Quarterly Report

(December 1996 through February 1997)

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

NSF Cooperative Agreement No. PHY-9210038

March 1997

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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

March 1997

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, 1996 through February 28, 1997.

1.0 Introduction

The Laser Interferometer Gravitational-Wave Observatory (LIGO) Project will open the field of gravitational-wave astrophysics through the direct detection of gravitational waves. LIGO detectors will use laser interferometry to measure the distortions of the space between free masses induced by passing gravitational waves. The design, construction, and operation of LIGO is being carried out by scientists, engineers, and staff at the California Institute of Technology (Caltech) and the Massachusetts Institute of Technology (MIT). Caltech has prime responsibility for the project under the terms of the Cooperative Agreement[1] with the National Science Foundation (NSF). LIGO will become a national facility for gravitational-wave research, providing opportunities for the broader scientific community to participate in detector development, observations and data analysis. LIGO welcomes the participation of outside scientists at any of these levels. The initial LIGO facility will comprise one three-interferometer detector system. The site allows for expansion of the facility to a multiple-detector configuration to enable simultaneous use by several gravitational-wave detectors.

The LIGO Project was described in the LIGO Proposal[2] submitted to NSF in December 1989, and the Technical Supplement[3] submitted to NSF in May 1993. Project organization is described in the LIGO Project Management Plan[4]. The cost of the construction activities for the observatory facilities and the initial detector equipment was presented in the LIGO Cost Book[5], which was reviewed in September, 1994.

This quarterly report covers activities accomplished during the first quarter of the sixth year (LIGO fiscal year 1997) of the Design and Construction Phase of the LIGO Project, and the related Research and Development. This phase includes facility construction, support equipment acquisition, initial interferometer design and fabrication, and the concurrent research to refine the initial detectors and data algorithms. LIGO Design/Construction began December 1, 1991 as defined in the Cooperative Agreement and will end with the acceptance of the vacuum systems at both sites and completion of the fabrication of the third interferometer.

2.0 Executive Summary

The project continues to make excellent progress. The project is 45 percent complete. The rate of accomplishment, as measured by our Performance Measurement tracking systems, has accelerated to reflect the effort in active subcontracts with a total contract value in excess of $120 million.

The first meeting of the LIGO Program Advisory Committee (PAC) was held at Caltech in January 1997. The LIGO PAC is the principal advisory group to the LIGO Management. The committee will meet approximately twice a year and will give advice on policy, management, and technical issues. The PAC will review all aspects of the program regularly, including LIGO related research by outside groups. Some of this work may be done by subcommittees, which can include outside members. The committee will assist LIGO in giving NSF input on LIGO related issues.

A proposal for the Advanced R&D to begin in FY 1997 has been submitted to the NSF.

Facilities. The activities of the Facilities Group continued to expand during the first quarter of 1997 due to the commencement of building and infrastructure construction on the Louisiana site. Woodrow Wilson Construction Co. (Baton Rouge, LA) began site road work and preparation for placement of the slabs along both arms of the interferometer. Hensel Phelps Construction Co. (Little Rock, AK) has begun excavation of the building foundations in preparation for building erection. Two LIGO personnel (Gerry Stapfer and Allen Sibley) are now resident on the Livingston site along with Parsons Construction Management personnel to oversee this activity. This work is proceeding on schedule.

In Washington, over three quarters of the beam tube sections comprising the northwest arm of the interferometer have been installed and individually leak tested. Fabrication of the beam tubes in the Chicago Bridge and Iron (CB&I) factory in Pasco, WA is running slightly ahead of schedule, with more than 250 beam tubes fabricated out of 400 needed for the entire Hanford site. Field installation work is running 3-4 weeks behind schedule due to start up problems encountered last fall that have since been resolved. CB&I is rapidly recovering schedule. Most recently, they have been installing beam tubes at 140-160 percent of the anticipated production rate, narrowing the 5-6 week schedule delay that existed at the beginning of the quarter to its present level. It is anticipated that CB&I will complete beam tube fabrication and installation activities on the Hanford site on schedule.

Civil construction at the Washington site has been delayed 28 days relative to the planned schedule due to a series of weather related delays. We expect that this will cause some realignment of the Process Systems International (PSI) schedule for installation of vacuum equipment in the mid- and end-stations of the northwest arm.

PSI began production fabrication of the large vacuum vessels and spool pieces needed for the Hanford site. Three Beam Splitter Chambers and one Horizontal Access Module have been completely assembled and are being readied for bake and final vacuum test. Large gate valves required for termination of the beam tubes (an overdue item last quarter) have been delivered to the site. PSI is proceeding on schedule.

Beam Tube Baffles. A problem with beam tube baffles was recognized early in the installation process when glass particles (from the porcelain coating) were found at the base of the baffles in the beam tube after baffle installation. The source of the problem was traced to a previously unrecognized high-stress region in the porcelain coating near the base of the baffle serrations. The problem was exacerbated by the unseasonably cold weather experienced at Hanford early in the year. Installation of the furfuraceous baffles was suspended and a tiger team was assigned to investigate the cause of the problem and develop corrective action. The investigations cover rework of existing porcelain-coated baffles, design and/or manufacturing process changes to eliminate the problem in future production, and development of a porcelain-free backup solution (with reduced technical performance). In addition, a plan was developed to permit continued installation of beam tube without baffles with baffle installation deferred until Fall '97 or Winter '97/'98 to allow time for the investigations to yield a technically adequate solution.

Detector. The seismic isolation preliminary design (carried out by Hytec, Inc.) was completed, and several prototypes of constrained-layer-damped springs are in testing. The first prototype Small Optics Suspension is in test in the 40-meter interferometer, and tests on a Large Optics Suspension are also underway.

The first blanks for the Core Optics have been delivered to the polishing vendors, and the first coating on a full size optic has been applied to one of the Pathfinder test masses. A pre-stabilized laser for R&D use has been delivered to the Phase Noise Interferometer, and the information is being incorporated into the Pre-Stabilized Laser subsystem design activity. Core Optics Support has made significant strides in the development of requirements and conceptual designs for the relay optics and internal anti-scatter baffling.

The Detector Subsystems Requirements Review was held this quarter, establishing the baseline requirements for the initial detector design. The optical layout advanced to the point of delivering critical wedge angles and distances needed for subsystems designs.

The Control and Data System activities included the start of fabrication of the first deliverable hardware, the racks for the Vacuum Controls, following the Final Design Review held in January. A prototype data acquisition system with LIGO-standard hardware and software has been configured and successfully bench tested; it will be installed in the 40-meter interferometer for further tests. Support for R&D tasks, in particular the 40-meter and Phase Noise Interferometer, continued.

The Phase Noise Interferometer work using the Argon laser source was completed, with a well-understood noise spectrum. The conversion to the Nd:YAG 1064 nm wavelength is underway. The physical re-configuration of the 40-meter interferometer for recycling has been completed as well.

Reviews. A semi-annual review of LIGO was conducted on behalf of NSF on October 22-24, 1996 at Caltech. The focus of this review was on technical progress and plans. Comments received from the committee were favorable. The next semi-annual review, which will also focus on the technical status of the project, is scheduled for April 15-17, 1997. There will be a visit to the Hanford site by a subset of the review committee on April 13 and 14.

Aspen Winter Conference. The Aspen Winter Conference on Gravitational Waves and their Detection, held during the week of January 27-31, 1997 was an Advanced Detector Workshop. There were several scheduled and impromptu meetings during the Workshop to facilitate consolidation of the collaborative R&D plans.

Visitor's Program. An active visitors program is being developed, roughly equivalent to three full-time equivalents (FTEs) each year (more during later years) with the participants involved in research for periods of six months or longer.

LIGO Collaboration. The University of Florida has submitted a proposal that would establish a LIGO Collaboration for the design and fabrication of the Input Optics (part of the Input/Output Optics Subsystem) in support of the initial LIGO Detector development and construction. A subcontract was awarded in November 1996 to initiate the design effort. The University of Florida proposal and modifications to the subcontract for continued effort are currently being considered by NSF.

The Input Optics provide the interface between the laser and the interferometer including mode cleaning and mode matching to the core optics, frequency modulation of the carrier, and additional frequency stabilization of the laser. The Input Optics design effort consists of design requirements definition (completed), conceptual design development (in progress), and experimental and analytical verification of design parameters and preparation of final design documentation for Input Optics fabrication.

The preliminary designs of the RF Modulation Subsystem, the Mode Cleaner Subsystem, and the Telescope/Beam Steering Optics Subsystem will be completed next quarter.

2.1 Project Milestones

The status of the significant milestones identified in the Project Management Plan (PMP) for the LIGO Facilities is summarized in Table 1. Contracts to begin Slab Construction and Building Construction on the Livingston, Louisiana site were awarded in December 1996 to Woodrow Wilson and Hensel Phelps respectively.

TABLE 1. Status of Significant Facility Milestones

Milestone Description	Project Management Plan Date[a]		Actual (A)/Projected (P) Completion Date	
	Washington	Louisiana	Washington	Louisiana
Initiate Site Development	03/94	08/95	03/94 (A)	06/95 (A)
Beam Tube Final Design Review	04/94		04/94 (A)	
Select A/E Contractor	11/94		11/94 (A)	
Complete Beam Tube Qualification Test	02/95		04/95 (A)	
Select Vacuum Equipment Contractor	03/95		07/95 (A)	
Complete Performance Measurement Baseline	04/95		04/95 (A)	
Initiate Beam Tube Fabrication	10/95		12/95(A)	
Initiate Slab Construction	10/95	01/97	02/96 (A)	12/96 (A)
Initiate Building Construction	06/96	01/97	07/96 (A)	12/96 (A)
Accept Tubes and Covers	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 approved by NSF in October 1996

Table 2 shows the status of the significant milestones for the Detector. The projected completion date for the *Core Optics Support Final Design Review* is now December 1997 (vs. April 1997). Some of the scope originally in this task has been moved to the Susoension task. This defers some need dates. The delay does not affect the expected date for first operation of the LIGO interferometers. A better understanding of the requirements and design for the Core Optics Support has reduced the expected fabrication time, and all critical components are expected to be ready in time to avoid installation delays.

The *Core Optics Components Final Design Review* has also been delayed by approximately three months. In this case, an aggressive procurement strategy has been instituted which permits initial fabrication steps to be started prior to the FDR without incurring significant risk and, in fact, reducing costs by permitting rework of any parts damaged during fabrication as opposed to requiring more numerous spares.

As of the end of February 1997, all significant project milestones can be achieved.

TABLE 2. Status of Significant Detector Milestones

Milestone Description	Project Management Plan Date		Actual (A)/Projected (P) Completion Date	
	Washington	Louisiana	Washington	Louisiana
BSC Stack Final Design Review	07/97		08/97 (P)	
Core Optics Support Final Design Review	04/97		12/97 (P)	
HAM Seismic Isolation Final Design Review	07/97		08/97 (P)	
Core Optics Components Final Design Review	07/97		10/97 (P)	
Detector System Preliminary Design Review	12/97		12/97 (P)	
I/O Optics Final Design Review	04/98		05/98 (P)	
Prestabilized Laser Final Design Review	08/98		08/98 (P)	
CDS Networking Systems Ready for Installation	09/97		07/97 (P)	
Alignment (Wavefront) Final Design Review	04/98		02/98 (P)	
CDS DAQ Final Design Review	04/98		05/98 (P)	
Length Sensing/Control Final Design Review	05/98		12/97 (P)	
Physics Environment Monitoring Final Design Review	06/98		08/97 (P)	
Initiate Interferometer Installation	07/98	01/99	07/98 (P)	01/99 (P)
Begin Coincidence Tests	12/00		12/00 (P)	

2.2 Financial Status

Table 3 summarizes costs and commitments as of the end of February 1997. Figure 1 on page 9 shows the costs and commitments as a function of time.

2.3 Performance Status (Comparison to Project Baseline)

Figure 2 on page 10 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. Figure 3 shows the same information as a function of time for the LIGO Project.

TABLE 3. Costs and Commitments as of the End of February 1997

WBS	Description	Costs Thru Nov 1996	Dec-96	Jan-97	Feb-97	Cumulative Costs	Open Commitments	Total Cost Plus Commit-ments
1.1.1	Vacuum Equipment	21,254	869	43	44	22,210	22,662	44,872
1.1.2	Beam Tube	17,262	107	3,427	1,260	22,057	35,292	57,349
1.1.3	Beam Tube Enclosure	6,237	251	459	247	7,195	12,269	19,465
1.1.4	Civil Construction	14,117	1,665	1,567	1,474	18,822	30,239	49,061
1.2	Detector	6,270	478	281	762	7,791	6,014	13,805
1.3	R&D	16,816	272	153	420	17,661	1,229	18,890
1.4	Project Management	16,288	457	411	583	17,740	1,964	19,704
	Unassigned (See Note)	2	(1)	-	1	2	131	132
	TOTAL	98,246	4,098	6,342	4,791	113,477	109,800	223,277
	Cumulative Actual Costs	98,246	102,344	108,686	113,477			
	Open Commitments	91,492	113,149	112,583	109,800			
	Total Costs Plus Commitments	189,738	215,493	221,269	223,277			
	NSF Funding	*208,468*	*208,468*	*265,389*	*265,389*			

Note: "Unassigned costs" have not been assigned to specific LIGO Work Breakdown Structure element, but are continually reviewed to assure proper allocation.

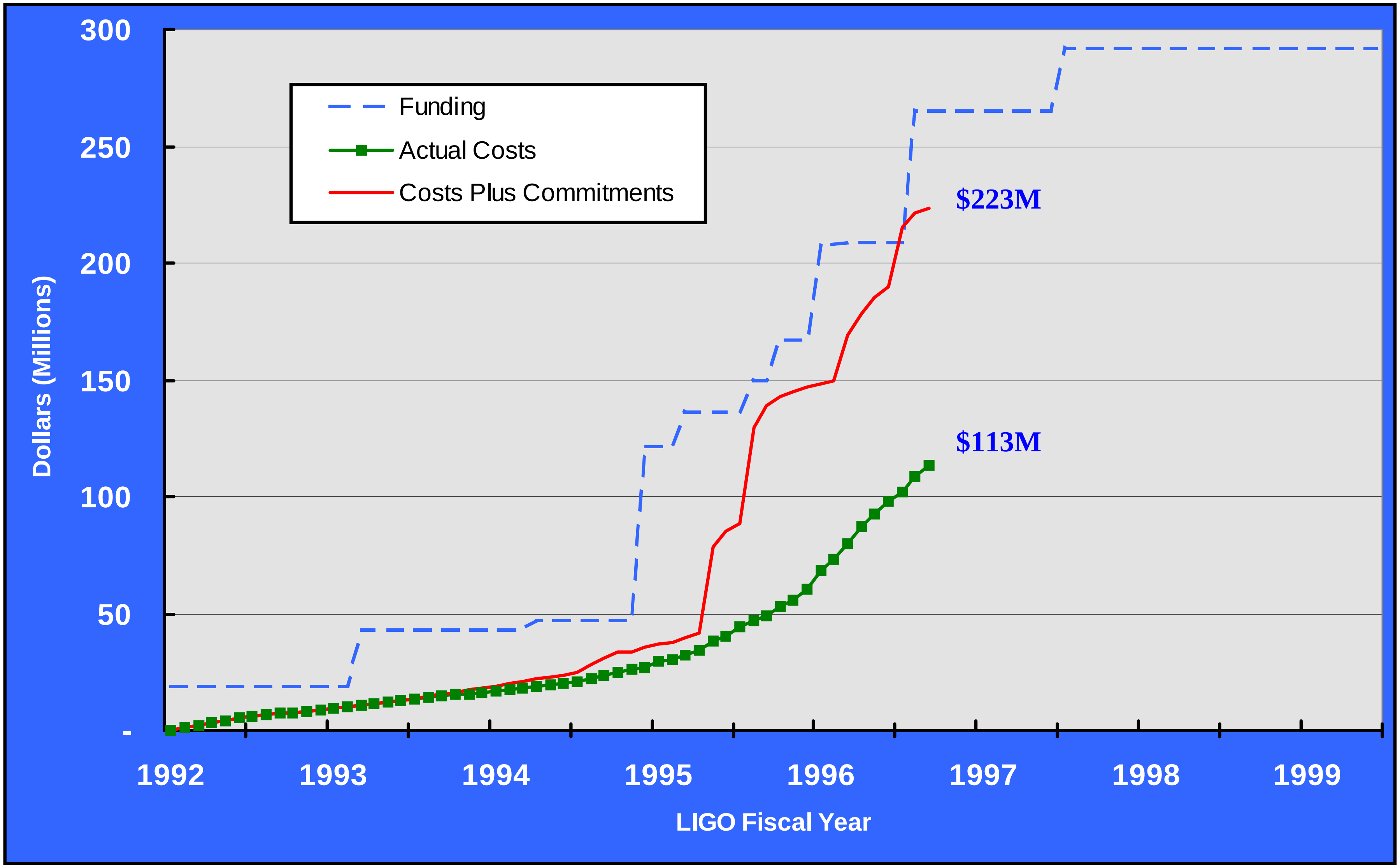

FIGURE 1. Costs and Commitments as a Function of Time (End of February 1997)

Run Date: 26MAR97	COST / SCHEDULE STATUS REPORT (CSSR)			Page 1
CONTRACTOR: Caltech LOCATION: Pasadena, CA	CONTRACT NUMBER: PHY-9210038	CONTRACT BUDGET BASELINE	REPORTING PERIOD: 31JAN97-28FEB97	PROJECT FILE NAME: 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	23580	23423	22210	(157)	1213	42113	42113	0
1.1.2 : Beam Tubes	20527	22282	22057	1755	226	47298	47298	0
1.1.3 : Beam Tube Enclosur	8641	8151	7195	(490)	956	19384	19384	0
1.1.4 : Facility Design &	18548	19589	18822	1042	767	48311	48311	0
1.2 : Detector	10327	8928	7753	(1399)	1175	52567	53336	(769)
1.3 : Research & Developme	18429	18121	17661	(309)	460	23490	23490	0
1.4 : Project Office	17844	17844	17740	0	104	27074	27074	0
SUBTOTAL	117896	118338	113437	441	4901	260238	261007	(769)
CONTINGENCY						0	31087	(31087)
MANAGEMENT RESERVE						0	0	0
TOTAL	117896	118338	113437	441	4901	260238	292094	(31856)

COBRA (R) by WST Corp.

FIGURE 2. Cost Schedule Status Report (CSSR) for the End of February 1997

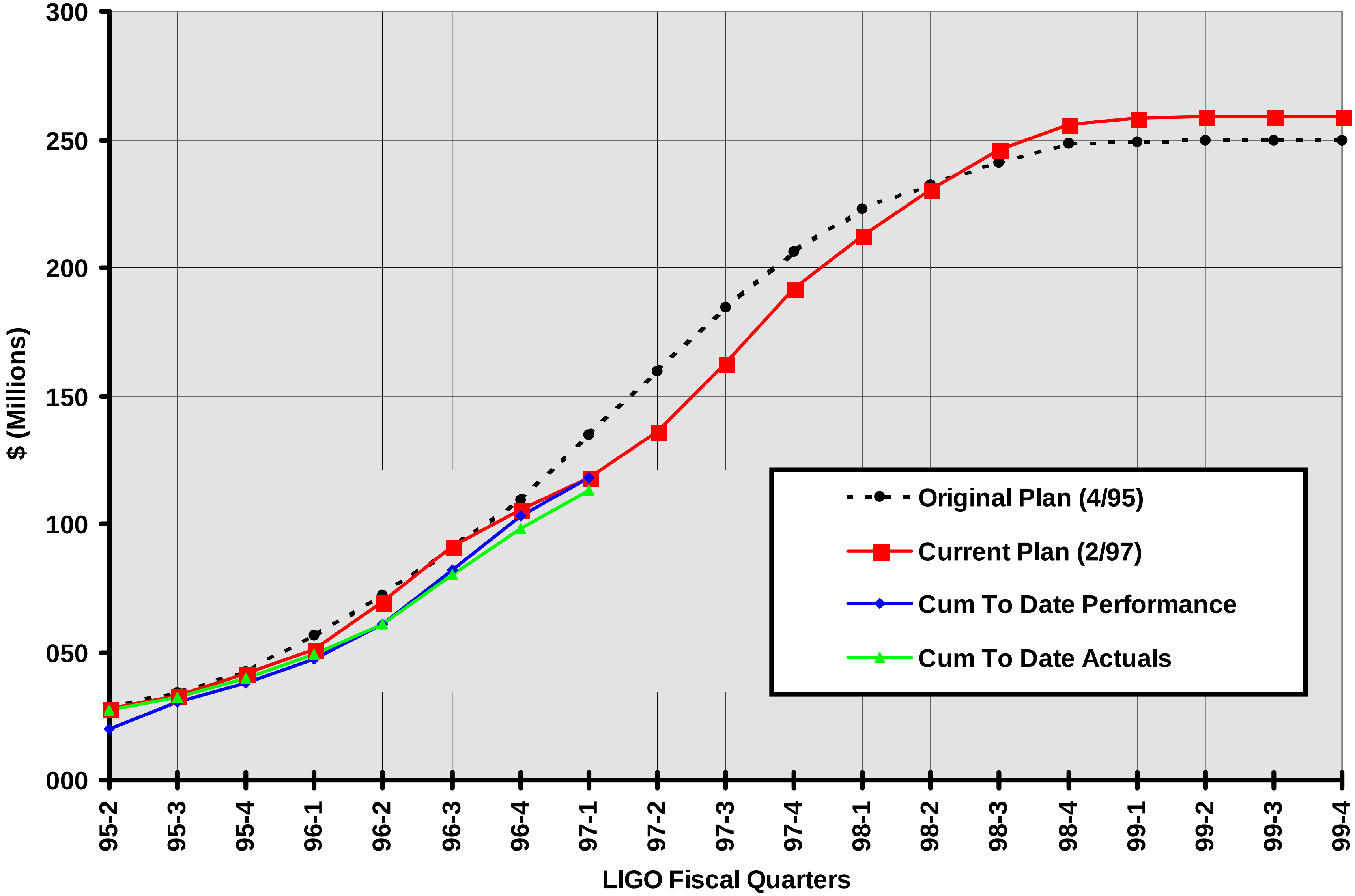

FIGURE 3. LIGO Project Budget, Earned Value, and Actual Costs as a Function of Time

Vacuum Equipment. Vacuum Equipment (WBS 1.1.1) shows a favorable cost variance primarily due to the delays in the processes of invoicing and payment which will not translate into a projected underrun at the end of the project. Efforts during FY 1996 to expedite payments have reduced this effect. Vacuum Equipment is slightly behind schedule. A large number of components have been fabricated but are waiting to be cleaned and tested.

Beam Tube. The favorable schedule variance in the Beam Tube (WBS 1.1.2) reflects purchases of stainless steel that were advanced to take advantage of favorable prices and which offset a behind schedule position in beam tube installation.

Beam Tube Enclosure. The Beam Tube Enclosure (BTE) (WBS 1.1.3) started behind schedule due to a late start by CB&I installing the Beam Tube. In addition there have been weather delays caused by high winds during the winter season that preclude crane operations. Levernier, the contractor responsible for BTE installation, is installing at rates up to 35 BTEs per day enabling them to regain schedule. However, Levernier's progress is limited somewhat by the Beam Tube contractor's rate of aligning the Beam Tube.

The favorable cost variance reflects normal delays in processing invoices.

Civil Construction. (WBS 1.1.4) Favorable cost and schedule variances are reported. Actually there have been some delays in Washington on the critical path because the planned supplier for the siding for the buildings is no longer providing the required materials. A new supplier has been identified.

New schedules have been developed based on detailed plans provided by the subcontractors selected in Louisiana, and these new schedules will be incorporated into the LIGO baseline during April.

The favorable cost variance reflects normal delays in processing invoices.

Detector. The Detector (WBS 1.2) is behind schedule and under cost. LIGO has been attempting to hire additional staff, but this has not been accomplished quickly enough to avoid some delays. In addition personnel have been diverted to the R&D tasks. It will be noted that a year ago the R&D effort was approximately six months behind relative to the plan proposed in September 1994, but that during the past year the status of these R&D tasks has improved dramatically. Priorities are being adjusted to assure that all critical milestones will be met.

Specific tasks that are behind schedule include:

- The laser is behind relative to the internal LIGO plan. However, this reflects the fact that the vendor's plan included a longer time for development and a correspondingly shorter time for production. All final milestones are on track.
- A behind schedule position in the Seismic Isolation task is due to explorations of alternative designs that are outside of the original scope of work. It is anticipated that schedule will be recovered during fabrication.
- Budget is not adequate for the Length Sensing Control (LSC) effort, and this is being addressed through the change control process.

2.4 Change Control and Contingency Analysis

One Change Request (CR) in Table 4 was approved during the first quarter of FY 1997. The change request was approved with a not-to-exceed cost of $150,000 and will be entered into the baseline when actual costs can be determined. The current contingency pool is $31.9 million.

TABLE 4. Approved Change Requests

Change Request No.	Description	Date Approved	Allocated From/(To) Contingency
CR-970003	WBS 1.1.4 Civil Construction - Air ducts, manufacturing processes and specifications	February 13, 1997	See text

2.5 Staffing

The LIGO staff currently numbers 104 (full time equivalent). Of these, 21 are contract employees. Eighty-seven LIGO staff are affiliated with CIT including four graduate students. Seventeen are located at MIT including three graduate students. Of these, six are now located at the Hanford, Washington site, and three are located in Livingston, Louisiana.

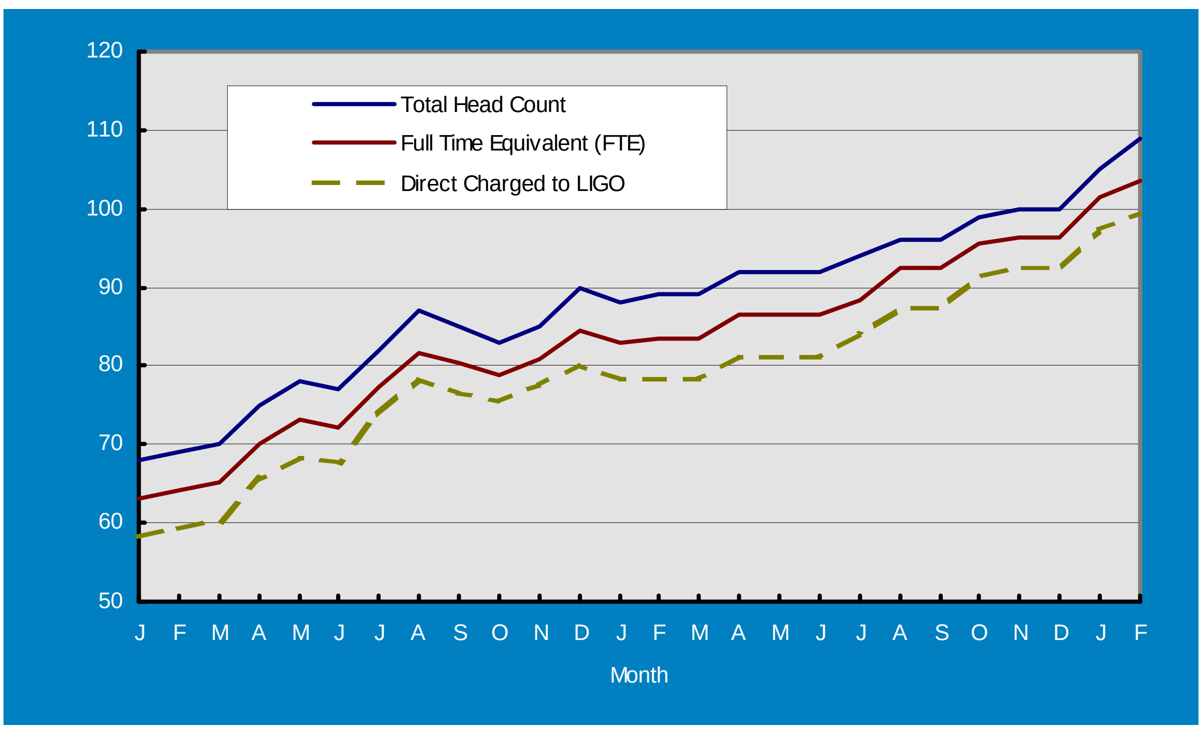

FIGURE 4. LIGO Staffing History since January 1995

3.0 Vacuum Equipment (WBS 1.1.1)

Significant accomplishments during this quarter

- Mechanical completion of first Horizontal Access Modules.
- Receipt of first two production Beam Splitter Chambers from RANOR.
- Completed and tested short 80k pump reservoirs.
- Complete delivery of large GNB gate valves for the Beam Tube contractor.
- Received first bids from potential installation contractors.
- Receipt of first purge air supplies.
- Receipt of all production quantity stainless steel material.
- Receipt of all small ion pumps.
- Start fabrication of small gate valves.

In December 1996 Process Systems International (PSI) issued the Washington installation bid package. A bidders meeting was held in Richland, Washington to answer questions and to allow the bidders to view the site. PSI plans to select a contractor in April 1997.

The first Horizontal Access Module (HAM) chamber was mechanically completed in January and has now been cleaned. The chamber is assembled in the clean room facility at PSI to be baked and vacuum tested. Figure 5 and Figure 6 show the HAM chamber during assembly in the clean room.

FIGURE 5. Horizontal Access Module Chamber

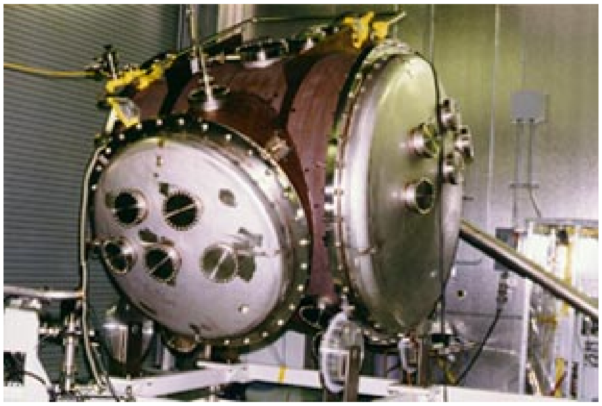

FIGURE 6. HAM Chamber with Doors

PSI now has on hand three production Beam Splitter Chambers (BSCs). RANOR recently began work on the Louisiana BSCs well ahead of the planned start date of June 1997. Figure 7 shows two production BSCs at the PSI facility ready for cleaning and final assembly.

FIGURE 7. Production Beam Splitter Chambers at PSI

During this quarter PSI has completed and tested three 80K pump reservoirs. Figure 8 shows two of the reservoirs. During this period PSI has also completed fabrication of many spool pieces. Figure 9 shows a flange being welded to a bellows unit in the spool fixture.

Work to be accomplished during the next quarter includes

- Select the installation contractor for the Washington site.

FIGURE 8. 80K Pump Reservoirs

FIGURE 9. Welding a Flange onto a Spool

- Receive the first production bakeout blankets.
- Commission the PSI hot air bakeout system.
- Perform bakeout and vacuum testing on production chambers.
- Begin fabrication of the large liquid nitrogen dewars for Washington.

4.0 Beam Tube (WBS 1.1.2)

Significant accomplishments during this quarter

- 225 of the 400 tube sections required for the Hanford site were fabricated and checked for leaks.
- 154 tube sections were installed and checked for leaks at the Hanford site (as of March 13).
- A facility was leased for fabricating beam tube sections in the Livingston, Louisiana area.

Discussion of accomplishments and work in progress

Coil processing continued, with favorable low hydrogen outgassing readings. Both tube section leak checks (fabrication shop) and girth seam leak checks (installation site) have continued to be 100 percent leak free.

After a slow start due to weather and normal start-up problems, the tube section installation rate has now exceeded plan by 30 percent, and completion of installation of beam tube modules on the first (X) arm is expected to be one month late. The contractor, Chicago Bridge & Iron (CB&I), expects to finish the Hanford site on schedule.

An inspection of installed tube revealed that some of the installed baffles are shedding glass shards at a rate that would threaten interferometer measurements. Baffle production and installation were placed on hold, and actions were taken to better understand the problem and to develop a solution. Both baffles with improved glass coatings and baffles without glass are being considered, and tests are being developed to give assurance of coating integrity. Currently installed baffles will be replaced, and plans are being formulated for installing baffles deeply into the modules.

Work planned to be accomplished during the next quarter:

- 87 percent of the beam tube sections for Hanford will be fabricated.
- Installation of beam tube sections for the first arm at Hanford will be completed.
- Acceptance testing of the first module will begin.
- The investigation for understanding baffle glass shedding will be completed. The choices for repair/new manufacture of baffles will be narrowed.

FIGURE 10. Aerial View of X Arm Beam Tube Installation.

FIGURE 11. Areas of Glass Shedding near Baffle Serrations

5.0 Beam Tube Enclosure (WBS 1.1.3)

Significant accomplishments during this quarter:

- Reached the 90 percent completion level of precast fabrication of the beam tube enclosure segments for the Hanford site.
- Completed the construction contract documents for the Site Work and Precast Fabrication and Installation of the beam tube enclosure for the Livingston site.
- Started the construction of the service roads, fabrication and installation of the beam tube enclosures at the Livingston site.

Discussion of accomplishments and work in progress

G970040-18-O-P

FIGURE 12. Delivery and Installation of the Beam Tube Enclosure Segments along the Northwest Arm at Hanford site

Hanford Site. Construction of the beam tube enclosures proceeded on schedule and it reached the 90 percent completion level by the end of this period. This included the completion of both service roads, beam tube enclosure slabs for the both arms and pre-casting of about 2,300 enclosure segments (each 10ft long). Installation of the beam tube segments followed the installation of the beam tube s and about 100 segments were placed successfully during this period (Figure 13).

Livingston Site.The Parsons I &T, the A-E contractor, completed the construction documents for Building and Site Work and Precast Fabrication and Installation for the beam tube enclosure con-

FIGURE 13. Installation of Beam Tube Enclosure Segments closely following the installation of the Beam Tube.

tract. Notice to proceed for the this contract was issued to Woodrow Wilson Construction Company. The LIGO and Parsons' construction management office was set up and the construction work began on the service road along southeast arm.

Work planned to be accomplished next quarter

- Complete the precast fabrication of the beam tube enclosure segments for the Hanford site.
- Complete the installation of the beam tube enclosure segments on the northwest arm of the LIGO Hanford site.
- Start the precast fabrication of the beam tube enclosure segments for the Livingston site.
- Submit and obtain the approvals of shop drawings for the beam tube enclosure contract for the Livingston site.
- Complete the finish grading and subbase preparation along both arms at the Livingston site.

FIGURE 14. View of Corner Station at the Hanford Site.

6.0 Civil Construction (WBS 1.1.4)

Significant accomplishments during this quarter:

- Completed the construction contract documents for the Building and Infrastructure for the Livingston site.
- Started the construction activities for the Buildings and Infrastructure at the Livingston site.
- Reached the 30 percent completion level for construction of the buildings and infrastructure at the Hanford site.
- Awarded the contract for the Surveying Support for the Livingston site to Simmons J. Barry & Associates.
- Awarded the contract for the Quality Assurance, Testing and Reporting for the Livingston site to Delta Testing and Inspection, Inc.

Discussion of accomplishments and work in progress

G970036-01-O-P

FIGURE 15. View of LVEA at Hanford

Hanford Site. Construction of the buildings and infrastructure continued at the site by Levernier Construction Company. Weather was a problem during this period. Total days lost through the end of this period due to inclement weather is 28 calendar days. However, the construction progress as the end of this period is only a few percent behind the baseline schedule. Construction of the buildings and infrastructure reached the 30 percent completion level at the Hanford site. This included placement of all concrete work for the building and technical foundations for the end and mid stations on southwest arm as well as the corner stations. Also, completed all structural steel framing for these stations. Siding and roofing of the mid and end stations on southwest arm has been completed and work inside these stations have started (Figure 16 and Figure 17).

G970036-11-O-P

FIGURE 16. View of Mid Station on Southwest Arm at the Hanford Site.

G970040-11-O-P

FIGURE 17. View of End Station on Southwest Arm at the Hanford Site.

Livingston Site.The Parsons I & T, the A-E contractor, completed the construction documents for Building and Infrastructure contract design for the Livingston site. This consisted of the signed and stamped technical specification and drawings for the awarded contract. Notice to proceed was issued for this contract to Hensel Phelps Construction Company and construction work started at the end station on northeast arm and corner station (Figure 18).

G970035-01-O-PV

FIGURE 18. Excavation for the Foundation for the End Station on Southeast Arm at the Livingston Site.

Simmon J. Barry & Associates of Baton Rouge, LA was selected and was awarded the contract for performing the surveying support for all construction work at the Livingston site.

Delta Testing and Inspection,Inc.of Baton Rouge, LA was selected and awarded the contract for Quality Assurance and Testing and reporting support for all the construction activities at the Livingston site.

Work planned to be accomplished next quarter

- Complete the construction work on the mid and end stations on the southwest at the Hanford site.
- Complete placement of concrete for the technical and building foundations for the end station on northwest arm at the Hanford site.
- Complete the siding on the corner station at the Hanford site.
- Complete all submittals and obtain approvals for the shop drawings for the buildings at the Livingston site

- Complete the placement of the concrete for the technical and building foundation for the end station on southeast arm as well as corner station.

7.0 Detector (WBS 1.2)

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

- WBS 1.2.1 Interferometer System, 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 Physics Monitoring System
- WBS 1.2.4 Support Equipment

Detector activities started in December 1994. As noted in the 1996 Annual Report, the schedule planned for FY96 was quite aggressive, and we have also had difficulty staffing the activities at the planned rate. As a consequence, we have replanned a number of activities, taking advantage of the staged installation schedule.

While we continue to report progress separately for R&D activities and Detector activities, the task groups enumerated above include the relevant R&D (most laboratory activities and exploratory modeling) with the objective of concentrating the activity on a given domain. In addition, the Detector Site Implementation and Operations task group reports activities focussed on these topics and also the activities in the 40-meter Interferometer facility, which is a primary tool for tests of operations and integration for the Detector group.

7.1 Suspensions and Isolation

Significant accomplishments during this quarter

- Produced and characterized (initial) the prototype coil and leaf springs for the seismic isolation system
- Completed the Preliminary Design of the Seismic Isolation System
- Installed and completed the first tests of a LIGO-design Small Optics Suspension prototype in the 40-meter interferometer

Seismic Isolation. The Preliminary Design phase of the Seismic Isolation took place during the first quarter of 1997. Hytec, Inc., performed extensive design and analysis of the isolation ‘stack’ itself, the structure linking the stack to the optics, the internal and external support structures, and the actuators. The latter present particular design challenges with requirements for moving 12 tons with sub-micron resolution; a combination of air bearings and a piezo-electric transducer (both commercial items) appears to meet the requirements. In addition, prototypes of the two constrained-layer spring designs were fabricated and underwent preliminary testing for stiffness, hysteresis, and damping. The coil spring appears to be satisfactory, and will be produced in larger quantities for further testing and production tuning. Documentation for the design effort was completed and circulated in preparation for the Preliminary Design Review planned for early in the second quarter.

Suspension Design. Work continued on the Final Design for both the Small and Large Optics Suspensions. Initial measurements of prototypes of the suspension cages showed lower than expected internal resonance frequencies (which could lead to thermally driven peaks in the interferometer output). Finite element analysis was performed to find the weak points in the design and small modifications to the design are in process. The Large Optic Suspension prototype underwent testing with a ‘dummy’ test mass to allow measurements of the controller performance, as well as fit and installation procedure checks. The Small Optic Suspension prototype was installed in the 40-meter interferometer (suspending the beamsplitter), where it will undergo system and noise tests.

Work planned to be accomplished during the next quarter

- Seismic Isolation. Conduct the Preliminary Design Review; start Final Design and prototype/first article activities and conduct tests for static and dynamic performance of the springs.
- Suspension Design. Prototype test reviews will be held for the Large and Small Optics Suspensions; Small optics final design revisions will be carried out.

7.2 Lasers and Optics

Significant accomplishments during this quarter

- Prestabilized Laser. An interim design review was held on December 18 for the Nd:YAG light source.
- Input Optics. Detailed designs for the input coupling telescope were carried out.
- Core Optics. The first substrates have been delivered to polishing vendors, and the first coating performed on a full-scale test optic.

Prestabilized Laser. Lightwave, Inc. continued in their development program for the LIGO 10W Nd:YAG laser, and an interim review was held at Lightwave on December 18. Results from the prototype effort has led to some redesign of the amplifier section of the system, but there are no difficulties anticipated in maintaining the initial schedule. Considerable in-house experience has been obtained with the 700 mW lasers which act as the master oscillator for the Lightwave 10W laser, through the development of a pre-stabilized laser for R&D work (see below) and the characterization of optical components in the infrared. This has allowed the control inputs to the laser to be exercised and is providing input to the conceptual design for the complete Pre-Stabilized laser. A collaborative effort with Stanford University is investigating the properties of a spatial and temporal filtering cavity which may be needed for the laser subsystem. The prototype has shown encouraging progress, and the optical efficiency is very high. The Design Requirements for the laser subsystem are being refined and documented in preparation for a review in the second quarter.

Input Optics. The University of Florida group responsible for the Input Optics is continuing the Preliminary Design. In addition, the Design Requirements Review last quarter led to a number of action items which are being worked, among them are a requirement for flexibility in the input optics parameters (leading to a challenging coupling telescope design), refinement of control systems, and integrating the design with the overall optical layout (which leads to length and modulation frequency requirements). Visits by both LIGO and University of Florida staff are maintaining the close coupling needed for a good integration of the effort.

Core Optics Components. This time-critical subsystem continues to advance well. The substrates for the recycling mirror, folding mirrors, and end test masses are in production (Corning, Inc.) with some initial deliveries complete. A readiness review for one of our polishing vendors, the Commonwealth Scientific and Industrial Research Organization, was held on January 20-21, and substrates have been sent to them for the start of production. A Pathfinder polished substrate has been sent to the VIRGO metrology lab for homogeneity tests. A second was sent to General Optics for polishing.

The coating uniformity studies have continued with Research Electro-Optics Inc. (REO). Special-purpose anti-reflective coatings are applied at REO which have a reflectivity with a strong dependence on the coating thickness. A spatial mapping of the reflectivity of the coatings is performed by LIGO, and a complete surface map synthesized from these measurements. These maps are used in the FFT numerical optics model of the complete interferometer to give us an accurate estimate of the performance of these coatings; in addition, recognition of geometric regularities in the coating thickness give indications of how the process can be improved and are shared with REO. This has enabled the first coating runs on full-size LIGO optics at the end of this quarter; these mirrors will be delivered to NIST for measurements.

LIGO plans to perform the final metrology in-house. Requirements for the critical measurement systems were developed this quarter and will be sent to prospective vendors in the next quarter.

Core Optics Support. The core optics support subsystem is responsible for handling the light leaving the interferometer; this includes the principal output beams from which the gravitational-wave will be read out and the other control signals developed, and also the stray light within the and vertex stations and the design of baffling for its control. An initial draft of a Design Requirements Document has been drafted, establishing a paradigm for the system, and the conceptual design has also advanced considerably this quarter.

Work planned to be accomplished during the next quarter

- Prestabilized Laser (PSL). Complete the Preliminary Design Review for the Lightwave 10 watt Nd:YAG lasers. The Design Requirements Review for the laser pre-stabilization subsystem will be held.
- Input Optics. Preliminary design will continue on the expanding optics, modulation system, mode cleaner, and telescope.
- Core Optics. The present fabrication activities will continue. Design/procurement of in-house metrology tools will take place.
- Core Optics Support. The Design Requirements review will be held and preliminary design will commence.

7.3 Interferometer Sensing/Control

Significant accomplishments during this quarter

- The Preliminary Design of the Alignment Sensing/Control Subsystem was completed.
- The Preliminary Design of the Length Sensing/Control Subsystem continued; tests of photo-detectors was carried out.

Alignment Sensing/Control. Preliminary design has dominated the activity this quarter. The information from the very successful R&D demonstration of wavefront sensing was integrated into the design, with a decision to use the prototype hardware as a close-to-final design for the wavefront sensors and demodulators. Several extensions of the models were made: one to allow larger angles to be analyzed (showing that the maximum alignment for lock acquisition is of the order of 10^{-7} radians) and another to allow transfer functions for control signals to be determined (showing that no new concerns lie in this part of the design). The LIGO alignment design team will make the detailed design for the input optics mode cleaner, and a collaborative visit to the group at the University of Florida led to firm plans and resolution of some interface issues. As this quarter closed, the Preliminary Design documentation was completed and sent out; a review will take place early in the next quarter.

Length Sensing/Control. The preliminary design for this subsystem continued, with most of the effort concentrated on the acquisition of the locked state. This work is closely coordinated with the Alignment acquisition studies and uses modeling tools developed for the alignment as well as models developed at JPL under contract for this purpose. The sensitivity of the acquisition sequence to parameter values was explored, with sign changes found for ‘under-coupled’ (cavity losses larger than input coupling mirror transmission) vs. ‘over-coupled’. The modeling is also applied to the configuration of the 40-meter interferometer as this will be where the design is verified (see below). In addition, measurements on InGaAs photodiodes were started to identify the commercial sources which can meet our requirements for power handling, frequency response, and linearity.

Work planned to be accomplished during the next quarter

- Alignment Sensing/Control. Final design will continue; initial alignment and wavefront sensing prototype fabrication will be started.
- Length Sensing/Control. Preliminary Design will continue.

7.4 Detector System Engineering/Integration

Significant accomplishments during this quarter

- The Detector Subsystems Requirements Review was held on December 4, 1996.

The Detector Subsystems Requirements Document was reviewed this quarter, and this document now is the definitive reference for the subsystem requirements. There are elements which need more definition, and that work continues in conjunction with the individual subsystems. The optical layout made significant progress and allowed some specific cross-subsystem design issues to be resolved, including exact lengths of resonant cavities and the wedge angles to be used on the Core Optics.

Work planned for next quarter

- System Design Requirements. The final interferometer subsystems Design Requirements Reviews will be held, and the refined documentation issued for designer reference.
- Optical Layout. The three-dimensional optical and mechanical layouts, integrated with the other project mechanical design tools, will be completed for the LIGO Hanford interferometers.

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

Significant accomplishments during this quarter

- The Final Design Review for the Vacuum Controls was held on January 8
- A prototype data acquisition/frame builder system has been configured and successfully bench tested

The CDS group has placed staff at the LIGO Hanford site to supervise the early activities. In addition, a strong local group is being built to be ready to take on the principal installation and debugging which will be starting soon.

Support for interferometer subsystems: The CDS group advanced in the design for several of the interferometer subsystems. The Alignment Sensing and Control system, which presents probably the most complicated design problems in the in the interferometer, advanced in parallel with the optics and sensing design reported above, and the CDS Design Requirements Document for this subsystem was circulated at the end of the quarter for review early next quarter. The Pre-stabilized laser system has gone through a prototyping stage in support of R&D activities (see below), and this has allowed the electronics design ‘high points’ to be identified and a first-cut design developed. The Suspension subsystem has seen the exercise of a LIGO-prototype control system in the

40-meter interferometer, with both electronic performance and in-vacuum wiring concepts tested. The Length Control and Sensing top-level concepts evolved with the modeling, and the states of the system are now identified. In addition, the difficult problem of analog to digital and digital to analog conversion (necessary to pass signals to the 4km-distant end mirrors) has been researched. The Physics Environment Monitor CDS Design Requirements Review was held, with detail in interface and data handling laid out in the associated Requirements and Conceptual Design documents.

Global system and Data acquisition: A full prototype data acquisition system is being developed and will be tested using the data (strain and environmental monitor) from the 40-meter interferometer. During this quarter the software for frame building was adapted from the VIRGO source (with some useful feedback to the VIRGO group on incompatibilities and errors) and is running on the target platform. Tape robot software was installed and configured. Data acquisition hardware was designed and produced, including anti-aliasing filters. As the quarter closes, the complete data system is functional and in test. Networking bandwidth tests using an ATM switch planned for LIGO was performed.

Vacuum Controls: The Final Design Review was held on January 8, enabling the start of hardware production. The wiring of the crates for this control system was half finished at the end of the quarter.

R&D support: Two research efforts received significant support. The 700 mW pre-stabilized laser, to be used on the Phase Noise Interferometer and for other early tests of IR lasers, was completed and shipped to MIT at the end of the quarter; feedback from measurements there will be used for the LIGO laser control design. The 40-meter Recycling experiment has presented a particular challenge, as the locking sequence has required a significant rework of the existing control electronics. This work continues as the quarter closes.

Work planned to be accomplished during the next quarter

- Interferometer Controls.The Pre-Stabilized Laser and Input Optics conceptual design will start. The Preliminary design for the Alignment Sensing/Control, Core Optics Support, and Seismic Isolation will be underway.
- CDS integration and global systems. Final Design activities will continue.
- Data acquisition. Preliminary design will continue.
- Vacuum system controls. Fabrication will continue.
- Interferometer Diagnostics. Refined science input to the design process will be completed and reviewed; Preliminary Design will continue.

7.6 Physics Environment Monitor (WBS 1.2.3)

Significant accomplishments during this quarter

- The Preliminary Design Review was held on February 5.

The Physics Environment Monitor preliminary design was completed during this quarter. Specific sensors and actuators were identified to meet the requirements, and data acquisition requirements fleshed out. The Preliminary Design Review took place on February 5, enabling the Final Design to begin. Most of the equipment is available commercially, but some sensors and actuators will need in-house development. We plan to make some early measurements at the two LIGO sites to characterize the near-virgin environment, and have thus started to plan a set of measurements using Physics Environmental Monitor hardware but without relying on the (not-yet-installed) CDS backbone but instead a portable PC-based system using commercial software.

Work planned to be accomplished during the next quarter

- The Final Design will continue.
- A system for early on-site measurements will be assembled and employed.

7.7 Support Equipment (WBS 1.2.4)

Definition of the required Support Equipment will continue.

8.0 Research and Development (WBS 1.3)

Significant accomplishments during this quarter

- Completed the physical reconfiguration of the 40-meter interferometer for recycling.
- Concluded work on the Argon-laser Phase Noise Interferometer.

40-meter Interferometer Investigations. The reconfiguration of the 40-meter interferometer as a LIGO-like Fabry-Perot recycled interferometer occupied the installation this quarter. New vacuum chambers were attached and qualified, equipped with seismic isolation systems, and the optical components installed. Some problems with existing 40-meter components were identified and repaired in the process. One important aspect of the reconfiguration is the use of a LIGO Small Optics Suspension for the beamsplitter, and the 40-meter team and the CDS group worked together to test this new system and to work out problems in installation and initial performance. The first light into the system was toward the end of the quarter with precision alignment underway at the close.

Development of Data Acquisition and Analysis Techniques. As reported above, the prototype LIGO data acquisition system is being deployed for use with the 40-meter, and this is a joint effort of the CDS and 40-meter team.

Phase Noise Research. 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-meter facility at MIT. The final research with the Argon-laser Phase Noise Interferometer was performed during this quarter. Low-frequency noise sources were specifically targeted. Contributions from parasitic interferometers (formed between the isolated, suspended in-vacuum components and the much seismically noisier input optics) were identified and reduced by improvements in optical surfaces; in addition, measurements were made at night then the ambient seismic noise spectrum was lower. Laser frequency noise was also a contributor and improvements in the control system were carried out to reduce the significance of this noise source. The final spectrum shows a shot noise sensitivity within a factor of three dB of the calculated value and with a well-understood low-frequency spectrum. This phase of the research was completed on January 17.

The reconfiguration of the Phase Noise Interferometer for Nd:YAG Infrared light has commenced. The preparation (attachments, vacuum baking) of the new optics and the installation of the Nd:YAG laser (input optics chain, electronics shakedown) were started. Tests of optical components in the infrared have led to some refinements of the matching scheme. To reduce the parasitic interferometer problems in the new configuration, an active isolation system was installed under the extra-vacuum laser table to reduce its relative motion. As the quarter closed, one of the two initial masses was successfully suspended, and the laser was locked to its reference cavity.

Interferometer Alignment Investigations. This research effort, directed toward testing the operational system of alignment for the LIGO initial interferometer, effectively concluded last quarter. Some final tests of the length control matrix and measurements of signals for very large angles were carried out.

Thermal Noise Investigations. No significant activity this quarter.

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. The work this quarter led to a complete tested and document stabilized laser, and it has now been delivered to MIT for use in the Phase Noise Interferometer. The performance of the laser appears to be quite good: The frequency noise, measured at the error point of the servo, was $\tilde{\nu}(f) \leq 10^{-2}\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$, and the relative intensity noise, also measured at the error point, was $\delta I(f)/I \leq 4\times10^{-8}/\sqrt{\mathrm{Hz}}$. The Phase Noise Interferometer will be used to make independent measurements of these quantities. The work will continue but will be focussed on the LIGO Pre-Stabilized Laser subsystem and will be discussed there in following reports.

Work planned to be accomplished during the next quarter

- 40 m Interferometer:
  Recombination and Recycling. The determination of transmission, fabrication, and preparation of the recycling mirror will be done; installation and shakedown of modulation system will take place.

  Suspension Development. Interferometer tests of the Small Optics Suspension will be performed.

  Data Acquisition and Analysis. Completion of the installation and shakedown of the LIGO-prototype data acquisition system. Test runs of environmental data acquisition and data analysis will be made.
- Phase Noise Demonstration. Installation will be completed of the first phase, which will consist of the prestabilized laser and a suspended two mirror cavity. An automatic alignment system using two wavefront sensors will also be installed. The laser will be characterized using this cavity.
- Thermal Noise Investigations. Tests of wire creep in the LIGO suspension fibers will start.
- Table-top Interferometer Investigations. No activity planned.

9.0 Systems Engineering (WBS 1.4.3)

9.1 Integration (WBS 1.4.3.1)

Significant accomplishments during this quarter

- Completed update of Beam Tube-Civil Construction Interface Control Document (ICD) to reflect as-built information.
- Developed a thermal and mechanical stress model of the Beam Tube system for performing trade-off analyses and defining Beam Tube Bake requirements.
- Completed preliminary availability allocations for the LIGO triple coincidence Operating Mode.
- Developed preliminary Interferometer fault tree structure.
- Completed preliminary version of the Vacuum Control and Monitoring System Failure Modes and Effects Analysis.
- Completed drafts of the Suspension System Fault Tree Analysis (FTA) and reliability predictions for components of the Suspension System.
- Issued draft LIGO Vacuum Compatibility and Preparations Document.
- Performed field measurement of the BT wall motion at Hanford to provide information for the trade study on identifying acceptable baffle surface preparations.
- Performed an analysis of LIGO Pathfinder Core Optics to determine the surface scatter (BRDF) from similar optics. This was performed in support to provide information for the trade study on identifying acceptable baffle surface preparations.

Discussion of accomplishments and work in progress

Beam Tube Baffles. Late in 1996 it was noticed at Hanford that the installed baffles within the beam tube were apparently shedding glass. This was recognized immediately to be a serious concern potentially limiting LIGO sensitivity to short duration signals. Microscopic glass particles traversing the cavity light beams produce excess phase noise at a level detectable with the interferometers. An analysis indicated that the level of non-Gaussian noise pulses arising from this process could be as large as 100X originally specified levels. This was deemed technically unacceptable. A Technical Review Board was convened to address the issue. A team of individuals from Systems Engineering and Facilities was assembled with the priority goal to identify the causes of the problem, find possible solutions and to recommend adoption of the best solution as soon as possible. It was immediately decided to suspend baffle installation, as it was deemed likely that any baffles installed may need to be removed at some later date. It was also determined that the BT contractor was capable of installing baffles deep into completed sections of BT at a later date.

A subsequent investigation determined that the source of the shedding was principally sharp edges near the serrations on the baffles. Sharp edges cause a concentration of residual stresses in the glass coating, and these stresses cause small particles to separate from the coating near the valleys of the baffle teeth. The glazing material was formulated by the frit manufacturer (Ferro Corp.) for

304SS. Under normal application conditions (i.e., uniform surfaces free of sharp edges) the glazed coating is under slight uniform compression (there is a 10 percent mismatch of the coefficients of thermal expansion between 304SS and the frit). This compression is designed to improve coating robustness. However, the broken symmetry near edges with sharp steep profiles results in unbalanced residual stresses which cause flakes to form. An earlier investigation into coating robustness with non-serrated coupons had not identified this problem.

Several experiments were conducted to search for quantifiable measures for assessing the degree of particle shedding. It was determined that thinning the coating near the sharp edges by either mechanical or chemical means could reduce the shedding to possibly acceptable levels. It has since been determined, however, that large scale application of such techniques for the LIGO baffles is not feasible either due to cost or to environmental concerns from the large quantities of acid that would be required. Another possible mitigation approach was found to be processing the glaze a second time to a its melt temperature in the presence of an O_2-rich gas flame. A local glass blower is presently being explored on a large scale on several baffles. In addition, several new baffles were fabricated with a thinner (1/2X) glaze coating. This, also demonstrated much improved performance with respect to shedding.

An evaluation procedure to identify acceptable baffle performance was developed utilizing repeated thermal cycling between -34C and +50C over the course of 24 hours to screen for shedding baffles. An environmental test oven at a thermal cycling facility (NTS) has been used to cycle test articles every two hours (12 cycles per day). The amount of shedding was measured and particle size distributions estimated using a microscope to survey the residues. To date, none of the identified fixes has been deemed acceptable. We are presently waiting to evaluate the O_2-rich flame process.

As a parallel effort in order to establish a backup approach, we resumed developing an oxidation process to produce blued 304SS baffles. The substrate is cold rolled, bright annealed sheet material with a low backscatter (BRDF). Oxidation produces an absorbing oxide layer on the steel which reduces the forward reflected light. The net contribution to LIGO residual phase noise from scattered light using oxidized baffles is estimated to be three times worse than expected from the best glazed baffle performance. An increase in the level of scatter of this amount is undetectable by the initial LIGO instruments. Accounting for the expected continued improvement of high quality optical surfaces and coatings, it is expected that advanced interferometers utilizing better mirrors will be able to regain this factor of three in phase noise.

Beam Tube Bake. Late in the previous quarter we held a Design Readiness Review (DRR) for the Beam Tube Bake. We are presently involved in performing a detailed design of the bake procedure, including developing procurement specifications for major purchased components. The Facilities Group identified a GFE source for high current power supplies that will be used for the bake. These are surplus magnet power supplies from FNAL which can be loaned to LIGO for the duration of the Beam Tube Bake activity at both LIGO sites.

Major Interface Definition and Control Documents (ICD). We are performing a final audit of the major LIGO Interface Control Documents. This audit involves capturing final as-built and as-designed interface details which were red-lined in earlier revisions. In addition, major previously undetermined details have been resolved and these are being updated. The first completely revised document has been the BT-CC ICD.

Integrated Layout Drawings. We are continuing to update the integrated layouts drawings of the LIGO systems. The LVEA and VEA drawings are being used to develop installation plans for the Detector subsystems.

Reliability Plan Development. A draft reliability plan has been released. It is presently awaiting incorporation of top-level allocation of reliability among major LIGO systems.

Vacuum Compatibility, Cleaning Methods and Procedures for LIGO Instrumentation Materials Specification Document. An initial draft is being revised for the standards and procedures by which major detector components will be deemed vacuum compatible and how they shall be prepared for installation into the LIGO vacuum chambers. A significant effort to develop vacuum compatibility evaluation facilities (cavity ring down measurements, surface absorption tests, optical contamination tests, out-gassing accumulation chambers) has been resumed, motivated by the need for acceptance criteria for vacuum compatibility.

Work planned to be accomplished during the next quarter

- Continue development of subsystem fault trees as PDR information becomes available.
- Initiate effort to obtain reliability data on various off the shelf equipments by contacting suppliers.
- Expand the Beam Splitter Chamber (BSC) and Horizontal Access Module (HAM) chamber mock-ups with a Seismic Stack representation and a clean room enclosure; plan and begin to exploit the BSC and HAM mock-ups.
- Complete revision of the Interface Control Documents
- Complete baffle redesign task.

9.2 Simulation, Modeling, and Data Analysis (WBS 1.4.3.3)

Significant accomplishments during this quarter

- Completed an analysis of core optics mirror coatings to determine their uniformity. This information was gathered as part of the Pathfinder detector task.
- Completed a time domain model with length and alignment degree of freedom. the next phase will be a validation of the model.
- Completed framework for the time domain end-to-end model work using 40-meter as the prototype.
- Reviewed the GRID modeling and simulation package from the GEO 600 collaboration.
- Integrated the GRASP (gravitational radiation analysis simulation package) onto the LIGO computer network.

Discussion of accomplishments and work in progress

The analysis of four mirrors with two kinds of anti-reflective coatings, one sensitive to Ta_2O_5 thickness and the other sensitive SiO_2 thickness, delivered from REO last December has been finished and the result was provided to REO for the next round of improvements.

This coating incorporates the result of the previous analysis and the uniformity was improved by factor of 5. The thickness of SiO_2 layer increases by 0.5 percent in the peripheral region (r ~ 3 inch) and that of Ta_2O_5 by 0.2 percent. In the peripheral region, a periodical structure was observed at every 60 degree. The size of the variation is around 0.1 percent P-V. Due to the correlation, it is difficult to resolve if the variation exists only in SiO_2 layer or in both layers (it is very unlikely that the variation is only in Ta_2O_5 layer). REO has improved the bearing to remove this periodical structure.

Four mirrors were coated under the same specification to see the planet-to-planet variation. Although the measured reflectance of those mirrors showed variation from one to another, the measurements (15P and 15S) were not enough to quantify the dependence.

The framework of the end-to-end model work for the 40-meter has been completed by M. Evans, M. Rakhmanov and H. Yamamoto based on the digital filter model designed by M.Evans. Within this frame, the configuration of the detector - complete system or partial system - can be easily setup. Several of the basic building blocks have been written, tested and improved, including optics elements, pendulum system, digital servo, etc. Time domain noise models are being developed.

The GRASP (gravitational radiation analysis simulation package) was integrated onto the LIGO computer network. This package was developed by Prof. Bruce Allen, a LIGO visiting scientist. The 40-meter data from November of 1994 has been reanalyzed for chirp signals. The package includes functionality for template generation, optimal filtering, stochastic background detection, and a collection of general purpose utilities. It also runs on a network of computers using MPI.

A kickoff meeting was held in Baton Rouge with LSU Administration officials to identify options for LIGO to gain access to Louisiana State University resources for Internet connectivity. The meeting identified several areas of mutual interest that will be explored further. These include participating in the state’s LAsernet consortium to bring vBNS (NSF-funded very High Bandwidth Network Services) service to LSU and the Baton Rouge area. We generated a letter of intent to use such facilities and support for the state in its proposal to NSF for this development.

A second kickoff meeting was held with computer systems and networking systems administrators at Battelle Pacific Northwest National Laboratory (PNNL). The intent of the meeting was to identify options for LIGO to gain access to high bandwidth communications infrastructure in the Pacific Northwest. It was agreed that LIGO and PNNL would work together to explore how to develop an interagency MOU to allow LIGO to gain access to ESNet in the northwest. It was determined that mutual interest and need existed in this regard because Battelle requires reliable access to Caltech’s CACR Supercomputers.

Work planned to be accomplished during the next quarter

- The latest four mirrors have been delivered using new bearings and incorporating the analysis. The analysis of these mirrors will be continued, and will be compared with the NIST measurement of the 40 layer high-reflectivity coating. A through analysis will be done for the four mirrors to quantify the planet-to-planet dependence.
- The end-to-end model for the 40-meter will be developed further so that it includes the minimal components so that the model can be used.

- The LIGO Data Analysis System will be characterized and reviewed by the project in the next quarter. In preparation for this review, documentation covering the science specifications, design requirements and software specifications and standards will be completed.
- A research project involving Caltech SURF (summer undergraduate research fellowship) students is planned which will involve recasting the LIGO noise models into an object oriented class library paradigm. The concept will be developed and finalized over the next quarter in preparation for the summer project.
- The GRASP package will be brought under software configuration management in the next quarter. This will most likely involve using the RCS and CVS version control systems. It will also act as a test bed for software configuration management for all LIGO software.

10.0 Support Services

10.1 Quality Assurance (WBS 1.4.2.1)

Work accomplished during this quarter

- Completed rewrite and revision of the LIGO Quality Assurance (QA) Plan
- Arranged and coordinated JPL QA engineering and other technical support
- Performed QA monitoring/oversight of annealing and pickling of beam tube coils
- Completed receiving and pre-ship inspection of over 600 porcelain coated baffles
- Completed QA surveillance visits and reports for the large gate valve and expansion joint vendors
- Prepared Quality Assurance Instruction (QAI) and data check list for core optic blank receiving inspection
- Completed review and provided comments for core optic blank grinding vendor's QA Manual
- Performed QA survey of core optic carrier component fabrication shops
- Provided technical and other support for the baffle shedding tests
- Performed vendor source inspection and coordination/QA monitoring of the baffle steam cleaning and high temperature oxidation of prototype/pre-production Bright Anneal baffles

Discussion of accomplishments and work in progress

During this quarter LIGO Quality Assurance (QA) has increased the QA engineering support to the Detector core optic blank activities. A receiving inspection QA instruction for the incoming blanks was prepared and has been implemented with LIGO QA assistance/input for creating the as-built data base. LIGO QA has also provided support to the core optic blank carrier fabrication work and helped arrange for the assistance of a JPL manufacturing/liaison engineer in support of the fabrication and assembly work. Another part of this fabrication task included verifying the presence/implementation of adequate QA systems at the component fabrication vendors.

LIGO QA personnel performed receiving inspection, in-process and final coating inspection/process monitoring for in excess of 600 beam tube baffles. This QA task included visual pre and post coating inspections for damage and coating quality. Spot checks/inspections of coating thickness and surveillance of the final cleaning and bagging of the baffles performed at JPL. LIGO QA has created a spread sheet database of this baffle inspection data for future reference.

Several visits and discussions were held with QA personnel at the vendors supplying the large gate valves and the expansion joints. The large gate valve vendor has now implemented what appears to be an effective QA tracking and NCR status reporting system where there was none before. For the expansion joint vendor there were test data errors, and it was not obvious whether the vendor was using or had available approved test procedures. Resolution of this concern is still pending the outcome of a Chicago Bridge and Iron (CB&I) QA audit report and the identification of QA issues/problems and vendor actions required. LIGO QA is continuing surveillance of this situation to assure acceptable closure.

Work planned to be accomplished during the next quarter

- Establish QA processes/procedures for fabrication and surface optical treatment for the Bright Anneal baffles
- Establish QA plan and procedures/processes for the Detector Control and Data Systems (CDS)
- Provide QA guidance for delivery of Vacuum Equipment Pump Carts and associated documentation
- Establish QA monitoring of Process Systems International (PSI) acceptance testing

10.2 Environmental Safety and Health (WBS 1.4.2.2)

Work accomplished during this quarter

- Provided Safety oversight in the preparation, review, and approval of LIGO contractor safety plans and procedures.
- Continued to provide Laser Safety training, initial and recurring.
- Continued with safety inspections of LIGO campus facilities in support of Caltech Safety to assure that Caltech located labs are in compliance with the University safety requirements.
- Continued with the LIGO hazard analysis.

Discussion of accomplishments and work in progress

The primary focus for Safety oversight has been with Chicago Bridge and Iron (CB&I) and Hensel Phelps Construction Company. Both companies have been excellent in outlining their safety approach and CB&I has been able to demonstrate compliance with OSHA, LIGO, and their own requirements at Hanford.

The project personnel certification program provides reporting and control for approved laser operators and workers. The Safety Officer has begun to assist with the establishment of laser operational procedures, and is performing reviews to assure that the procedures are being used or are revised for usability.

The LIGO Safety Officer is supporting Caltech Safety to assure that Caltech labs are in compliance with the University safety requirements. The Safety Officer also provided on-site support to assure that OSHA safety requirements are met at the observatory sites.

LIGO Safety is continuing with the development of the LIGO hazard analysis to include operational hazard analysis. The goal is to establish a capability to evaluate the adequacy of the safety of the system and assure that any unidentified hazards are not unnoticed or properly controlled.

Work planned to be accomplished during next quarter

- Continue to provide Safety oversight in the preparation, review, and approval of LIGO and contractor safety plans and procedures.
- Continue with Laser Safety training both, initial and recurring. Provide the project with a personnel certification program that will furnish listing and control for approved laser operators and workers. Assist with the establishment of laser operational procedures and follow-up that the procedures are in use or revised for usability.
- Continue safety inspections in support of Caltech safety to assure that Caltech located labs are in compliance with Caltech safety requirements. Establish a safety level of support to assure that Caltech and OSHA safety requirements are met at the observatory sites.
- Continue with the LIGO hazard analysis with the previously established safety review team (individuals external to the LIGO project) to evaluate the adequacy of the analysis and assure that any unidentified hazards are not unnoticed.

11.0 LIGO Visitor's Program

Bruce Allen - University of Wisconsin, Milwaukee. Dr. Allen has been at LIGO as a visitor/collaborator since August 1996, and plans to stay through July 1997. He also visited LIGO for five months at the end of 1995. Dr. Allen's work is in data analysis. This work is important for the timely development of a LIGO data-analysis infrastructure. The techniques which he is developing are being tested on data from the 40-meter prototype.

During Dr. Allen's visit, he has developed a data analysis package called GRASP (Gravitational Radiation Analysis and Simulation Package). This is a C-language object library of functions, together with documentation and source code. These functions are designed to allow analysis of interferometer data using the standard and specialized techniques described in the literature. The package can be used to compare new data analysis techniques with existing ones, and to study the behavior of data analysis algorithms on simulated noise or on real interferometer output. It can also be used to study such practical issues, such as the choice of whitening filters, the effect of non-linearities in the detector transfer function, effects of quantization noise in the analog to digital conversion, etc.

Dr. Allen's goal is that the GRASP package be used by LIGO to:

- study data analysis issues and perform benchmarking with "real world data",
- compare different data analysis techniques, and
- serve as a prototype for construction of the full-scale LIGO data analysis system.

In collaboration with LIGO the GRASP package will be distributed in the public domain and can be used and further developed by other groups and researchers.

Discussion of accomplishments and work in progress

A long review paper describing known mechanisms for stochastic background production and methods of detection was finished and will be published by Cambridge University Press as part of a Les Houches volume. This is the most comprehensive and complete article to date on this subject.

A paper examining the detectability of stochastic background produced by "stringy inflation" (an early universe model) was written in collaboration with Brustein and has just been accepted for publication in Physical Review.

A paper containing a number of new results is being prepared with Dr. Romano, a postdoc at Milwaukee. These include:

- a new Signal-to-Noise formula obtained without small signal approximations,
- sensitivity limits for the LIGO enhanced detector curves,
- detailed results comparing the data-analysis pipeline described below to theoretical expectations (agreement to better than two percent was ultimately obtained),
- sensitivity limit predictions for correlating European and US IFO sites,

- detailed limits on the correlated noise requirements that would permit useful stochastic background detection experiments using the two kilometer and four kilometer detectors at the Hanford site.

A data analysis pipeline for stochastic background searching has been under development for approximately two years. This data analysis pipeline is now finished and working properly on simulated data. The data-analysis pipeline gives results from Monte-Carlo testing which are in better than two percent agreement with theory.

The stochastic background signal simulation and data analysis library is now complete, and has been incorporated into the GRASP library and documentation. We are currently using these routines to analyze real 40-meter data now that the performance of the pipeline on simulated Gaussian noise is completely understood.

Dr. Allen has also developed techniques that could be used to determine (or place limits on) the multipole moments that characterize any anisotropy in the stochastic gravity wave background. A paper just completed in collaboration with Dr. Ottewill (faculty at University College, Dublin) and submitted to Physical Review describes one such technique in great detail. Dr. Otte will is currently visiting Caltech to work on related issues.

The binary-inspiral detection routines in GRASP have been tested on 40-meter data and a pair of different vetoing techniques have been developed. The binary inspiral filtering code has been parallelized and run both on workstation networks and on a dedicated parallel processor (the Intel Paragon) at the Center for Advanced Computing Research.

A users manual (about 210 pages, at present) has been completed for GRASP.

Work planned to be accomplished during next quarter

- Finish binary inspiral analysis of 45 hours of 40-meter data.
- Shepherd GRASP through installation at the first half-dozen sites.
- Test and optimize the binary inspiral code on the IBM SP2 and Intel Paragon machines.
- Generalize the parallel inspiral analysis code for dynamic allocation of template lists.
- Implement/test multi-taper analysis of correlations and removal of line features.
- Modify GRASP to deal in real time with arriving data in the FRAME format.

Richard Gustafson, Keith Riles - University of Michigan. Dr. Gustafson has been resident at the LIGO 40-meter facility since October 96. He has focused on learning the 40-meter systems and exploring operational realities directed towards making lock robust, running the system, and reducing the most egregious noise sources and processes. The larger goal is to make operation routine and to identify and address actual noise sources and limits. A physics interest is the gravitational wave detection of hums, clicks and chirps, and studying inertia ideas as expressed in binary coalescence signals. Riles plans a sabbatical at LIGO during the winter of 1998 working on Data Acquisition and analysis.

12.0 REFERENCES

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