall fabrication and installation plans are well thought out and reflect an appropriate balance of the technical and logistical trade-offs needed to optimize the end-to-end process. Very few weaknesses were detected all of which are judged to be minor and easily corrected. We found a positive, productive ‘can-do’ attitude on the part of the participants in this review and would fully expect CB&I’s endeavors to be successful.”

The first batch of stainless steel coils (of eight batches), 58 tons for expansion joints, was successfully processed and sent to the expansion joint manufacturer. The hydrogen outgas screening test verified an effective degas bake, with outgas levels a decade below the maximum allowable. All of the weld wire for the beam tube contract, 5.5 tons, was processed with the same procedure used during the qualification test. The second batch of stainless steel coils, 100 tons for tube sections, has been started through the process cycle. Monitoring of these operations has been helpful in identifying and removing potential sources of contamination. Both LIGO team members and JPL QA personnel are being used to monitor beam tube activities.

CB&I signed the lease on the temporary fabrication building at Pasco, WA, and has started work to modify it for beam tube fabrication. These modifications include upgrading the facility electrical supply, installing walls to isolate the leak check and cleaning areas and installing a tracked tube transport system. CB&I has located office trailers at the WA site and plans to move management staff from Pasco to Hanford as soon as telephones are installed.

Two hardware changes have been incorporated in the beam tube contract: one adds "soft" supports under the termination gate valves. The second implements a value engineering design change (a shared cost reduction) for the beam tube supports.

Contracts have been let for fabrication and coating all baffles for both LIGO sites. Prototype baffles are being fabricated to check out vendor fixtures and processes. These will be used for the same purposes by the glass coating contractor. The beam tube model is being used to check out baffle installation procedures.

The spiral tube mill and the tube end expander/cutoff machine are in final development and will be qualified in June.

**Work to be accomplished during the next quarter:**

- Incorporation of all changes resulting from the updated design review.
- Completion of the fabrication facility modifications
- Qualification of the spiral tube mill, including an outgas measurement of spiral tube mill welding
- Qualification of all fabrication equipment and fixtures
- Completion of stainless steel coil batch #2 process
- Completion of the first two lots (40) of expansion joints
- Conduct the fabrication readiness review
- Initiation of beam tube fabrication
- Completion of fabrication and coating of the first 200 baffles

## 2.3 Beam Tube Enclosure (WBS 1.1.3)

**Significant accomplishments during this quarter:**

- Completed the finish grading and site work for the beam tube enclosure at the Hanford site.
- Completed the base preparation for the service road along the both arms at the Hanford site.
- Completed the slip-forming and placement of concrete for the beam tube enclosure slab at the Hanford site (See Figure 6 on page 8).

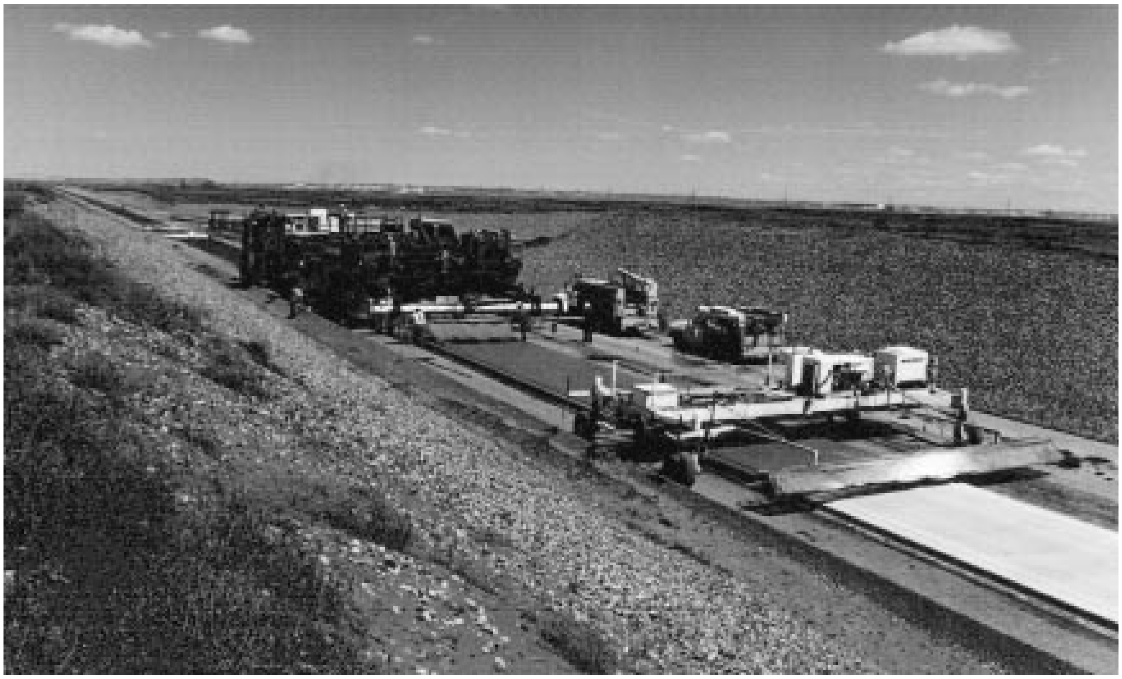


**FIGURE 6. Slip-forming and placement of concrete for beam tube enclosure slab**

- Completed the fabrication of about 100 concrete segments of the enclosure for the Hanford site.
- Prepared the Request for Proposal package for the beam tube enclosure installation for the Hanford site.
- Completed the design package for the site work and precast fabrication of the enclosure for the Livingston site.
- Signed a contract with Shannon & Wilson, Inc. to provide quality assurance services for the slab and beam tube enclosure contract at the Hanford site.
- Signed a contract with Rogers Surveying, Inc. to provide surveying audit services for the slab and beam tube enclosure contract at the Hanford site.

### Discussion of accomplishments

During this period the LIGO and Parsons' construction management office was set up at the Hanford site. Construction of the beam tube enclosure proceeded on schedule and all the major schedule milestones were achieved at the Hanford site.

Parsons I&T, the A-E contractor, completed the beam tube installation package for the Hanford site. They also completed the design package for the beam tub enclosure at the Livingston site.

**Significant work to be accomplished during the next quarter:**

- Complete the beam tube enclosure installation bid package for the Livingston site.
- Issue the Request for Proposal and select a contractor for the beam tube enclosure installation for the Hanford site.
- Award a contract for the beam tube enclosure installation contract.
- Prepare the bid package for the site work and precast fabrication for the beam tube enclosure at the Livingston site.
- Prepare the Request for Proposal package for the beam tue enclosure installation package for the Livingston site.

## 2.4 Civil Construction (WBS 1.1.4)

**Significant accomplishments during this quarter:**

- Completed the final design package for the facility (buildings) for the Hanford site.
- Conducted the final design review design of the facility (buildings)
- Prepared a bid package and issued an Invitation for Bid for the facility (buildings) for the Hanford site.
- Installed the electric power line and telecommunication services from Area 400 to the Hanford site.
- Completed the electric distribution system along the both arms at the Hanford site.
- Signed a contract with Dixie Electric Membership Corporation for providing electric power to the Livingston site
- Signed a contract with ABMB Engineers Incorporated to provide surveying audit services for the rough grading construction at the Livingston site.
- All activities related to the pipeline crossings at the Livingston site have been completed.

**Discussion of accomplishments**

The Parsons I&T, the A-E contractor, completed the final design of the facility (buildings) for the Hanford site. This design consisted of two sets of drawings, specification, calculations and cost estimates. One set for the two interferometers arrangement and the other set for the three interferometers arrangement. Parsons I&T also completed and submitted a bid package for the three interferometers arrangement for the Hanford site. The final design review/approval process for the facility (buildings) at the Hanford site took place during this period.

Parsons I&T has continued to work on the development of the detailed design for the Livingston site. The final design package was 90% complete at the end of this period. The Invitation to bid for the facility (buildings) at the Hanford site was issued to about 140 plan holders about 19 of them are general contractors. The bidders conference/job walk took place at the Richland, WA on May 2, 1996. The public bid opening will take place at Richland, WA on June 18, 1996.

**Hanford Site.** The Public Utility District (PUD) completed the contract for providing electric power to the Hanford site. PUD installed the 13.8 KV underground power cables from 400 Area to the LIGO site. PUD also installed the utility electric power distribution system along the both arms at the Hanford site.

The Westinghouse Hanford Company installed a 50 pair telephone cable and a 12 fiber single mode fiber optics cable from the 400 Area to the construction site.

**Livingston Site.** Figure 7 shows the status of construction of the berm along the southeast arm at

**FIGURE 7. Construction of berm along the southeast arm at the Livingston site**

the Livingston, LA site. The rough-grading and drainage work continued at the site by Stranco Inc. Inclement weather was a problem during this period. A total of 68 days have been lost as of the end of the reporting period due to inclement weather. Activities continued to focus on drying the site, installation of the culvert pipes and construction of the berm along the arms. The estimated completion date for rough-grading is mid August (the scheduled completion date is August 1, 1996).

**Significant work to be accomplished during the next quarter:**

- Select a general contractor and award contract for construction of facility (buildings) at the Hanford site.
- Complete the detailed design package for the facility (buildings) at the Livingston site.
- Perform the final design review and approval process for facility at the Livingston site.
- Prepare the bid package for the facility (buildings) for the Livingston site.
- Initiate the bid process for the facility (buildings) for the Livingston site.
- Develop the detailed design package for the facility (buildings) for the Livingston site.

# 3.0 Detector (WBS 1.2)

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

- WBS 1.2.1 Interferometer System, which is organized into three major task groups each responsible for several subsystems:
  - Suspensions and Isolation
    - Seismic Isolation
    - Suspension Design
  - Lasers and Optics
    - Prestabilized Laser
    - Input/Output Optics
    - Core Optics Components
    - Core Optics Support
  - Interferometer Sensing/Control
    - Alignment Sensing/Control
    - Length Sensing/Control
- WBS 1.2.1.9 Detector System Engineering/Integration
- WBS 1.2.2 Control and Data Systems
- WBS 1.2.3 Physical Environment Monitor System
- WBS 1.2.4 Support Equipment.

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.

## 3.1 Suspensions and Isolation

**Significant accomplishments during this quarter:**

- The requirements, interfaces, and the conceptual design of the Seismic Isolation subsystem were documented in a Design Requirements Document, and successfully reviewed. This allowed the Preliminary Design phase to commence.

**Seismic Isolation.** The Seismic Isolation subsystem requirements were developed, taking into account new ground noise measurements at the Livingston, LA site, and the design constraints imposed by the Suspension design, resulting in a Design Requirements Document for the subsystem. Tidal and meteorological data in the literature were evaluated for low-frequency input to the design. A conceptual design was also developed, including practical approaches for the actuators required to compensate for mechanical drift and tidal forces. A review was held on April 29, with the recommendation that the preliminary design proceed immediately.

HYTEC, an independent subcontractor, has continued to develop conceptual design solutions (within the envelope defined by the Design Requirements Document) for 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 review was held on April 4, in which trial designs and their analyses were presented; considerable progress on both fronts had been made. Structural innovations and new lossy spring designs were discussed, and the work continues with feedback from the LIGO project.

**Suspension Design.** The Preliminary Design of the subsystem and its documentation has continued, with the Preliminary Design Review planned for June 6. In particular, details of the allocation of thermal loss noise contributions and practical approaches to realize low-loss suspension concepts have been addressed; considerable simplification of the connections in the suspension cage have been implemented to reduce the likelihood of stress-release noise sources.

**Work planned for the next quarter:**

- Seismic Isolation. The trade study will continue and will transition to the Preliminary Design.
- Suspension Design. The preliminary design phase will be reviewed early in the quarter. Attention will then focus on the test of a prototype suspension in the 40m interferometer and the Final Design of the suspensions.

## 3.2 Lasers and Optics

**Significant accomplishments during this quarter:**

- A vendor for the LIGO 10 W Nd:YAG laser was selected and the contract signed.
- There was significant progress in the Pathfinder process for the Core Optics with the receipt and review of the polished substrates from the trial vendors.

**Prestabilized Laser.** Responses to the Request for Proposal for the development of a 10 W Nd:YAG laser were evaluated, and a vendor (Lightwave Electronics) chosen. This starts a 16 month development and production cycle for the laser to be used for the initial LIGO detectors. In a parallel activity, several medium-power Nd:YAG lasers have been ordered and received from the same vendor, and a program started to convert the control systems previously developed for Argon lasers (see Section 4 above); to the maximum extent, the well-developed system for Argon will be adapted to the Nd:YAG. Work on the Design Requirements Document for the Nd:YAG Pre-Stabilized Laser subsystem began toward the end of the quarter.

**Input Optics.** The Input Optics subsystem underwent a minor redefinition to simplify the interfaces and to improve testability. Because the initial LIGO will not require an output mode cleaner, the subsystem now encompasses exclusively the input optics for the interferometer. The requirements received some attention as our knowledge of the Core Optics, Length and Alignment Sensing/Control requirements improved.

**Core Optics.** The focus of work has continued in the area of the full size LIGO optics “pathfinder” effort. The ground and polished Pathfinder optics were delivered to the metrology vendor (NIST) for measurements in the coming quarter, and the two high-precision vendors (CSIRO and

Hughes-Danbury) were reviewed. Both vendors performed well, with some of the results exceeding LIGO requirements—a remarkable achievement. Collaborative interaction with the coating vendor (REO) also continued with both in-house testing and measurements at REO. Close coordination with VIRGO has facilitated the specification of mirror blank material, and there will be a joint metrology effort between VIRGO and LIGO for bulk and surface absorption.

**Work planned for the next quarter:**

- Core Optics Metrology. The independent metrology of the Pathfinder substrates will be completed, enabling a choice of polishing vendors. There will be continued measurements of coating uniformity and interaction with the coating vendor.
- Core Optics. The Requests for Quotes for the Core Optics blanks (substrate material) and for the Core Optics Polishing will be issued.
- Input Optics. The design requirements, interfaces, and conceptual design will receive attention, and a draft Design Requirements Document will be prepared for this subsystem.
- Pre-stabilized Laser. The stabilization in frequency and intensity of the medium-power Nd:YAG will be completed and the design and a laser system readied for use on the Phase Noise Interferometer.

## 3.3 Interferometer Sensing/Control

**Significant accomplishments during this quarter:**

- The requirements, interfaces, and the conceptual design of the Length Sensing/Control subsystem were documented in a Design Requirements Document, and successfully reviewed. This allowed the Preliminary Design phase to commence.

**Alignment Sensing/Control (ASC).** The revised Design Requirements Document progressed in this quarter, with an improved basis for calculating the beam jitter sensitivity of a realistic system and a better understanding of the tilt spectrum and the correlation that is anticipated between the 4km-separated vertex and end stations. Some prototype components for the Optical Lever have been ordered and some of these have been received. A test program to verify performance has been developed.

**Length Sensing/Control (LSC).** The Design Requirements Review for the Length Sensing/Control system took place on April 30. The requirements for the subsystem and the conceptual designs have both evolved significantly. A change in the baseline design to a single carrier/single modulation sensing system resulted during this process. The conceptual design presented meets LIGO performance requirements with a realistic servo-system design for operations, and the modeling of dynamics of cavities and interferometers was used to present a sequential locking scheme which appears robust. The Preliminary Design was started after the successful review.

**Work planned for the next quarter:**

- Alignment Sensing/Control. Preparations for the Design Requirements Review, planned for mid-summer, will continue. The Optical Lever prototyping will yield the principal results needed, with feedback to the design process.
- Length Sensing/Control. The Preliminary Design will continue.

## 3.4 System Engineering/Integration

The Detector Systems Engineering/Integration has focussed on the requirements flowdown and the trade studies required to deliver the sensitivity of the initial LIGO detector. Design Requirements Reviews for Length and Alignment Sensing/Control, Seismic Isolation, and CDS Vacuum Controls were conducted this quarter. Integration of noise models into the LIGO Systems Integration modeling effort was pursued using input parameters keyed to the top-down requirements to assure a coherent set of requirements for the Detector.

**Work planned for the next quarter:**

- Design Requirements. The Alignment Sensing/Control Design Requirements Review and the Suspension Preliminary Design Review will be conducted.
- Optical Layout. Effort on the optical layout will continue, in particular to refine the specifications for the wedge angles on the Core Optics and to allow the Suspension heights to be fixed.

## 3.5 Control and Data Systems (CDS) Activities (WBS 1.2.2)

**Significant accomplishments during this quarter:**

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

**Requirements and Conceptual Design.** The CDS group carries the responsibility for the controls systems for the Vacuum Equipment, and the requirements and conceptual design for this task were developed and reviewed on May 1. The preliminary design is now proceeding. Some prototype tests of equipment for the Control and Monitoring system (reviewed last quarter) have started as part of the Preliminary Design process. Early definition of the bandwidth requirements for the Physics Environmental monitor has been made as input to an accurate requirement for the overall data acquisition backbone throughput. A similar effort to define and delimit the Interferometer Diagnostics has advanced that conceptual design and helped scope the bandwidth and flexibility needed.

**Prototyping and R&D support.** CDS has worked on prototype electronic and software systems for several efforts during the last quarter with the focus on obtaining advance design information for the final LIGO designs. As noted elsewhere, exercising the Argon PSL software and hardware at the 40m interferometer has been a rich source of information concerning human interface and hardware design. The software for data collection on the Alignment Fixed Mass Interferometer is now being used, and the CDS group has supported its customization; in addition, the fabrication of the Wavefront Demodulator circuit board has been a significant undertaking. Additional support in the development of electronics (servo systems, RF modulation/demodulation systems) for the recycling modifications was also provided for the 40m interferometer facility.

**Work planned for the second quarter:**

- Data acquisition. Develop the requirements and conceptual design for a Requirements Review to be conducted in the second quarter.
- Vacuum Feedthrough and Cabling. Continue preliminary design, to be reviewed in the Preliminary Design Review in the second quarter.
- Interferometer Monitor and Control. Continue preliminary design, to be reviewed in the Preliminary Design Review in the second quarter.

## 3.6 Physical Environment Monitoring (WBS 1.2.3)

Development of requirements and conceptual designs for the Physics Environmental Monitor continues this quarter, with a primary objective being to ensure that the bandwidth required for data acquisition will be supported by the Control and Monitoring system.

## 3.7 Support Equipment (WBS 1.2.4)

The definition of the Support Equipment required will continue through the second quarter leading to a review of the Design Requirements in the third quarter.

# 4.0 Research and Development (WBS 1.3)

**Significant accomplishments during this quarter:**

- The second step of the Phase Noise research, a recycled Michelson, began with very encouraging initial recycling gain (a maximum of 450) and contrast (1 – $= 2.3\times10^{-4}$) measurements.
- The length control system for the Fixed-Mass Interferometer used in the research on alignment techniques was successfully debugged and brought into operation
- Work on the recombined 40m configuration continued, with the integration of the Argon PSL and the development of an operations plan
- A low-power Nd:YAG laser system, to be used on the Phase Noise Interferometer and other R&D projects, was characterized and designs for a stabilization system developed.

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 longer-term 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 40m Interferometer Investigations

**Operations.** One of the crucial missions of the 40m interferometer is to develop techniques for achieving the very high availability planned for LIGO. This involves both making hardware reliable and also developing work routines which support the continuous operation (in both the senses of observation and machine refinement) which LIGO will require. After careful planning, this mode of operations was started late in the quarter. Data are being gathered on hardware changes which will be needed for the 40m (and thus LIGO) to maintain high availability. All scientists are dedicating some shifts working with the 40m, both to bring a variety of experience to the research and to train scientists for their installation, commissioning, and operations work at the LIGO sites.

**Optical Recombination.** The principal effort on the 40 m was research on the recombined non-recycled Fabry-Perot Michelson configuration. A major re-alignment of the system from the ground up was undertaken, allowing drifts to be better tracked. The internal optics were cleaned, leading to a significant reduction in the optical loss of the 40m arm cavities; this leads to operation with 'under-coupled' cavities (as will be used in LIGO). A parallel program of modeling of the servo sensing and control system (using LIGO models with 40m parameters) has improved the understanding of the system and directed experimental effort. These efforts have led to more reliable operation at improved noise levels over the quarter; however, some important questions must be resolved before moving away from this configuration. The new operations approach is helping to make progress on this front.

**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. Detailed design, and fabrication of optical and electronic components, continued in this quarter. The critical test-mass coating parameters were derived and the masses are now being prepared for coating.

**Integration of LIGO Argon PSL.** The 40m interferometer performs as an integration testbed for interferometer subsystems. The use this quarter of the newly installed LIGO Argon Pre-stabilized Laser, with the control and monitoring system planned for the LIGO sites, has been a rich source of feedback to the hardware and software engineering team. In particular, the user interface has been given an early and intense test, helping both the engineering and scientific teams to realize a practical approach to LIGO equipment specifications.

**Development of Data Acquisition and Analysis Techniques.** Previously acquired 40m data has been analyzed for binary inspirals as a test of data-handling and analysis routines. Improvements in the tape hardware and the template software has allowed a real-time throughput of 5 inspiral templates on a standard workstation.

## 4.2 Suspension Development

The effort to install a new design for test mass suspensions for the 40 m interferometer has continued. Fabrication of a first article of this suspension was completed early in this quarter. The mechanical design was exercised by developing test-mass hanging techniques. The electronic sensors and actuators, which are of a new design, were characterized and aligned to ensure orthogonality of the translation and angular systems. Installation of this first article will proceed at a window of opportunity in the 40m program, with fabrication of the other suspensions after a shakedown and test cycle.

## 4.3 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 ($\sim 10^{-10}\ \mathrm{rad}/\sqrt{\mathrm{Hz}}$). 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. During this quarter, the research on the non-recycled Michelson configuration was completed.

**Recycled Michelson.** The effort this quarter focused on developing servo-control techniques for the recycled Michelson. The control system must be integrated with the laser frequency control to permit a wide-bandwidth control system, and this leads to a hierarchical configuration. Difficulties due to mechanical resonances, in particular those in the recycling mirror itself, limit the design. Several different configurations were developed and tried; once short durations of correct ‘locking’ were achieved, however, rapid convergence to a workable scheme was made. The configuration now in use is not final, in that the modulation sidebands used to read out the length information are not yet exactly in resonance. For this reason, no noise measurements have yet been taken in the recycled configuration. However, for optimal alignment, the power build-up due to recycling has been measured to be 450, consistent with estimates of the optical losses (including an exceptionally small loss due to the contrast defect of $1 - C = 2.3\times10^{-4}$). The Figure shows the power in the recycling cavity (normalized to the peak power, roughly 17 W) on the top trace; and the contrast defect $1 - C$ on the bottom trace for a period of roughly one minute.

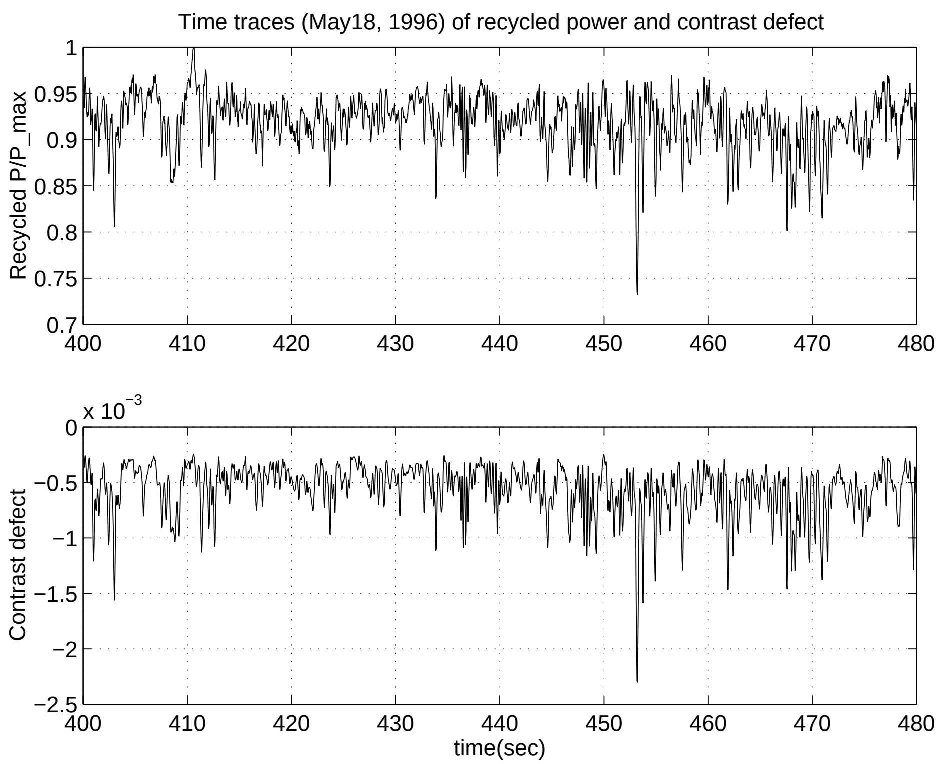



**FIGURE 8. Phase Noise Interferometer recycling cavity power (top) and contrast defect (bottom)**

This recycling factor of 485 is much higher than the planned value for LIGO, but will allow the phase noise measurements to be made with our moderate-power Ar laser and will support the modeling used for both R&D and implementation (LIGO) design efforts.

**Preparations for upgrades.** Two significant additions to the Phase Noise Interferometer are being prepared in connection with other research. A wavefront alignment system is in production, which will allow the critical alignment to be held for indefinite periods; this uses the sensors and demodulators developed for the Interferometer Alignment research discussed below, as well as some specific analog servo circuitry. The interferometer will be converted to 1064 nm and will employ a Nd:YAG laser; this development is described in a later section.

## 4.4 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, where the discriminants at all interferometer ports will be measured and compared with a semi-analytical model.

In this quarter, reliable operation of the length system was achieved. Additional modeling was initiated to address unexpected signals with the result that the dependence of some error signals on relative losses and loss balance was clarified. With a change in a modulation frequency, and some refinement in the alignment procedure for the interferometer, locking of all four degrees of freedom was accomplished and parameters adjusted for extended operation.

Attention has now turned to the programming of the data acquisition system. The low-level routines and the overall structure were developed by the CDS group in their R&D support role. Specific routines for experimental procedures are now being written and debugged. Construction of the alignment sensing hardware (wavefront sensors and demodulators) continued this quarter. All of the units are now complete. Tuning of the RF resonant circuits and testing will follow.

## 4.5 Nd:YAG Characterization and Stabilization

To gain familiarity with infrared techniques and to develop a basis for the LIGO Nd:YAG laser subsystem design, moderate-power (700 mW) commercial lasers are being prepared for use in the campus laboratories. The laser used is very similar to the master laser to be used in LIGO, and so the experience gained is directly applicable to the LIGO design. These lasers, with frequency and intensity stabilization, will be used in the Phase Noise Interferometer (where precision tests of the performance of the 700 mW and later 10W laser will be performed), in mirror contamination testing (where long-term exposure of mirrors to possible contaminants will be evaluated in the presence of high circulating optical powers), and in the 40 m interferometer (where systems tests will be performed). The first of these lasers will be delivered to the Phase Noise Interferometer in late summer.

During this quarter, the laser has been characterized in intensity and frequency noise. The actuators for frequency and intensity have also been characterized after a simple initial control system was put in place. Based on these measurements, and the requirement that this laser meet the performance specifications of the LIGO laser in intensity and frequency noise, a control configuration has been developed and requirements for the performance of the electronics modules have been written.

**R&D Work planned for the next quarter:**

- Install and complete characterization of one new prototype suspension in 40m interferometer; modify the design as indicated, start on fabrication of complete replacement set of suspensions.
- Prepare new high-transmission vertex arm input coupling mirrors to be used in recycling the 40m interferometer.
- Perform measurements with the Recycled Phase Noise Interferometer; installation of a wave-front sensor for alignment control. Background preparations for conversion to Nd:YAG/1064 nm.
- Test the alignment sensors and computer data acquisition system on the Fixed Mass Interferometer; perform initial comparisons of the alignment signals with the detailed theory.

# 5.0 Project Office

## 5.1 Project Management (WBS 1.4.1)

**Staffing.** The LIGO staff currently consists of 87 equivalent employees. Of these, 13 are contract employees. During the quarter LIGO added the following personnel:

**TABLE 1. New LIGO Employees (March 1996 - May 1996)**

| | |
|---|---|
| Cecil Franklin | Vacuum Equipment Engineer, CIT |
| Valerie Beasley | Document Control Center, Contract, CIT |
| Cleveland Mak | Administrative Support, Contract, CIT |
| Edward Jasnow | Subcontracts Manager, CIT (previously JPL) |

Seventy-two LIGO staff are located at CIT including four graduate students. Fifteen are located at MIT including five graduate students. Figure 9 shows the history of personnel growth on the LIGO Project since January 1995.

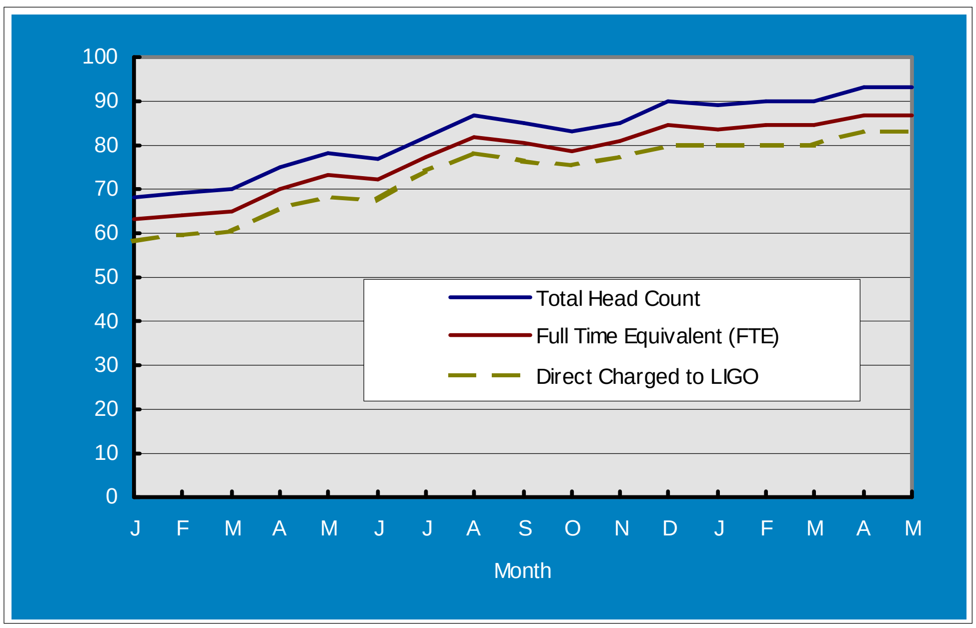



**FIGURE 9. LIGO personnel history since January 1995**

**Schedule Status.** 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 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. The projected milestone dates were presented in detail during the NSF review in April and in Revision B to the Project Management Plan submitted to NSF on April 24, 1996.

**TABLE 2. 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 | | 03/95 (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 (P) |
| Initiate Building Construction | 06/96 | 01/97 | 06/96 (P) | 01/97 (P) |
| Accept Tubes and Covers (Post B/O) | 03/98 | 03/99 | 03/98 (P) | 03/99 (P) |
| Joint Occupancy | 09/97 | 03/98 | 09/97 (P) | 03/98 (P) |
| Beneficial Occupancy | 03/98 | 09/98 | 03/98 (P) | 09/98 (P) |
| Accept Vacuum Equipment | 03/98 | 09/98 | 03/98 (P) | 09/98 (P) |
| Initiate Facility Shakedown | 03/98 | 03/99 | 03/98 (P) | 03/99 (P) |

a. Project Management Plan, Revision B, LIGO-M950001-B-M submitted April 1996

Table 3 is the status for the significant milestones for the Detector. This schedule was revised to reflect the change to the Nd:YAG laser, was also presented in detail at the April NSF Review, and was included in the proposed revision to the Project Management Plan. Note that as of the end of May 1996, <u>all significant milestones can be achieved</u>.

**TABLE 3. Status of Significant Detector Milestones**

| Milestone Description | Project Management Plan Date[a] | | Actual/Projected (P) Completion Date | |
|---|---|---|---|---|
| | Washington | Louisiana | Washington | Louisiana |
| BSC Stack Final Design Review | 07/97 | | 07/97 (P) | |
| Core Optics System Final Design Review | 04/97 | | 04/97 (P) | |
| HAM Seismic Isolation Final Design Review | 07/97 | | 07/97 (P) | |
| Core Optics Components Final Design Review | 07/97 | | 07/97 (P) | |
| Detector System Preliminary Design Review | 12/97 | | 12/97 (P) | |
| I/O Optics Final Design Review | 04/98 | | 04/98 (P) | |

## TABLE 4. Actual Costs and Commitments through May 1996

| WBS | Description | Costs through Nov 1995 | First Quarter LFY 1996 | March 1996 | April 1996 | May 1996 | Cumulative Costs | Open Commitments | Total Costs Plus Commitments |
|---|---|---|---|---|---|---|---|---|---|
| 1.1.1 | Vacuum Equipment | 4,080,835 | 3,241,865 | 608,793 | 68,527 | 2,022,966 | 10,022,987 | 30,995,135 | 41,018,122 |
| 1.1.2 | Beam Tubes | 2,736,036 | 1,619,551 | 1,809,182 | 73,631 | 59,416 | 6,297,816 | 33,691,412 | 44,989,229 |
| 1.1.3 | Beam Tube Enclosures | 467,558 | 24,735 | 4,042 | 52,782 | 1,365,279 | 1,914,397 | 403,628 | 2,318,024 |
| 1.1.4 | Facility Design and Construction | 6,677,089 | 1,365,223 | 1,060,250 | 327,135 | 80,700 | 9,510,396 | 4,796,293 | 14,306,689 |
| 1.2 | Detector | 2,429,521 | 789,053 | 111,776 | 407,823 | 461,430 | 4,199,603 | 7,818,199 | 12,017,802 |
| 1.3 | R&D | 13,321,268 | 524,071 | 361,515 | 586,845 | 501,179 | 15,294,878 | 1,545,051 | 16,839,929 |
| 1.4 | Project Office | 10,151,521 | 1,354,537 | 481,185 | 696,295 | 733,124 | 13,416,661 | 1,831,348 | 15,248,010 |
| | Unassigned[a] | 78,830 | (123,705) | 563 | 1,009 | (1,175) | (44,478) | 434,157 | 389,679 |
| 1.0 | Total Project Costs | 39,942,659 | 8,795,329 | 4,437,307 | 2,214,046 | 5,222,920 | 60,612,260 | 86,515,223 | 147,127,484 |
| Cumulative Project Costs | | 39,942,659 | 48,737,988 | 53,175,294 | 55,389,341 | 60,612,260 | | | |
| Open Commitments | | 44,992,602 | 89,933,846 | 89,526,108 | 89,434,110 | 86,515,223 | | | |
| Costs Plus Commit-ments | | 84,935,262 | 138,671,833 | 142,701,403 | 144,823,451 | 147,127,484 | | | |
| NSF Funding | | 136,088,935 | 149,888,935 | 167,088,935 | 167,088,935 | 167,088,935 | | | |

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 for the end of May 1996**

Run Date: 10JUN96 — COST / SCHEDULE STATUS REPORT (CSSR) — Page 1

| CONTRACTOR: Caltech<br>LOCATION: Pasadena, CA | CONTRACT NUMBER:<br>PHY-9210038 | CONTRACT BUDGET BASELINE<br>292,100,000 | REPORTING PERIOD:<br>30APR96-31MAY96 | PROJECT FILE NAME:<br>LIGO Master Merged PMB - WBS 1.0 |
|---|---|---|---|---|

PERFORMANCE DATA ( K$s )

| REPORTING LEVEL | CUMULATIVE TO DATE | | | | | AT COMPLETION | | |
|---|---|---|---|---|---|---|---|---|
| MPR LEVEL | BUDGETED COST | | ACTUAL COST | VARIANCE | | BUDGET | ESTIMATE | VARIANCE |
| | WORK SCHEDULED | WORK PERFORMED | WORK PERFORMED | SCHEDULE (2-1) | COST (2-3) | (BAC) | (EAC) | (6-7) |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| 1.1.1 : Vacuum Equipment | 14475 | 11527 | 10023 | (2948) | 1504 | 42285 | 42285 | 0 |
| 1.1.2 : Beam Tubes | 6743 | 6648 | 6298 | (95) | 350 | 48882 | 48907 | (25) |
| 1.1.3 : Beam Tube Enclosur | 2934 | 3258 | 1914 | 324 | 1344 | 19687 | 19687 | 0 |
| 1.1.4 : Facility Design & | 11676 | 11069 | 9510 | (607) | 1558 | 49100 | 49100 | 0 |
| 1.2 : Detector | 4313 | 4013 | 4200 | (299) | (186) | 51195 | 51964 | (769) |
| 1.3 : Research & Developme | 16334 | 15135 | 15295 | (1199) | (159) | 23490 | 23490 | 0 |
| 1.4 : Project Office | 12875 | 12875 | 13417 | 0 | (542) | 24492 | 24492 | 0 |
| SUBTOTAL | 69350 | 64526 | 60657 | (4825) | 3869 | 259133 | 259926 | (794) |
| CONTINGENCY | | | | | | 0 | 32171 | (32171) |
| MANAGEMENT RESERVE | | | | | | 32965 | 0 | 32965 |
| TOTAL | 69350 | 64526 | 60657 | (4825) | 3869 | 292098 | 292098 | 0 |

COBRA (R) by WST Corp.

**TABLE 3. Status of Significant Detector Milestones**

| Milestone Description | Project Management Plan Date[a] | | Actual/Projected (P) Completion Date | |
|---|---|---|---|---|
| | Washington | Louisiana | Washington | Louisiana |
| Prestabilized Laser Final Design Review | 08/98 | | 08/98 (P) | |
| CDS Networking Systems Ready for Installation | 09/97 | | 09/97 (P) | |
| Alignment (Wavefront) Final Design Review | 04/98 | | 04/98 (P) | |
| CDS DAQ Final Design Review | 04/98 | | 04/98 (P) | |
| Length Sensing/Control Final Design Review | 05/98 | | 05/98 (P) | |
| Physics Environment Monitoring Final Design Review | 06/98 | | 06/98 (P) | |
| Initiate Interferometer Installation | 07/98 | 01/99 | 07/98 (P) | 01/99 (P) |
| Begin Coincidence Tests | 12/00 | | 12/00 (P) | |

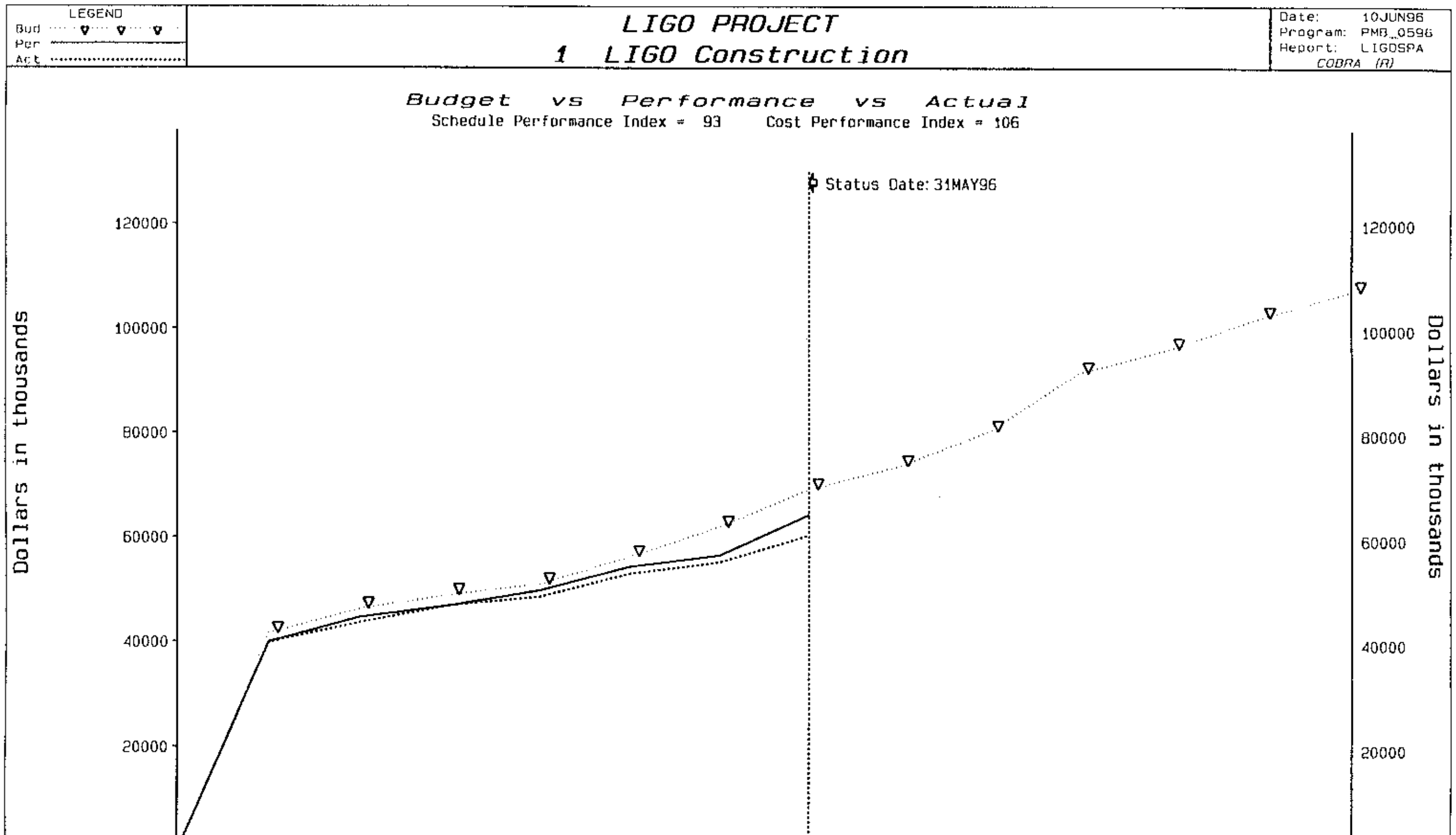
a. Project Management Plan, Revision B, LIGO-M950001-B-M submitted April 1996

**Financial Status Report.** Table 4 on page 23 summarizes costs for the second quarter and commitments as of the end of May 1996.

**Performance Status.** Table 5 on page 24 is a Cost Schedule Status Report (CSSR) for the end of May. 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 10 on page 26 shows the same data graphically as a function of time. The revised plan is in place and was used for reporting progress as of the end of May.

There is a significant unfavorable schedule variance in the Vacuum Equipment (WBS 1.1.1). During the quarter, Process Services International (PSI) missed several payment milestones which were the primary contributors to the schedule variance. Two were actually delayed by Caltech because the PSI final design had not received final approval. Three other milestones related to the placement of orders also linked to the approval of the final design. There is no anticipated schedule impacts since the lead times allowed in the original PSI schedule provide sufficient slack.

Facility Design and Construction (WBS 1.1.4) is behind schedule. The design effort is nearly complete and a related schedule variance should be eliminated in June. At Hanford the power and telecom service was completed one month late, but with no expected long term schedule impact. The Rough Grading Contract in Louisiana was scheduled to begin in August, while the notice to proceed was issued early in November. Recent weather conditions in Louisiana have continued to delay the contractor. 'Work-around' schedules have been developed and are reflected in the performance baseline that was presented to the NSF Review committee. LIGO continues to work




| | NOV95 | DEC95 | JAN96 | FEB96 | MAR96 | APR96 | MAY96 | JUN96 | JUL96 | AUG96 | SEP96 | OCT96 | NOV96 | SCALE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Planned Budget | 41,556 | 46,348 | 49,027 | 51,168 | 56,547 | 62,161 | 69,350 | 73,844 | 80,524 | 91,746 | 96,416 | 102,382 | 107,232 | K$ |
| Performance | 40,003 | 44,706 | 47,046 | 49,962 | 54,586 | 56,741 | 64,526 | | | | | | | K$ |
| Actuals | 39,863 | 43,730 | 47,029 | 48,777 | 53,219 | 55,432 | 60,656 | | | | | | | K$ |
| Schedule Variance | -1,553 | -1,642 | -1,981 | -1,206 | -1,961 | -5,420 | -4,824 | | | | | | | K$ |
| Cost Variance | 140 | 976 | 17 | 1,185 | 1,367 | 1,309 | 3,870 | | | | | | | K$ |

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

FIGURE 10. End of May 1996 Performance Measurement Data

with Parsons and the subcontractor to identify additional ways to accelerate the effort and is closely monitoring progress.

The unfavorable schedule variance in R&D (WBS 1.1.3) is primarily in the Phase Noise Research WBS element and in the effort in the 40 meter facility for Recombination and Recycling.

There is a significant favorable cost variance in Facilities. This variance is primarily due to the delays in the processes of invoicing and payment and do not translate into a projected underrun at the end of the project.

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, the document control center, and project support. Change Board actions are being considered to allocate the needed resources.

**Change Control and Contingency Allocation.** The Change Requests in Table 6 have been

**TABLE 6. Approved Change Requests**

| Change Request No. | Description | Date Approved | Amount |
|---|---|---|---|
| CR-960010A | 1.1.1 Vacuum Equipment - BSC Removable Spool Sections | March 11, 1996 | $110,000 |
| CR-960011 | 1.1.1 Vacuum Equipment - BSC Floors (reduced number, increased loading) | March 4, 1996 | $11,962 |
| CR-960012 | 1.1.1 Vacuum Equipment - Chillers for Deliverable Pump Carts | March 4, 1996 | $62,145 |
| CR-960013 | 1.1.1 Vacuum Equipment - Reduce budget for miscellaneous | March 4, 1996 | $(700,000) |
| CR-960014 | 1.1.1 Vacuum Equipment - BTD Pump Cart modifications | March 4, 1996 | $40,031 |
| CR-960015 | 1.1.1 Vacuum Equipment - Annulus Conductance Specification | March 4, 1996 | ($41,427) |
| CR-960016 | WBS 1.1.3 Beam Tube Enclosure, Hanford - shift Access Module centerline | March 4, 1996 | $5,200 |
| CR-960009B | 1.4.1.1 Project Office - Allocation of Labor Charges | April 3, 1996 | $1,951,786 |
| CR-960017A | WBS 1.4.1.1 Project Management Plan - NSF Reporting Milestones | April 3, 1996 | No Cost |

**TABLE 6. Approved Change Requests**

| Change Request No. | Description | Date Approved | Amount |
|---|---|---|---|
| CR-960018 | WBS 1.1.2 Beam Tubes - reduced cost beam tube supports | April 3, 1996 | ($206,955) |
| CR-960019 | WBS 1.1.1 Vacuum Equipment - delete 30 inch flanges from Mode Cleaner | April 1, 1996 | ($35,298) |
| CR-960021 | WBS 1.1.2 Beam Tube - Baffle manufacture and coating | April 26, 1996 | $436,200 |

approved. $1.63 million has been allocated from the contingency pool. Figure 11 shows the history of contingency allocation since November 1994. The top curve shows contingency dollars remaining as a function of time; the bottom curve is the contingency as a percentage of the cost estimate remaining to be committed.

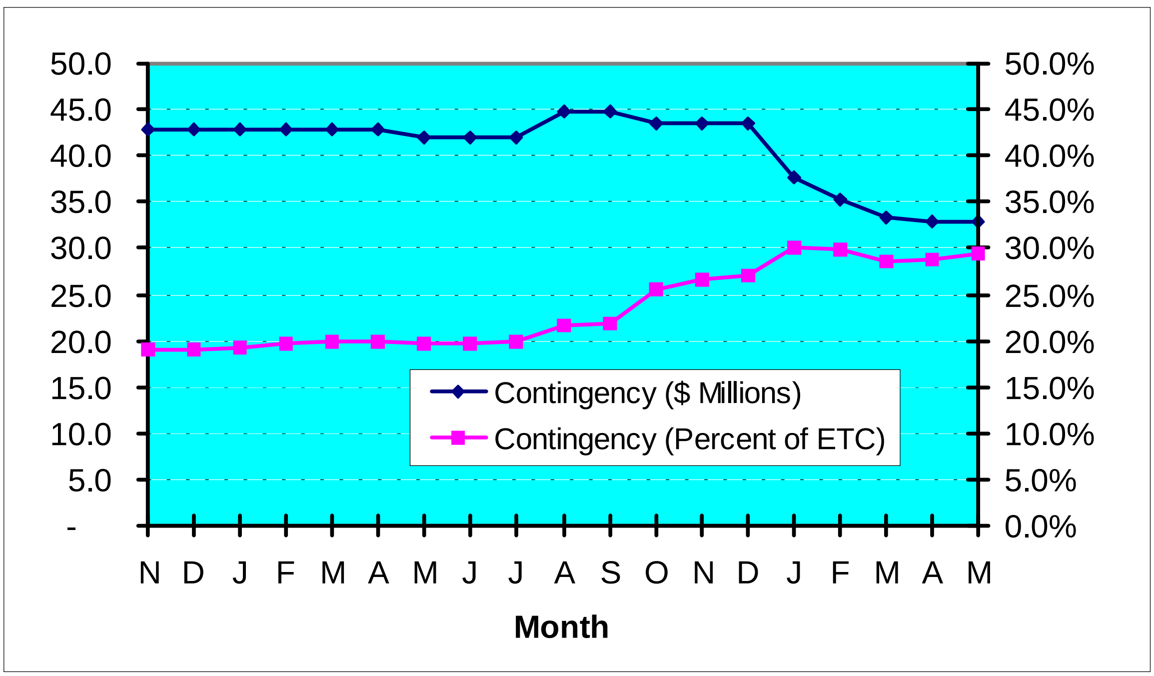



**FIGURE 11. History of Contingency Allocation**

## 5.2 Support Services (WBS 1.4.2)

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 quarter LIGO Quality Assurance focused on Facilities Group activities. This support included technical discussions regarding the Beam Tube Baffle design, procurement and QA plans for inspection and acceptance of the porcelain coating. LIGO QA also met with the Baffle vendors to review and approve their fabrication and QA plans. Preproduction and first article workmanship inspections were performed for one vender. LIGO QA monitoring of CB&I Beam Tube prefabrication activities was initiated with the assistance of JPL QA personnel.

LIGO QA coordinated JPL welding engineering support to develop a reliable and realistic method for spot welding the baffle tabs after installation in the Beam Tube. Pull tests were performed to establish and demonstrate reliable "joints" and welder tip geometry. A welding procedure was also prepared for CB&I guidance.

A QA planning review and audit was conducted with the LIGO Vacuum Equipment contractor. No significant problems or deficiencies were noted. LIGO QA also participated in the Vacuum Equipment Final Design as a Board Member.

Parsons Civil Construction design and bid documents were reviewed for QA adequacy. Proposals for slab QA/QC and surveying support contractors were evaluated. The Hanford Final Design Review documents were reviewed. QA also supported the Hanford design FDR as Review Board Member. Unannounced QA audits of both Livingston and Hanford site Construction Manager's QA records, files and other supporting data were conducted, the site support contractor activities and work accomplished status were audited.

**Safety Office.** The Laser Safety Program was accepted by LIGO management during the second quarter, a program was established, and Safety has moved aggressively to train and certify LIGO laser operators and workers. Four training classes have been completed. Twenty-three baseline eye checks were completed with a total of 21 LIGO personnel certified to perform work with lasers using the latest known safety precautions. The step remaining to complete the start-up phase of the laser safety program, is to finish the Safety/Standard Operating Procedures for the Caltech labs that will become the basis for the observatory laser safety programs. When this is accomplished, LIGO will move towards a monitored safety program that will be similar to the others required to meet OSHA safety requirements.

Safety reviewed the Parsons Civil Construction design and bid documents for safety requirement adequacy and supported the Hanford design FDR as a Review Board Member. Safety also supported the LIGO Vacuum Equipment FDR by reviewing the PSI hazards analysis to assure that all potential catastrophic events have been identified and controlled and was assigned as a FDR Board Member.

## 5.3 LIGO Research Community

A proposal for a LIGO Visitors Program to support three scientists per year for five years was submitted to the National Science Foundation on June 5, 1996.

The LIGO Pre-Program Advisory Committee (PAC), chaired by Peter Saulson (Syracuse University) held its second and final meeting on March 22-23, 1996 at MIT. The PPAC was charged to facilitate the organization of the LIGO Research Community (or “users’ group”) and the LIGO Program Advisory Committee (PAC) and the External Advisory Committee (EAC). The PPAC was also given the responsibility to serve as an interim Program Advisory Committee until the permanent PAC was formed. At the first meeting in September 1995, the PPAC completed drafting the Charter of the LIGO Research Community (LRC), set up a procedure and a schedule for elections of the first LRC Executive Committee, and proposed a slate of nine nominees for positions on the Executive Committee. The result was an LRC that is now fully operational with more than 200 members. At the March meeting, the PPAC decided that there was no current need for an EAC. Considerable time was devoted to discussion of the role and nature of the PAC. To that end a set of recommendations for the composition and role of the LIGO PAC was prepared and forwarded to the LIGO Principal Investigator.

The LRC has been very active following its formation. The Executive Committee, headed by L. S. Finn (Northwestern University) organized the first General Membership Meeting of the LRC as part of the Aspen Winter Conference on Gravitational Waves and their Detection, held January 15-20, 1996. The main order of business was the initiation of a self-study program to identify to primary concerns of the community, especially those not formally affiliated with the LIGO Project. Three special interest identification working groups (IIGs) on people; hardware; and sources, data and analysis were formed to poll LRC members including those who were unable to attend the Aspen meeting. Viewpoints were solicited concerning the best ways to interact with LIGO and which aspects of LIGO operations are of greatest importance to future scientific participation. The community responses were discussed at the second General Membership Meeting held as part of the Spring APS Meeting on May 2-5 in Indianapolis. The complete discussion of LRC aims and goals can be found on the LIGO World Wide Web pages under the heading “LIGO Research Community.”

# 6.0 Systems Engineering (WBS 1.4.3)

## 6.1 Integration (WBS 1.4.3.1)

**Significant accomplishments during this quarter:**

- Completed baffle design drawings and relayed electronic information to vendors for CNC parts production
- Designed a BSC full-scale mock-up to be built by Caltech shops for use in integration and assembly design
- Developed a physical model to quantify beam tube alignment tolerance.
- Held a Quarterly Science and Integration Meeting at MIT, May 20-21, 1996

**Description of accomplishments and work in progress**

**BT baffles.** The design of the LIGO Beam Tube baffles was completed and responsibility for procurement was handed off to the Facilities Group.

**Major Interface Definition and Control Documents (ICD).** Two Interface Control Documents (ICD) were issued in this quarter:

- Detector (Det) - Civil Construction (CC) ICD
- Detector (Det) - Vacuum Equipment (VE) ICD

These documents have been reviewed internally and by Parsons and PSI. A number of minor revisions are pending and some definition awaits completion of subcontracted/vendor design input. Completion of the ICDs and their revisions is an on-going activity with high priority. Now that the major system final design reviews have been completed, the balance of interface definition is largely available to finalize these documents.

**Internal Interface Control Documents (IICD).** An outline/template for the development of internal interface controls, for use within the detector effort, has been developed and applied to the Suspension-Core Optics Components interface.

**EMI/EMC Plan Development.** An Electromagnetic Interference/Compatibility Plan (EMICP) has been written by the Systems and CDS groups. The plan addresses the management philosophy for EMI control and procedures for design control of EMI through appropriate grounding and shielding methods. It is presently being circulated for project-wide review.

**Reliability Plan Development.** The reliability program plan draft has been completed and has been circulated for review and comments. A draft Reliability Plan has been written and reviewed by the Systems group. The plan is currently out for broader project review and signature.The plan addresses all facets of LIGO reliability tasks. It also establishes the top level availability goals for the LIGO system.

Work on the fault Tree Analysis of the vacuum System has begun. The creation of the reliability block diagram of the CDS is in progress, as well as evaluation of reliability of the cable vacuum feed through connection. We are also supporting the Vacuum Equipment contract by reviewing the Failure Modes and Effects Criticality Analysis (FMECA) done by PSI. We will also be working on preparation of reliability block diagrams and a preliminary FTA for the LSC and Seismic Isolation subsystems. We are working with the Facilities group to estimate maintenance downtimes and impact on LIGO availability.

**Vacuum Compatibility, Cleaning Methods and Procedures for LIGO Instrumentation Materials Specification Document.** Work on the development of a compatible materials list and the methods and procedures by which materials are qualified for use and properly cleaned continues. A draft LIGO vacuum compatible materials list has been written and is in the review and approval process.

**Work planned for the next quarter:**

- Revise and finalize the Interface Control Documents
- Issue the Configuration Management Plan
- Issue the System Design Requirements Document
- Issue a (first draft) Detector Integration Plan
- Design of a HAM chamber full-scale mock-up and oversight of construction of the BSC and HAM mock-ups
- Plan and implement utilization of the BSC and HAM mock-ups
- Continue updating the integration drawings; implement 3D chamber integrated layout drawings

## 6.2 Modeling and Analysis (WBS 1.4.3.3)

### Summary of Significant Accomplishments

- Completed AVS5 based Twiddle development and generated a manual for AVS Twiddle.
- Began efforts to study the requirements for LIGO data analysis as well as the current analysis techniques used at the 40 meter interferometer.
- Met with members of the VIRGO project in Annecy, France to discuss modeling and simulation as well as data formats for VIRGO and LIGO data. Continued the collaboration with the VIRGO modeling group to compare IFO simulation results.
- Developed a White Paper for advanced parallel computer hardware for data analysis under IBM's University Grants Program

### Description of accomplishments and work in progress

The effects of laser and modulation frequency and amplitude noises were modeled to be directly used in Twiddle and future end-to-end models. This code includes the effect of the mode cleaner. The effects of the non-resonant sidebands, especially the noises caused by the interference between higher harmonics were studied to find that there is no big noise source of this kind once the system is locked.

Five AVS noise modules were developed to calculate contributions from noise sources that play a significant role in the sensitivity of the initial LIGO detector. They can be used to model 40 meter interferometer noise by using appropriate parameter values. By default the values of the parameters in the model correspond to the initial LIGO design.

TopPlate - this module calculates the thermal noise associated with the top plate of the isolation stack based on the mass, temperature, resonance frequency and Q of the top plate and the coupling through the suspension to the test masses.

RadPress - this module calculates the displacement noise associated with the radiation pressure force fluctuation on the test masses in a recycled interferometer.

GravGrad - this module calculates the seismic gravity gradient noise based on the theory of Rayleigh and Love waves. Separate transfer functions are used to model the differences in stratification between the Hanford, WA. site and the Livingston LA. site. The user can select the ground spectrum which most closely characterizes the site.

ResidGas - this module calculates the phase induced displacement noise due to the residual gases found in the vacuum of the interferometer. The model calculates contributions from any of H2, H2O, N2, O2, CO, CO2, CH4 and a user specified hydrocarbon based on partial pressures and ability to polarize the individual gas species.

Quantum - this module calculates the quantum limited noise due to optimal laser power in the interferometer having test masses of mass m.

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. These noise sources are statistically combined and shown along with the individual sources in Figure 12 on page 34

The red curve represents the combined displacement sensitivity from these dominant noise sources. The black curve represents the curve outline from the Science Requirement.

Efforts at the 40 meter lab have begun to focus on enhancing the data collection capability of this instrument. In preparation for this new focus, the data analysis algorithms that have been used previously have been studied and improved. Part to this effort has had a significant impact on the design efforts that have begun for future LIGO data analysis. A working group was formed to study the various data analysis scenarios associated with LIGO data and the repercussions that such data analysis scenarios could possible have on the data acquisition system. These studies were reported at the May Science and Integration meeting at MIT.

A presentation on the current status and prospects for LIGO was given in late March at the data analysis session of the “Mathematical Aspects of Theories of Gravitation” at the Institute of Mathematics, Polish Academy of Science in Warsaw, Poland. Members of the GEO and VIRGO projects were also in attendance and gave status reports on those projects.

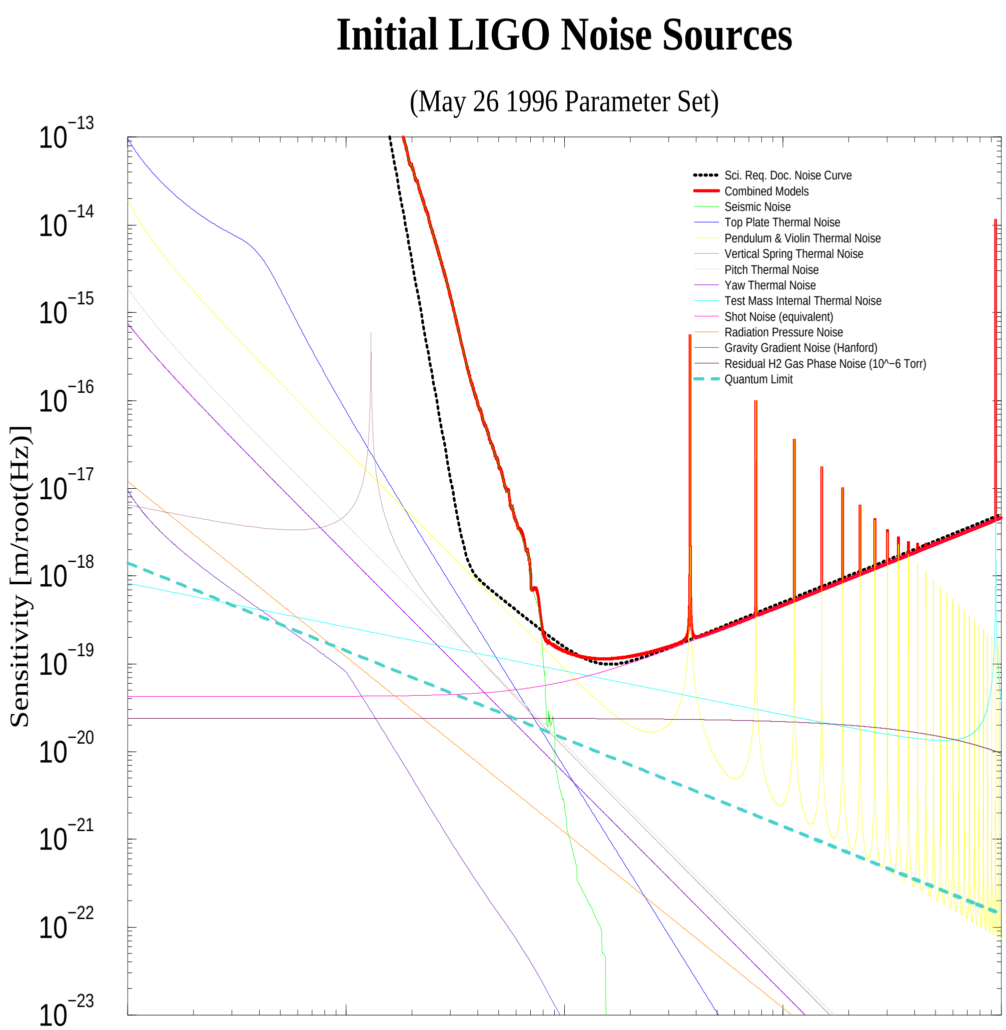



**FIGURE 12. Noise models developed during the past year provide an envelope for the dominant noise sources expected in the LIGO Interferometer.**

In a subsequent side trip to visit VIRGO representatives at LAPP in Annecy, France, discussions were held about the status of the VIRGO simulation software package known as SIESTA. SIESTA is a time domain computational model of the VIRGO interferometer with components for noise, optics and lasers, controls, and data analysis. While in Annecy discussions were also held on the data format that VIRGO has developed based on the C structure and how it might be made universal enough to be the standard for LIGO. These discussions continued in mid March when a group from VIRGO visited Caltech to discuss issues concerning joint data formats and data distribution between the two projects. Working groups were formed to look in more detail at these issues.

As part of the joint effort for data formats and data distribution with VIRGO, several tests of the LIGO and VIRGO modeling efforts were proposed. One of these tests compared the results for the internal test mass thermal noise. The results of this comparison indicated that the VIRGO model was significantly out of bounds with the numerical and the “quick” analytic values for this noise term. No word has been received at this time from VIRGO as to whether or not they have resolved this difference.

One of the actions identified by the working group on data formats was to conduct a thorough study of the public domain data formats that are being supported such as HDF at the NCSA Centers and CDF at NASA’s NSSDC. The preliminary findings from studies of these formats are that HDF is the most widely used and has the most potential for grow and adaptation in the future.

After the May Science and Integration meeting at MIT, a single day side trip was made to IBM’s Watson Research Center in Yorktown Heights, NY. The purpose of this meeting was to explore the types of technologies and potential for collaboration that exists within IBM on issues of data analysis for LIGO, especially in areas where scalable parallel computers become important such as in the case of the binary inspiral problem and the pulsar problem. After giving a presentation on LIGO at IBM, meetings were held which identified several researchers with enough interest and commitment to become collaborators with LIGO on data analysis issues.

In pursuit of a prototype data storage and analysis system for the 40 meter interferometer with clear scalability to LIGO, a joint proposal with Tom Prince, Kip Thorne, LIGO and internal IBM collaboration for IBM University Grants Program funding was developed. Through this proposal we are hoping to acquire additional IBM parallel computer architecture based equipment allowing the implementation of the algorithms to be used for binary inspiral and pulsar searches on the 40 meter interferometer data much as it would be accomplished with LIGO data.

**Work Planned for next Quarter**

- Develop AVS-Twiddle based IFO models with simple control systems and noise models for LIGO and implementation of those models in the full LIGO end-to-end modeling environment.
- Continue work with LSC to calculate various transfer functions together with efforts to implement new codes/models for the end-to-end model.
- Meet with the VIRGO project to converge on data formats. This meeting will actually occur in the fourth quarter, but prior to that meeting work will focus on evaluating the differences between the VIRGO format and the public domain HDF format, particularly in the area of performance and extensibility
- Design and develop the prototype data storage and analysis system for the 40 meter interferometer and determine how it will scale to the LIGO data storage and analysis requirements.
- Supervise the Caltech SURF students to improve the FFT programs so far developed at MIT. This effort will include optimizing the parallel FFT code in use on the Intel Paragon parallel computers at Caltech with a focus on making the code parallel portable using the paradigms of message passing interface standard (MPI) and High Performance Fortran (HPF); and implementing the front user interface on the LIGO Unix workstation to simplify / speed up using the FFT program, including the preprocessing, running and post processing the job.