LIGO Quarterly Progress Report

(June 1997 through August 1997)

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

NSF Cooperative Agreement No. PHY-9210038

October 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

September 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 June 1, 1997 through August 31, 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[4,6]. 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 third 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 and is 62 percent complete as of the end of August 1997. Civil Construction at the Hanford, Washington site is in its final stages. The Beam Tube for the first arm at Hanford has passed vacuum performance tests, and Process Systems International (PSI) has started installing the Vacuum Equipment. All Beam Tube Enclosures have been fabricated and are in place at Hanford. In Louisiana the first four kilometer Beam Tube slab is expected to be completed early in September 1997, and the factory for fabricating the Beam Tube sections has been moved from Hanford.

Vacuum Equipment. A large number of components are being shipped by PSI to Hanford. Installation will begin in September. During the summer of FY 1997, the Edwards vacuum pumps provided by PSI were used by Chicago Bridge and Iron (CB&I) for pumping the first beam tube modules at the Hanford site. Apollo Sheet Metal of Kennewick was selected in June 1997 as the Washington site installation contractor for the Vacuum Equipment.

Beam Tube. All of the Beam Tube fabrication and installation for the Hanford site is now complete. The Beam Tube contractor, Chicago Bridge & Iron (CB&I), has demobilized at Washington and has re-mobilized in Louisiana at a new fabrication facility in Denham Springs. Re-mobilization of the installation task at the Louisiana site is underway. The Fabrication Readiness Review for the Louisiana task will be held on September 18, 1997. The Completion Review for the Washington task is scheduled to be held early in October 1997.

A new baffle design was made after discovery of a shedding problem with the glass coating on the original baffle, which could have threatened interferometer sensitivity. The new baffle is made of oxidized bright annealed stainless with no coating. All of the baffles installed at the Hanford site are of the new design.

Highly sensitive vacuum leak tests of the 400 Beam Tube sections (23 miles of weld) and the 404 field girth seams (1 mile of weld) were performed with no failures, a tribute to CB&I's welding and inspection skills. Acceptance testing of two of the four two kilometer Beam Tube modules demonstrated that vacuum performance meets LIGO requirements. Alignment checks of one module confirmed that the 14 mm tolerance allowed to meet the required clear aperture budget. The construction phase of the Hanford Beam Tube modules is nearly complete.

Virgo Scientists and engineers visited the Hanford site June 9 and 10 to tour the facility and to discuss Beam Tube issues.

Beam Tube Enclosure. At the Hanford site all of the pre-cast Beam Tube Enclosures have been fabricated and set in place.

The LIGO/Parsons construction management office was set up at the Livingston site. The Beam Tube Enclosure contract proceeded on schedule and all major schedule milestones were achieved at the Livingston site. The first arm of the Beam Tube slab is will be completed early in September.

Washington Civil Construction. Facilities construction is in the final stages. At the end of July 1997 LIGO assumed joint occupancy of the ‘Y’ arm mid- and end-stations with beneficial occupancy expected to follow at the beginning of September. Joint occupancy of the Laser and Vacuum Equipment Area (LVEA) is also expected in September. Joint occupancy of the Operations Support Building (OSB) and the ‘X’ arm mid- and end-stations is expected in October 1997.

Louisiana Civil Construction. Hensel Phelps Construction Company was awarded the contract for the Building and Infrastructure and on-site construction work started on Feb. 3, 1997. Construction is on schedule.

Detector. The preliminary design for the seismic isolation system (carried out by Hytec, under LIGO supervision) was completed this year. Success with prototype constrained layer damped metal springs led to their being adopted in the baseline design. Fabrication drawings for first articles, to be fabricated and tested to verify the design, were completed and requests for quotes by vendors have been issued.

The final designs of the small and large optics suspensions have been completed. Prototypes of both designs have been fabricated and tested.

Core Optics fabrication has progressed significantly this year. Orders for fused silica blanks were placed with Corning and Hereaus, and approximately half have been received. Two polishers, General Optics and the Commonwealth Scientific and Industrial Research Organization (CSIRO) were placed under contract and together have completed 13 of the 40 total substrates. Coating tests at Research Electro Optics (REO) have demonstrated sufficient uniformity for the initial interferometers, and a first full-size test mass was coated under our Pathfinder process.

The input optics subsystem preliminary design was completed by the University of Florida group and reviewed by LIGO. Final design has started, and long-lead material procurements have been authorized.

The preliminary designs for the length and alignment sensing and control systems have been competed. Electronic implementation of the critical new technologies required to transmit high dynamic range signals along the arms are underway.

Control and Data System activities included the delivery of the first racks and Versa Modular Eurocard (VME) crates to the Hanford site, completion of the fabrication of the vacuum monitoring and control system (which will be used to control the vacuum equipment supplied by PSI), and completion of the Data Acquisition System Preliminary design. A prototype Data Acquisition System has been installed in the 40 meter interferometer for testing in a realistic operating environment.

The Phase Noise Interferometer experiments with the Argon laser were completed. The sensitivity in the shot noise limited regime was reduced to below 3×10^{-10} rad/Hz$^{1/2}$. The conversion to operate with a Nd:YAG laser has been completed and initial experiments to characterize the laser and understand the noise are underway. Reconfiguration of the 40 meter interferometer to include recycling is underway.

LIGO Scientific Collaboration. The first meeting of the LIGO Scientific Collaboration (LSC) was held on August 14-16, 1997. The LSC is a new structure and the purpose of this meeting was formatory. The meeting was held at Louisiana State University (LSU). Two hundred one participants have joined the LSC from 20 institutions. Nineteen were represented at the meeting. Forty-nine of the participants were from countries other than the U.S. Several groups committed people to the sites. GEO formally joined the collaboration and offered to share detector data.

Memoranda of Understanding (MOUs) have been developed between the LIGO Laboratory and each participating group. MOUs are intended to reflect planned activities for six months and will be updated every six months. Each group will be requested to report progress against the plan in the MOU. Participants of the meetings were given tours of the Livingston, Louisiana site as well as the CB&I facility being set up to manufacture the beam tube sections for the Louisiana site. There were working groups on Saturday for the Laser and Optics group, the Advanced Configurations group and the Suspensions group.

The next collaboration meeting will be held in Hanford, March 13-15, 1998.

2.1 Project Milestones

Table 1 summarizes the status of the significant milestones identified in the Project Management Plan[4] for the LIGO Facilities.

The milestone for Joint Occupancy at the Hanford, Washington site has been subdivided into several milestones to reflect the current construction plan and to provide access to facilities at the earliest possible dates for the vacuum equipment and other subcontractors. Joint Occupancy of the Arm 1 mid- and end- stations was provided at the end of July 1997. Joint Occupancy of the Laser and Vacuum Equipment Area (LVEA) is expected in September 1997. Joint Occupancy of the Operations Support Building (OSB) and the ‘X’ Arm mid- and end-stations is expected in October 1997. Typically Beneficial Occupancy is following Joint Occupancy by one month.

The projected milestone dates were presented in detail to the NSF Review Committee during the Semi-Annual Review held in April 1997.

Table 2 shows the status of the significant milestones for the Detector. This schedule was also presented in detail during the April 1997 NSF Review and has been included in the proposed revisions to the Project Management Plan[4]. The projected completion date for the Core Optics Support Final Design Review is now February 1998 (vs. April 1997). Significant scope originally in this task has been moved to the Suspension 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 (reviewed and documented in the Design Requirements Review held in April 1997) has reduced the expected fabrication time, and all critical components are expected to be ready in time to avoid installation delays.

Table 1. Status of Significant Facility Milestones

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

The Core Optics Components Final Design Review (FDR) 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, reduces costs by allowing time for rework of any parts damaged during fabrication as opposed to requiring additional spares.

Table 2. Detector Milestones

Milestone	PMP Date (April 1996)	Projected Date
Beam Splitter Chamber Stack Final Design Review	07/97	04/98
Core Optics Support Final Design Review	07/97	02/98
Horizontal Access Module Stack Final Design Review	07/97	04/98
Core Optics Components Final Design Review	07/97	10/97
System Preliminary Design Review	12/97	12/97
Input/Output Optics Final Design Review	04/98	04/98
Pre-Stabilized Laser Final Design Review	08/98	08/98
Control and Data System Network Installation	04/98	04/98
Alignment Sensing Control Final Design Review	04/98	04/98
Control and Data System DAQ Final Design Review	04/98	04/98
Length Sensing and Control Final Design Review	05/98	05/98
Physical Environment Monitoring System Final Design Review	06/98	06/98

2.2 Financial Status

Table 3 on page 8 summarizes cost and commitments as of the end of August 1997. Figure 1 on page 9 provides the same information graphically as a function of time.

Table 3. Construction Costs and Commitments as of the End of August 1997

(All entries in $Thousands)

WBS	Description	Costs Thru Nov 1996	First Quarter LFY 1997	Second Quarter LFY 1997	Third Quarter LFY 1997	Cumulative	Open Commit-ments	Total Cost Plus Commit- ments
1.1.1	Vacuum Equipment	21,254	956	3,646	1,758	27,614	18,221	45,835
1.1.2	Beam Tube	17,262	4,795	3,687	3,795	29,539	16,778	46,317
1.1.3	Beam Tube Enclosure	6,237	958	2,933	1,747	11,875	9,347	21,223
1.1.4	Civil Construction	14,117	4,705	7,555	8,659	35,036	16,819	51,855
1.2	Detector	6,270	1,521	2,267	1,717	11,775	8,744	20,519
1.3	R&D	16,816	845	802	733	19,196	1,614	20,810
1.4	Project Office	16,288	1,452	2,102	1,542	21,384	2,038	23,422
	Unassigned (see note)	2	-	8	(2)	8	45	53
	TOTAL	98,246	15,231	23,000	19,950	156,427	73,606	230,033
	Cumulative Actual Costs	98,246	113,477	136,477	156,427			
	Open Commitments	91,492	109,800	98,775	73,606			
	Total Costs plus Commitments	189,738	223,277	235,252	230,033			
	NSF Funding	*208,468*	*265,389*	*265,389*	*265,389*			

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

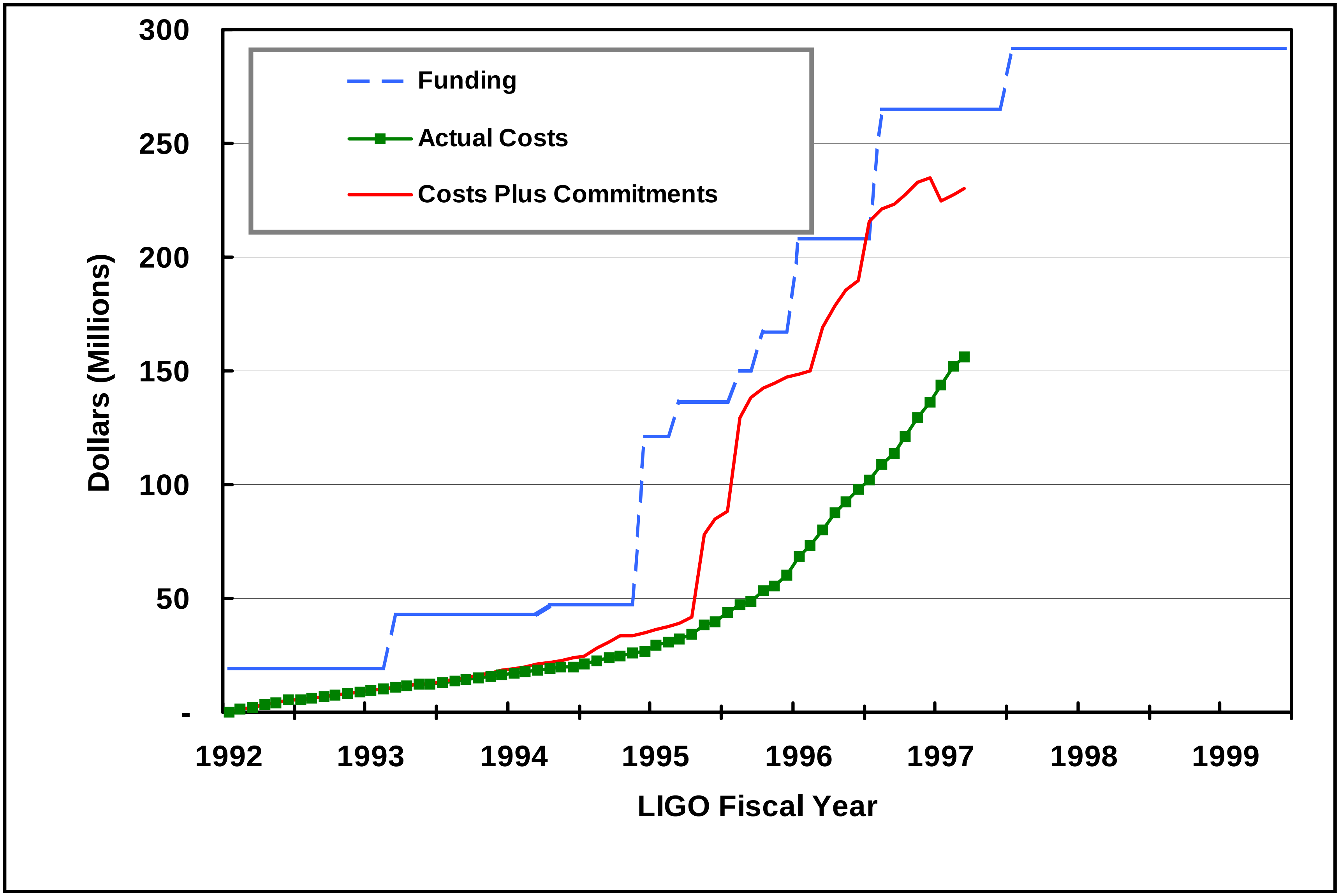

Figure 1. LIGO Construction Actual Costs and Commitments as a Function of Time.

2.3 Performance Status (Comparison to Project Baseline)

Figure 2 on page 12 is a Cost Schedule Status Report (CSSR) for the end of August. 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 on page 13 shows the same information graphically as a function of time.

Vacuum Equipment. (WBS 1.1.1) The Vacuum Equipment has recovered most of an unfavorable schedule variance previously reported. A large number of components have been fabricated. Several large chambers have been cleaned and checked for leaks. A number of components have been shipped, and assembly in Hanford will begin in September.

The favorable cost variance reflects normal delays in processing invoices. Some overruns have been incurred for fabrication support activities including Quality Assurance and travel.

Beam Tube. (WBS 1.1.2) LIGO is within a week of the schedule for acceptance of the Beam Tube in Hanford, Washington.

The unfavorable cost variance reflects overruns in fabrication support activities including Quality Assurance and travel as well as baffle fabrication.

Beam Tube Enclosure. (WBS 1.1.3) All Beam Tube Enclosures are fabricated and in position on the Hanford site. Fabrication of the Beam Tube Enclosures (BTEs) is behind schedule in Livingston, Louisiana. The subcontractor responsible for casting the concrete enclosure sections has fabricated a number of sections. However, acceptance has been delayed pending review and approval of the casting procedures. The schedule for BTE construction activities in Louisiana, currently in the LIGO Integrated Project Schedule, is a very aggressive schedule based on planning that was done in 1995 and 1996. Schedules have now been negotiated with the selected subcontractor, Woodrow Wilson, that will be incorporated into the Integrated Project Schedule and will reduce the unfavorable schedule position.

The favorable cost variance reflects normal delays in processing invoices.

Civil Construction. (WBS 1.1.4) Favorable cost and schedule variances are reported. Civil Construction is ahead of schedule in Washington, but behind schedule in Livingston, Louisiana due to a problem encountered with blistering of the building paneling. This problem is being monitored closely. Joint occupancy of the Hanford, Washington Laser and Vacuum Equipment Area (LVEA) is expected in September.

The favorable cost variance reflects normal delays in processing invoices.

Beam Tube Bake. (WBS 1.1.5) A change request has been processed to create a new third level work breakdown structure (WBS) element to track the Beam Tube Bake. The change request moved $4 million into 1.1.5 from the Beam Tube (WBS 1.1.2) where the budget for the vacuum bake had been held and from contingency (Change Requests CR-970018 and CR-970021, as reported for the previous quarter). Beam Tube Bake activities begin in Hanford during the next quarter.

Detector. (WBS 1.2) The Detector is behind schedule and under cost. LIGO has been hiring additional staff, but this has not been accomplished quickly enough to avoid some delays. In addition personnel have been diverted to R&D tasks. The Detector Plan has been reviewed and adjusted to reflect the current status and a reassessment of the work remaining. A Change Request (CR-970025) was submitted and approved during this quarter to adjust the schedule and to add budget for additional resources. Priorities are being adjusted to assure that all critical milestones will be met.

Specific Detector tasks that are or have been behind schedule include:

- Deliveries of optical glass has been delayed due to difficulties encountered achieving the needed purity in large enough blanks. The production of optics and optical coatings is progressing however.
- The Design Readiness Review for the Prestabilized Laser was held in July. The Preliminary Design Review (PDR) for the Input Output Optics (IOO) was held on August 22, 1997, and the PDR for the Core Optics Supports (COS) is scheduled September 5.
- Some slip has been experienced in the subcontractor (Hytec, Inc.) schedule for Seismic Isolation. Requests for quotations for materials in support of First Article fabrication were scheduled to have been released in June, but have been delayed to September and October. LIGO is working closely with NSF to facilitate the review and approval of these procurements.
- The Alignment Sensing and Control (ASC) effort is behind schedule because resources have been shared to accomplish R&D tasks supporting interferometer development.

Favorable cost variances reflect, in part, the fact that resources have not been sufficient to accomplish scheduled tasks. Also the favorable cost variance reflects normal delays in processing invoices.

(All entries in $Thousands)

Run Date: 02OCT97 — COST / SCHEDULE STATUS REPORT (CSSR) — Page 1

CONTRACTOR: Caltech LOCATION: Pasadena, CA	CONTRACT NUMBER: PHY-9210038	CONTRACT BUDGET BASELINE 292, 100, 000	REPORTING PERIOD: 31JUL97-31AUG97	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	30654	30531	27614	(123)	2918	42763	42763	0
1.1.2 : Beam Tubes	30265	30175	29522	(90)	652	45047	45047	0
1.1.3 : Beam Tube Enclosur	14146	13375	11875	(771)	1500	19796	19796	0
1.1.4 : Facility Design &	35005	36617	35036	1612	1581	48581	48581	0
1.1.5 : Beam Tube Bake	0	0	0	0	0	4005	4005	0
1.2 : Detector	16147	13710	11729	(2437)	1981	54957	54957	0
1.3 : Research & Developme	20110	19942	19196	(168)	746	23490	23490	0
1.4 : Project Office	20748	20748	21384	0	(636)	27074	27074	0
SUBTOTAL	167074	165098	156356	(1977)	8742	265714	265714	0
CONTINGENCY						0	26386	(26386)
MANAGEMENT RESERVE						26386	0	26386
TOTAL	167074	165098	156356	(1977)	8742	292100	292100	0

COBRA (R) by WST Corp.

Figure 2. Cost Schedule Status Report (CSSR) for the End of August 1997.

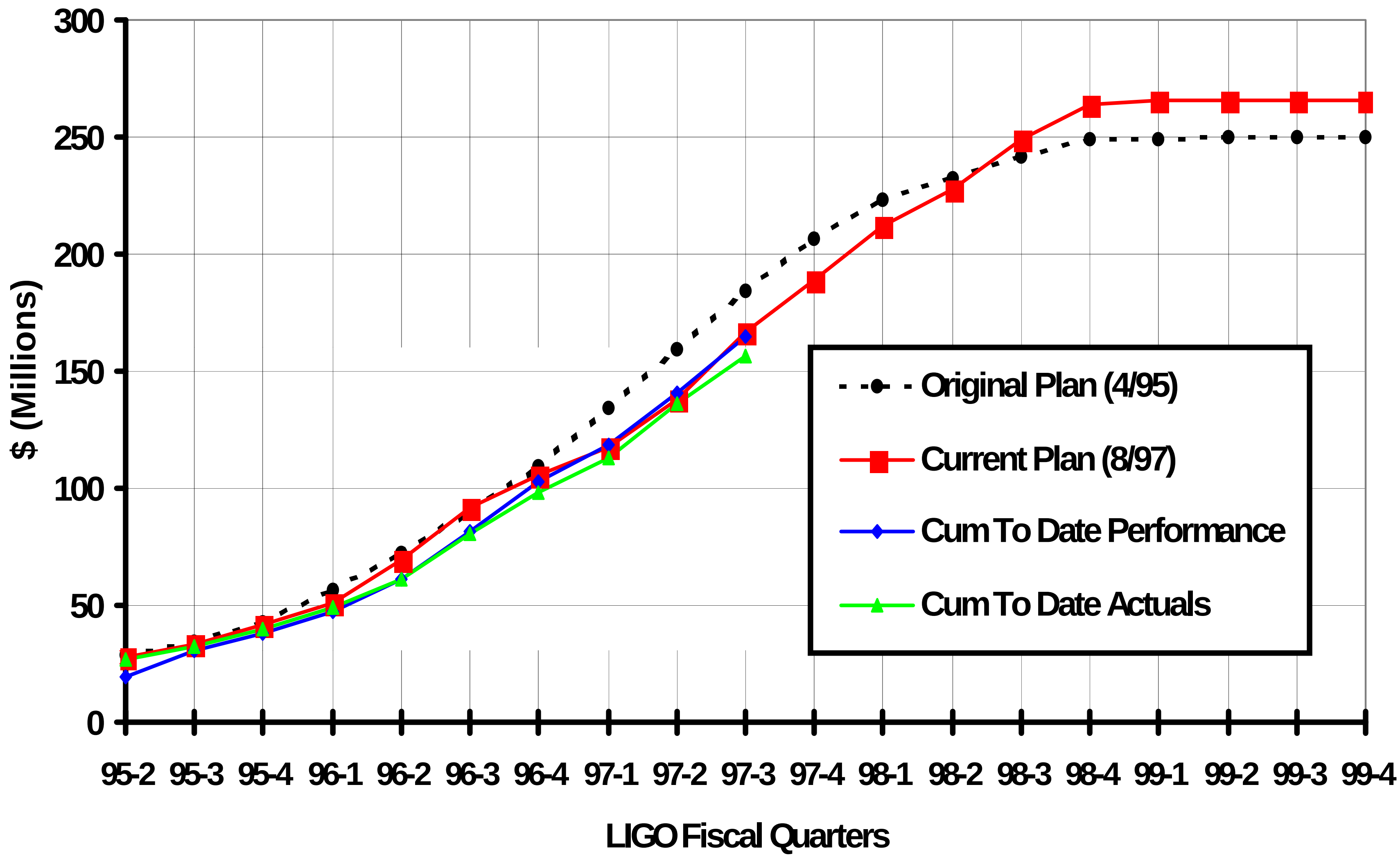

Figure 3. LIGO Project Budget Baseline, Earned Value, and Actual Costs as a Function of Time.

2.4 Change Control and Contingency Analysis

Twelve Change Requests (CRs) shown in Table 4 were approved and incorporated into the baseline during this quarter. The net effect of these change requests was to allocate $8.22 million from contingency. The contingency as of the end of August is $26.4 million.

Table 4. Approved Change Requests

Change Request No.	Description	Current Status	Disposition Date
CR-970021	WBS 1.1.5 - Beam Tube Vacuum Bake - Establish new WBS with Technical Scope per T960178-01-P	Approved $4,005,000	June 26, 1997 L970333
CR-970022	WBS 1.2 - Detector - Seismic Isolation, Scope Changes	Approved $3,857,217	June 5, 1997 L970289
CR-970023	WBS 1.2 - Detector - Seismic Isolation, Remove Active Isolation	Approved ($1,140,000)	June 5, 1997 L970289
CR-970024	WBS 1.2 - Detector - Seismic Isolation, Remove Six HAM Stacks	Approved ($1,090,380)	June 5, 1997 L970289
CR-970025	WBS 1.2 - Detector Staffing	Approved $2,117,944	June 26, 1997 L970333
CR-970026	WBS 1.1.4 - Civil Construction, Livingston, Fencing	Approved $130,000	June 26, 1997 L970333
CR-970027	WBS 1.1.2 - Beam Tube, Miscellaneous	Approved $51,675	July 17, 1997 L970443
CR-970028	WBS 1.1.2 - Beam Tube, Early Procurement of Stainless Steel	Approved ($259,470)	July 17, 1997 L970443
CR-970029	WBS 1.1.2 - Beam Tube, Baffle Installation Premium Tasks	Approved $134,624	July 17, 1997 L970443
CR-970030	WBS 1.1.2 - Beam Tube, Account and Budget for Hanford Taxes	Approved $189,199	July 31, 1997 L970467
CR-970031	WBS 1.1.3 Beam Tube Enclosure - Livingston, Louisiana, Incentivization (5C532)	Approved $160,000	July 31, 1997 L970467
CR-970032	WBS 1.1.4 Civil Construction, Hanford - Telecommunications, Security, Emergency Services	Approved $63,000	July 31, 1997 L970467

2.5 Staffing

The LIGO staff currently numbers 106 (full time equivalent). Of these, 23 are contract employees. Eight-nine LIGO staff are located at CIT, including four graduates students. Seventeen are located at MIT, including three graduate students.

3.0 Vacuum Equipment (WBS 1.1.1)

Figure 4. Long 80K Pumps Shown in Final Assembly.

Significant accomplishments this quarter:

- The ‘X’ arm mid- and end- station components are ready for shipment to Washington.
- Assembled three additional Beam Splitter Chambers (BSCs) bringing the total to 11. Four additional Horizontal Access Modules (HAMs) have been assembled bringing the total to 12. Ten chambers have been cleaned, baked and vacuum tested bringing the total to 14. All ‘Y’ arm mid- and end-station components are ready for shipment to Washington.
- Assembled two additional 80K pumps bringing the total to eight. Four 80K pumps have been cleaned, baked and vacuum tested. All liquid nitrogen dewars are ready to be shipped to Washington.
- Awarded the installation contract for the Washington site to Apollo Sheet Metal.
- Received all 2500 liter per second main ion pumps for Washington.
- Used the Edwards vacuum pumps to successfully pump down the first Beam Tube module.
- Held the Installation Readiness Review for Washington on August 21, 1997.

Figure 5. Short 80K Pumps Awaiting Shipment to Washington.

Discussion of accomplishments and work in progress:

This quarter Process Systems International (PSI) continued to fabricate, clean and test chambers for Hanford. The large component bake oven has been in steady use performing the bulk of chamber bakeouts. In parallel, some Horizontal Access Modules (HAM) chambers are being baked in blankets at the Flanders Road facility. Two shifts are operating at PSI with the second shift staffed by bake and test crews. Currently, PSI has baked, tested and prepared for shipment, all the components for the 'X' arm mid- and end-stations, as well as most of the components required for the corner station.

Figure 6. Beam Splitter Chambers in Storage.

Figure 7. Beam Splitter Chambers on their Shipping Cradles.

PSI does not gain access to the 'Y' arm buildings until October 28. However, components such as the large liquid nitrogen dewars, the main ion pumps and the 44 inch gate valves were completed for the site this quarter.

A contract has been awarded to Apollo Sheet Metal of Kennewick who plan to mobilize on site the first week of September.

Work planned to be accomplished during the next quarter:

- Begin on site installation.
- Complete installation of all liquid nitrogen storage dewars at Washington.
- Complete installation of 'Y' arm mid- and end-station components.
- Begin vacuum testing of 'Y' arm mid- and end-station components.
- Complete the Louisiana Beam Tube gate valves.

Figure 8. Horizontal Access Modules in Storage Ready for Shipment.

Figure 9. Small Spools Ready To Ship.

4.0 Beam Tube (W.B.S. 1.1.2)

Significant accomplishments this quarter:

- Completed installation of ‘Y’ arm modules at Hanford.
- Completed vacuum acceptance testing of ‘X’ arm modules at Hanford.
- Began retrofit of baffles in ‘X’ arm modules at Hanford.
- Completed demobilization of fabrication activity at Washington.
- Started mobilization of fabrication activity at Magnolia Beach at Louisiana.

Discussion of accomplishments and work in progress:

All of the beam tube modules have now been installed at Hanford by Chicago Bridge & Iron (CB&I), the beam tube contractor. This required 400 tube sections, each 20 m long, which included over 23 miles of spiral welding in the fabrication shop at Big Pasco. Highly sensitive vacuum leak tests of each section were performed with no failures. The 404 girth seams required over a mile of welding in the field and again, tested with no failures. This exceptional performance is a tribute to CB&I’s welding and inspection skills.

An independent check was made of CB&I’s alignment (in the vertical plane) of the first ‘X’ module. All 101 supports are within the ± 14 millimeters tolerance allowed by the clear aperture budget. Field checks are in process on the ‘X1’ lateral alignment; eventually, all modules will be checked.

The vacuum acceptance testing of both ‘X’ arm modules was completed during this period. The measurement technique for leakage and outgassing required Residual Gas Analyzer (RGA) measurements of overnight partial pressure accumulations and matrix calculations. Vacuum performance of the ‘X’ arm modules meets LIGO requirements in all areas. Pumpdown of the first ‘Y’ module is now in process.

After vacuum acceptance testing was completed on the ‘X’ arm, retrofitting of the baffles commenced. When the shedding problem with the original glass coated baffles was discovered, some baffles had already been installed in the ‘X’ arm (see previous FY97 reports). The balance of the ‘X’ arm tube sections were installed without baffles. All baffles installed in the ‘Y’ arm are of the improved, non-coated design. The retrofit operation requires personnel to penetrate the modules to distances up to one km, accessing the tubes from both ends, to remove glass coated baffles and to install improved baffles, and an additional module cleaning cycle. This work is progressing.

Equipment in the fabrication shop at Big Pasco was disassembled and shipped to a leased, newly-built facility at Magnolia Beach, in Denham Springs, Louisiana, which is 22 miles from the Livingston site. Installation of this equipment is nearly complete, with only the cleaning area to be finished. Quality spiral tube sections are being produced on the spiral mill, and qualification tests are in process on the remainder of the fabrication equipment.

Work planned to be accomplished during the next quarter:

- Complete retrofit of baffles in ‘X’ arm at Hanford.
- Complete vacuum acceptance testing of ‘Y1’ and ‘Y2’ modules at Hanford.
- Complete mobilization of fabrication activity at Magnolia Beach.

- Hold Fabrication Readiness Review at Magnolia Beach and initiate fabrication.
- Hold Completion Review at Hanford.
- Demobilize installation activity at Hanford and remobilize at Livingston.
- Hold Installation Readiness Review at Livingston and initiate installation of beam tube modules.

5.0 Beam Tube Enclosures (WBS 1.1.3)

Figure 10. View of the Completed Beam Tube Enclosure on the 'X' (Northwest) arm at the Hanford Site.

Significant accomplishments this quarter:

Hanford Site:

- Completed the placement of the Beam Tube Enclosure segments on the 'Y' (southwest) arm.
- Completed installation of the Beam Tube Enclosures to the 90 percent level (see Figure 10).

Livingston Site:

- Completed construction of the service road along the both arms.
- Poured concrete for the termination anchor foundation at the mid- and end-points of the 'X' arm.
- Completed placement of concrete for the Beam Tube Enclosure slab along the 'X' arm (accomplished early in September 1997.)

Discussion of accomplishments and work in progress:

Hanford Site. Construction of the Beam Tube Enclosures proceeded on schedule and was 100 percent complete by the end of this quarter. Both service roads, Beam Tube Enclosure slabs for the both arms, and 2,600 pre-cast enclosure segments (each 10 feet long) have all been completed. Installation of the Beam Tube segments is 90 percent complete.

Livingston Site. Construction of the service roads along both arms was completed on schedule. In addition, the placement of concrete for all the termination anchor foundations at the corner-station, as well as at the mid- and end-stations along both arms was completed.

Figure 11. Placing Concrete for the Beam Tube Enclosure Slab along the 'X' (Southwest) Arm at the Livingston Site.

The schedule for the Beam Tube Enclosure slab on the 'X' arm was accelerated to meet the early start date for the installation of the Beam Tube, and the slab was completed well ahead of schedule (Figure 12).

Figure 12. View of the Beam Tube Enclosure Slab along the 'X' (Southwest) Arm at the Livingston Site.

Work planned to be accomplished during the next quarter:

- Complete the remaining construction work associated with the installation of the Beam Tube Enclosure at the Hanford site.
- Pour the Beam Tube Enclosure slab along the ‘Y’ (southeast) arm at the Livingston site.
- Complete the precast fabrication of 700 Beam Tube Enclosure segments for the Livingston site.

6.0 Civil Construction (WBS 1.1.4)

Significant accomplishments this quarter:

Hanford Site:

- Accepted the mid- and end-stations on the ‘Y’ (southwest) arm for the joint occupancy.
- Reached the 90 percent completion level for construction at the corner station (Figure 13).
- Reached the 80 percent completion level for the mid and end stations on the ‘X’ arm.

Figure 13. View of Corner-Station from Main Entrance at Hanford Site.

Livingston Site:

- Reached the 80 percent completion level for the end-station on the ‘Y’ (southeast) arm.
- Poured concrete for the foundation of all the buildings at the corner-station.
- Poured concrete for the technical slab for the Laser and Vacuum Equipment Area (LVEA) at the corner stations as well as for the Vacuum Equipment Area (VEA) at the end-station on the ‘X’ arm.
- Reached the 50 percent completion level for the buildings at the corner-station (Figure 14).

Figure 14. View of Corner-Station from Main Entrance at the Livingston Site.

Discussion of accomplishments and work in progress:

Hanford Site. Construction of the buildings and infrastructure proceeded on schedule and all major milestones were achieved. The mid- and end-stations on the 'Y' (southwest) arm have been accepted for the joint occupancy. The LVEA at the corner-station is almost ready for joint occu-

Figure 15. View of Inside of LVEA at the Corner-Station at the Hanford site.

pancy, which is scheduled for September 9, 1997 (Figure 15). The mid- and end-station on the 'X' arm as well as the operation support building are 80 percent complete.

Livingston Site. Construction of the building and infrastructure proceeded on schedule and all major milestones were achieved. Concrete foundations and the technical slabs for all the buildings have been poured successfully. The end-stations on 'X' and 'Y' arms reached 20 percent and 80 percent completion respectively. The LVEA and Operations Support Building (OSB) are 50 percent complete (Figure 16).

Figure 16. View of Steel Framing of the Corner-Station at the Livingston Site.

Work planned to be accomplished during the next quarter:

- Complete the building and infrastructure at the Hanford site.
- Complete construction work at the mid- and end-stations on the 'Y' (southeast) arm at the Livingston site.
- Achieve 80 percent completion for the buildings and infrastructure at the Livingston site.

7.0 Detector (WBS 1.2)

Detector activities are organized according to the LIGO Work Breakdown Structure (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

7.1 Suspensions and Isolation

Significant accomplishments this quarter:

- Conducted Design Readiness Reviews on the intra- and extra-vacuum support structure of the seismic isolation system.
- Conducted the Final Design Review of the Small Optics Suspension.

Seismic Isolation. Hytec, Inc. has been developing the detailed construction drawings for the Horizontal Access Module (HAM) isolation system in anticipation of starting the first article procurement next quarter. Overall views of the Beam Splitter Chamber (BSC) and HAM designs are shown in Figure 17 on page 27. Design reviews of the internal and external support structures, using both LIGO and invited external reviewers, have been conducted. A number of important design details were addressed, for example, avoiding virtual leaks in the in-vacuum optical table and associated structures.

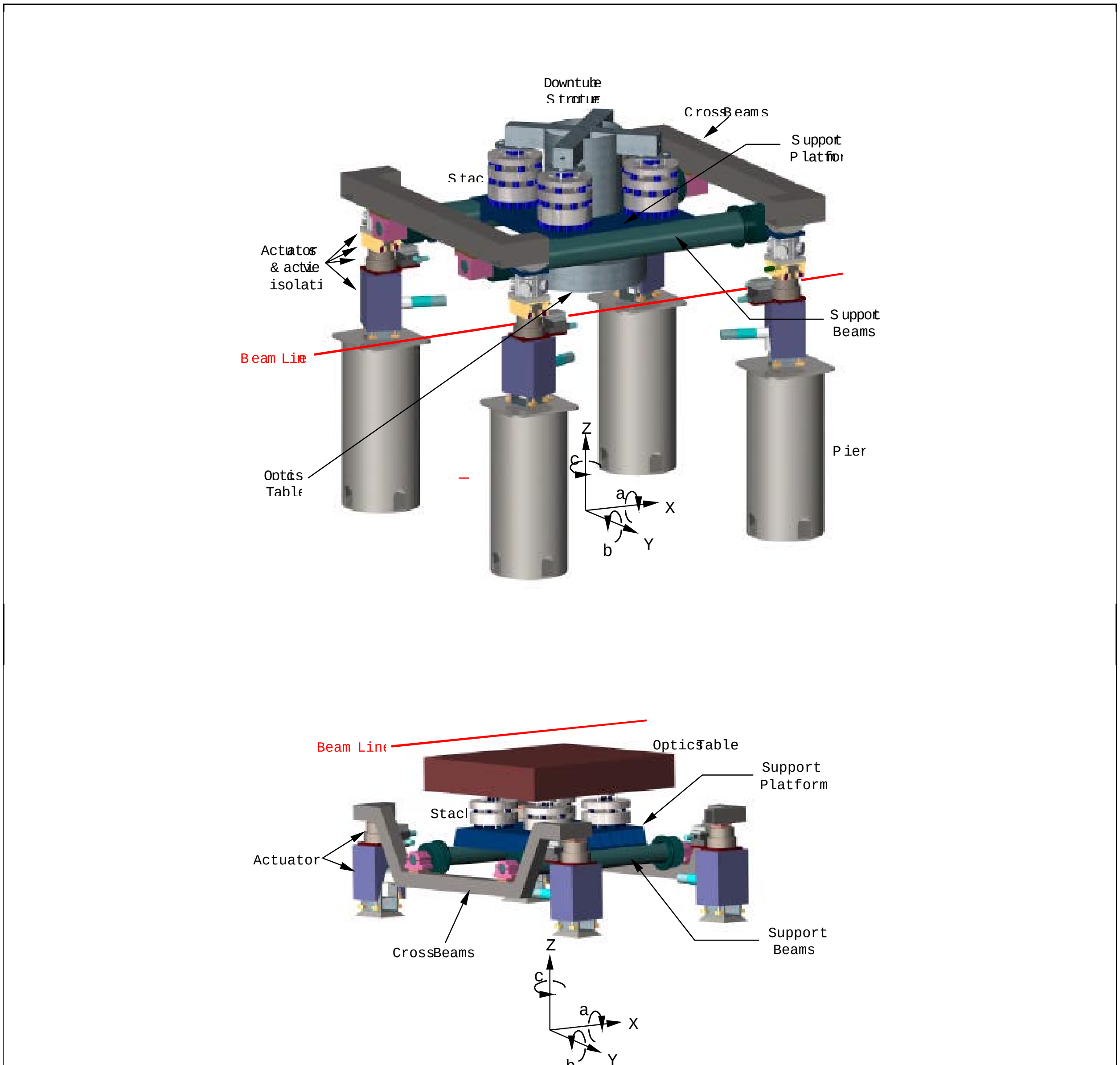

Figure 17. Views of the BSC and HAM Designs.

Seismic Isolation system designs. Top: Beam Splitter Chamber (BSC); Bottom: Horizontal Access Module (HAM). The vacuum chambers themselves are not shown for clarity. The four vertical support piers, the actuators, and the square box frames are outside the vacuum; the horizontal support beams penetrate the vacuum and support the multi-layer passive isolation ‘stack’ and optics table. The optics are hung below the BSC optics table; they are placed upon the HAM optics table.

Six coil springs went through a complete fabrication cycle. A new technique for spacing the aluminum slugs inside the coil spring was developed by Pegasus, Inc.-- the spring fabrication vendor--and the processes and final products appear satisfactory except for the welding of the end caps which must be refined. These springs are currently being tested in collaboration with JILA. One of the challenges is to determine if there is any internal noise generation (so-called ‘creaking’). A special-purpose high-sensitivity accelerometer and preamplifier is being used to look at minute motions in a test setup. The Fluorel elastomer seats for the springs have passed a Residual Gas Analyzer (RGA) outgassing test in their final fabricated form, thus eliminating any vacuum contamination concern.

The vacuum “feedthrough” vendor, Senior Flexonics, Inc., produced and tested sample bellows. One exceptional requirement for these bellows is their resistance to twist; the sample has been tested for and met axial, shear, and twist requirements, and in fact has completed a few twist cycles at very large deformations (49 mrad or 37 times the twist requirement) and exhibited no damage or leaks.

Suspension Design. The Small Optic Suspension design was finished during this quarter, culminating in the Final Design Review on July 10. The complete drawing set and assembly and test instructions have been shared with the University of Florida group executing the Input Optics design, and they are proceeding with a subcontract for a first article. These suspensions will be the first to be installed at the LIGO Hanford site. The Large Optic Suspension drawings are now nearing completion, and possible fabrication vendors have been approached.

Work planned to be accomplished during the next quarter:

- Seismic Isolation. Initiate first article fabrication.
- Suspension Design. Complete the Final Design for the Large Optics Suspension.

7.2 Lasers and Optics

Significant accomplishments this quarter:

- Prestabilized Laser. Conducted the Design Requirements Review for the Nd:YAG prestabilized laser subsystem; conducted the Final Design Review for the Lightwave, Inc., 10 W laser.
- Input Optics. Conducted the Preliminary Design Review for the Input Optics Subsystem.
- Core Optics. Coating trials were performed with excellent results.
- Core Optics Support. Continued Preliminary design.

Prestabilized Laser.

The Design Requirements Review for the Nd:YAG Prestabilized laser subsystem was held on July 11. The review affirmed the basic design decisions, including the use of an acousto-optic frequency shifter and fixed-length reference cavity, and the need for a pre-modecleaner in the prestabilized laser system to ensure that the laser exhibits shot-noise-limited intensity noise at the modulation frequencies (25 MHz and higher) used for the length control system. Figure 18 shows the elements of the design. The Stanford GALILEO project aided in the design of the pre-mode cleaner and visited LIGO to help in its integration. A complete LIGO testbed laser is now in fabrication. This testbed will be transferred to Hanford to serve as the light source for the first tests onsite of the laser and Input Optics subsystems. The 700 mW NPRO laser continues to operate in the Phase Noise Interferometer (see Section 8.0 on R&D), and information from that effort is incorporated in the 10W design as appropriate.

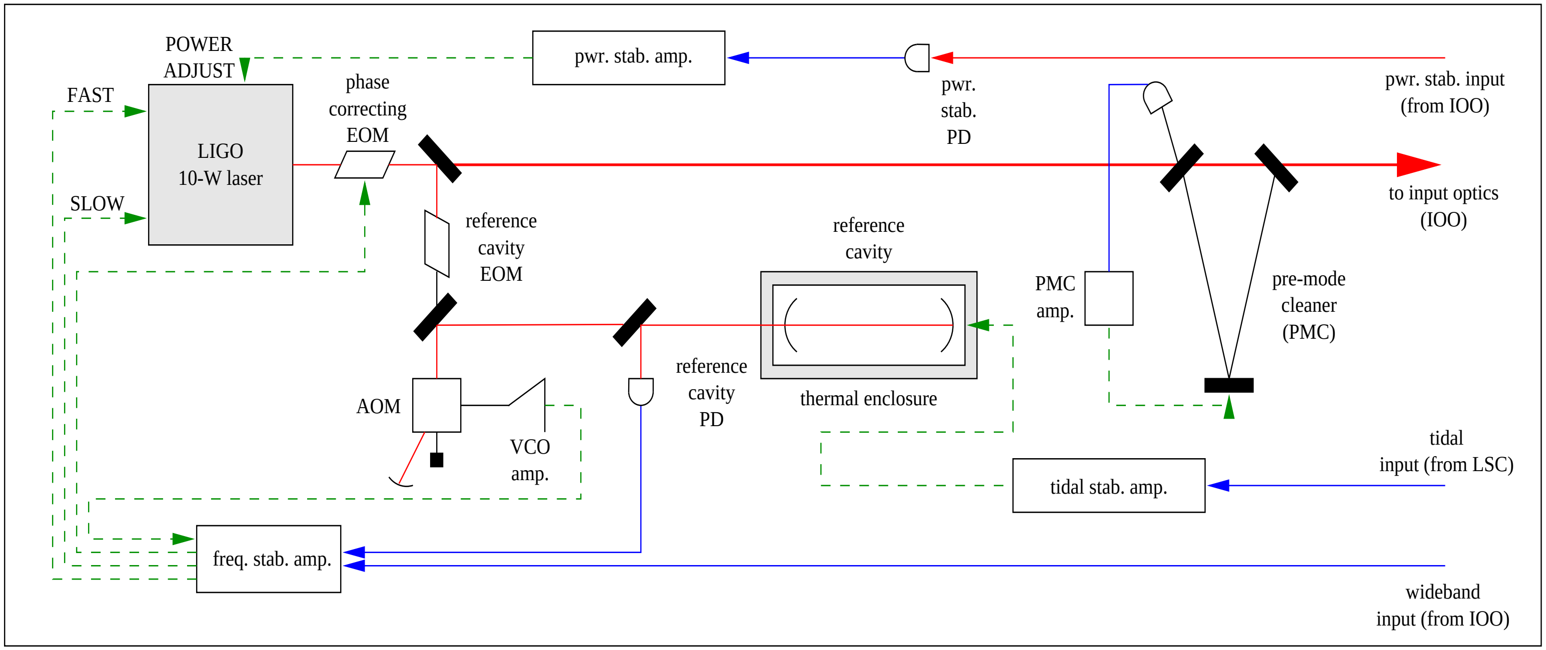

Figure 18. Pre-Stabilized Laser Layout.

The 10W source laser in the upper left is stabilized to a fixed-length reference cavity (center) via an acousto-optic frequency shifter. The output light is temporally and spatially filtered by a small rigid pre-mode cleaner at the right.

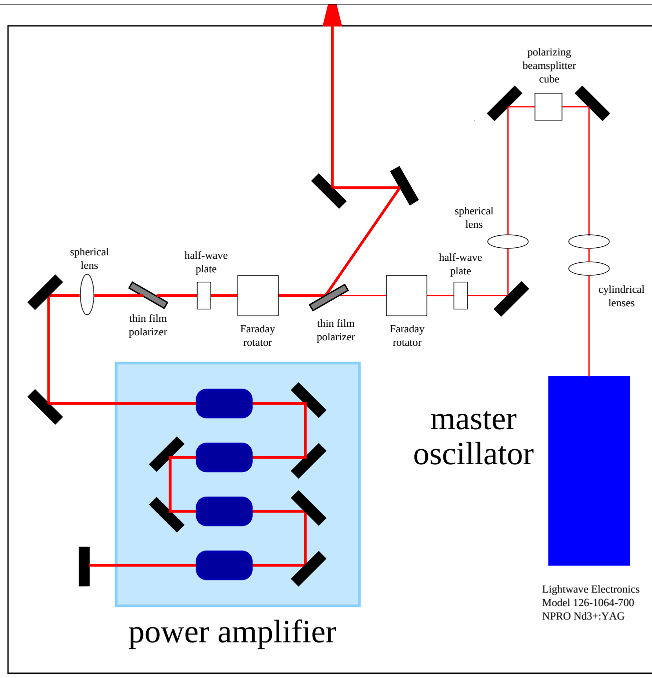

Figure 19. Lightwave 10 W Laser Internal Design.

A 700 mW Non-Planar Ring Resonator drives, through isolation and mode-matching optics, a double-passed diode-pumped amplifier with four gain elements.

Lightwave, Inc., continued development of the LIGO 10W Nd:YAG laser and conducted the Final Design Review on the June 20. A schematic of the internal elements of this source laser is shown in Figure 19. All components for the first lasers have been fabricated and assembly is underway. A reliability study addressing early aging of the pump laser diodes has identified contaminants in the form of condensable volatile material as the possible cause. Changes in cleaning and fabrication have been made to address this problem. The delivery of the first ‘alpha’ laser has been delayed to next quarter, in part to take advantage of the improved fabrication process.

Input Optics. The University of Florida group responsible for the Input Optics completed the Preliminary Design this quarter with a successful review on August 22, 1997. A number of important design issues were resolved including the phase modulation system to be used. A meeting to address this question was held at MIT July 14-15, with LIGO and University of Florida staff attending. The paths for possible cross-products of resonant and non-resonant sidebands to produce noise at the gravity-wave sensing port were discussed, as were practical questions concerning implementation of a Mach-Zehnder or simple series modulation approach. The recommendation was to pursue series modulation, and ways to better separate the modulation frequencies, and thus their cross-products, will be investigated by the Interferometer Sensing and Controls group.

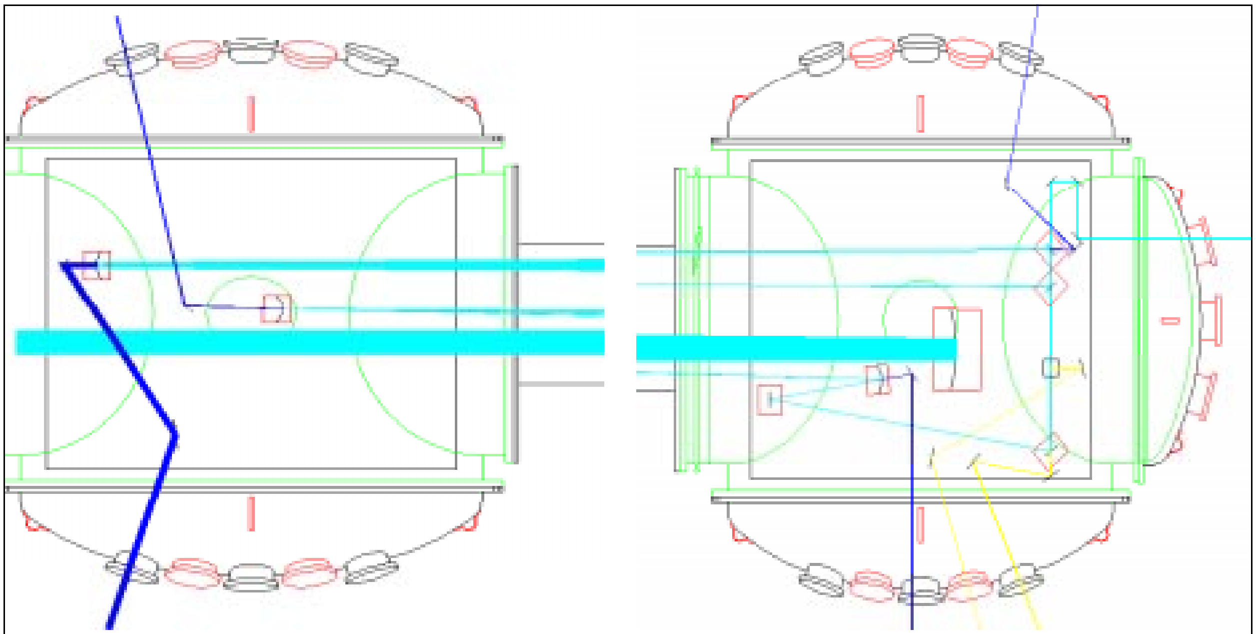

Figure 20. Input Optics Layout.

The input beam enters in the right Horizontal Access Module (HAM) vacuum chamber (topmost of the three ports); it passes through the phase modulator, and then the triangular mode cleaner (two mirrors at 45 degrees in the right HAM, one curved mirror in the left HAM). Light then is mode matched to the interferometer by a three-mirror telescope, whose last element is in the right HAM. Sample beams for control and monitor are brought out of the interferometer in both HAMs.

Other technical issues addressed during this quarter included the influence of stray magnetic fields from an in-vacuum Faraday isolator on nearby suspended optics, methods to measure and adjust for optimal matching into the interferometer, and allowable power levels in critical components. Final design is now underway. The suspensions and the final telescope mirror will be fabricated as early as possible to reduce technical and schedule risks.

Core Optics Components. As noted last quarter, the suppliers of substrate material, Heraeus GMBH and Corning, Inc., have both experienced delays. Heraeus reported concerns about the level of absorption of Nd:YAG light based on one measurement of a special glass being produced for the VIRGO project. During this quarter, samples of the type 311 fused quartz planned for LIGO were characterized by the Ecole Supérieure in Paris, and found to absorb between 5-7.5 ppm/cm, an acceptable level for LIGO. Heraeus immediately began production of the substrate material, and plans to deliver 13 optical substrates in September. Corning had difficulty in producing boules of sufficient thickness to meet our required dimensions. During discussions with Corning it was discovered that LIGO has specified a thickness slightly beyond a critical threshold. By making a small adjustment in the fabricated thickness specified for the test masses (from 100 to 97.5 mm) it is possible for Corning to successfully produce substrate material. Polishing and coating schedules are being adjusted to match anticipated substrate availability.

The Commonwealth Scientific and Industrial Research Organization (CSIRO) has completed polishing a set of folding mirrors for the half-length interferometer at Hanford; these parts are presently being certified by LIGO. An in-process visit was made to CSIRO on July 14-16 which left a very positive impression. Our second polisher, General Optics, has delivered five end test mass substrates to NIST for metrology.

Further coating trials have been made by Research Electro-Optics, and the analysis of the metrology of the surfaces before and after coating is underway. Preliminary results indicate that the RMS roughness contributed by the coating (dominated by low spatial frequencies) is acceptable (on the order of 1-2 nm RMS over a 10 cm diameter).

LIGO in-house metrology is moving forward with an order--with Phase Shift Technology, Inc.--for a 1064 nm optics profiling interferometer which will be used to characterize the final coated optics. The reference optics are being polished by CSIRO, ensuring excellent quality and a good understanding of the surfaces.

Core Optics Support. Preliminary design is nearly complete for this subsystem which is responsible for handling the light leaving the interferometer. This includes the principal output beams from which the gravitational-wave signal and control signals are derived as well as the stray light within the vertex-, mid-, and end-stations. The baffles to control stray light are also in this subsystem. The detailed design of the telescopes used to extract beams was performed. These optics must meet requirements for phase flatness, to allow wavefront sensing, as well as compactness and weight, since they are mounted on the passive seismic isolation optical tables. A reflective, slightly off-axis design has been selected.

Work planned to be accomplished during the next quarter:

- Prestabilized Laser. Receive Lightwave 10 W laser.
- Input Optics. Place order for final telescope substrate material.
- Core Optics. Conduct the Preliminary and Final Design Reviews.
- Core Optics Support. Start Final Design activities.

7.3 Interferometer Sensing/Control

Significant accomplishments this quarter:

- Alignment Sensing/Control. Prototyping hardware tools for initial alignment.
- Length Sensing/Control. Conducted the Preliminary Design Review.

Alignment Sensing/Control. Final Design continued this quarter; the initial alignment prototyping was the primary focus, and fabrication and procurement for the optical lever prototype was completed. Testing of the laser and fiber is underway. The stability of the mounts for the complete assembly will then be tested. A detailed plan for initial alignment was developed and circulated. This activity affects planning for the Civil Construction, Beam Tube, and Vacuum Equipment systems as well as the Detector since monuments are used throughout the sites and careful coordination is required to plan the installation.

Because of the close link between the length and alignment and the use of digital servo techniques, a coordinated approach to diagnostics is being undertaken, and a top-level design was developed this quarter. In addition, an alignment data acquisition prototype is being set up with the Control and Data System to test the conceptual design for this multiple-input multiple-output system.

Length Sensing/Control. The preliminary design for the Length Sensing and Control system was completed this quarter. A sense of the structure and some elements of the design can be obtained from the functional block diagram in Figure 21. Figure 22 provides a more detailed look at one of the photodiode tables (integrated with the alignment sensing systems); and Figure 23 shows the conceptual design for the photodiode assembly.

The requirements for the photodetector system are demanding: roughly 600 mW of light must be detected with shot-noise-limited noise performance, high quantum efficiency, linearity, spatial uniformity, and at high (25-30 MHz) frequencies. The results of research this quarter into InGaAs photodiodes from Hamamatsu, Inc., were very encouraging. The response is linear to beyond 100 mW per device and with noise performance as required at the modulation frequencies. There is no damage at up to 700 mW per device allowing some margin for locking transients in the interferometer. The backscatter as presently measured from this diode is greater than desired, and preparations for a more careful scatterometer and subsequent measurement are underway. Discussions with Hamamatsu as well as alternative manufacturers are continuing.

The operations mode servo design was added as part of the preliminary design package, as was acquisition modeling. Higher-order phase-modulation sidebands are now included, and alternative pickoff methods incorporated. The various states and signals for the locking sequence have been identified and several sequences targeted for further development. With the completion of this single-mode model of acquisition, the development of a multi-spatial-mode version was initiated via a contract with JPL.

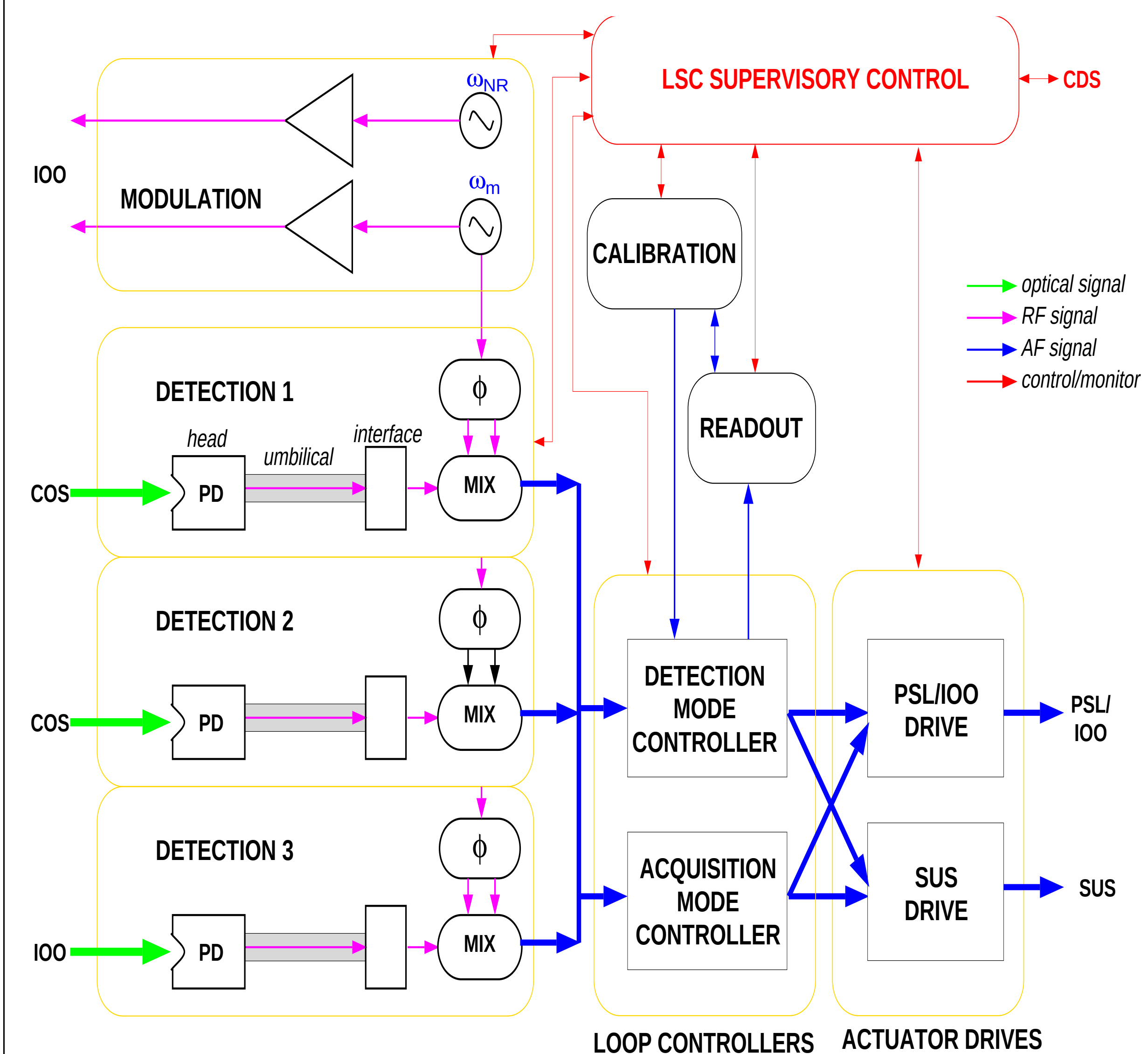

Figure 21. Length Sensing/Control subsystem functional block diagram, showing principal signal interfaces.

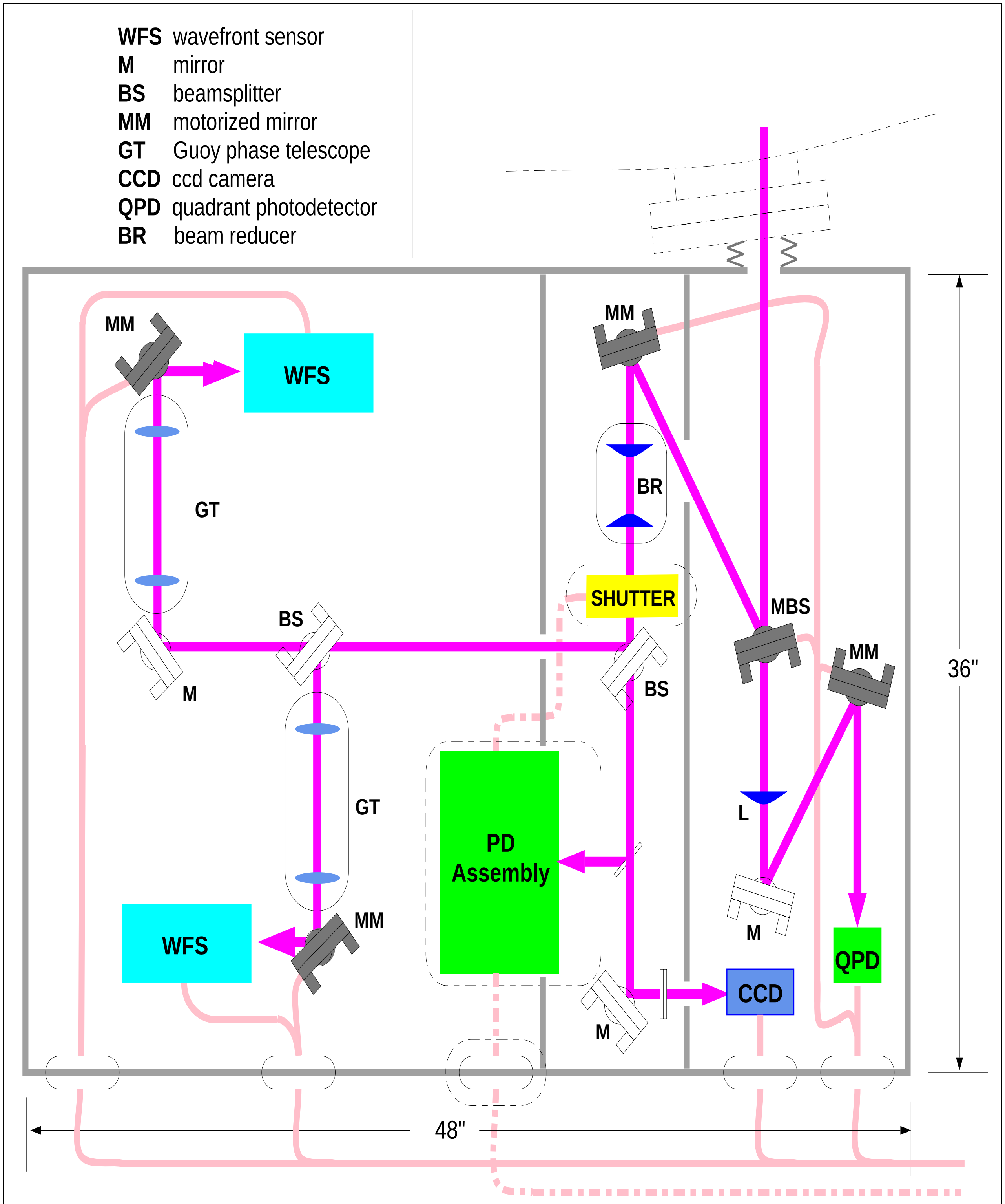

Figure 22. Preliminary Interferometer Sensing/Control table layout with photodiode assembly indicated.

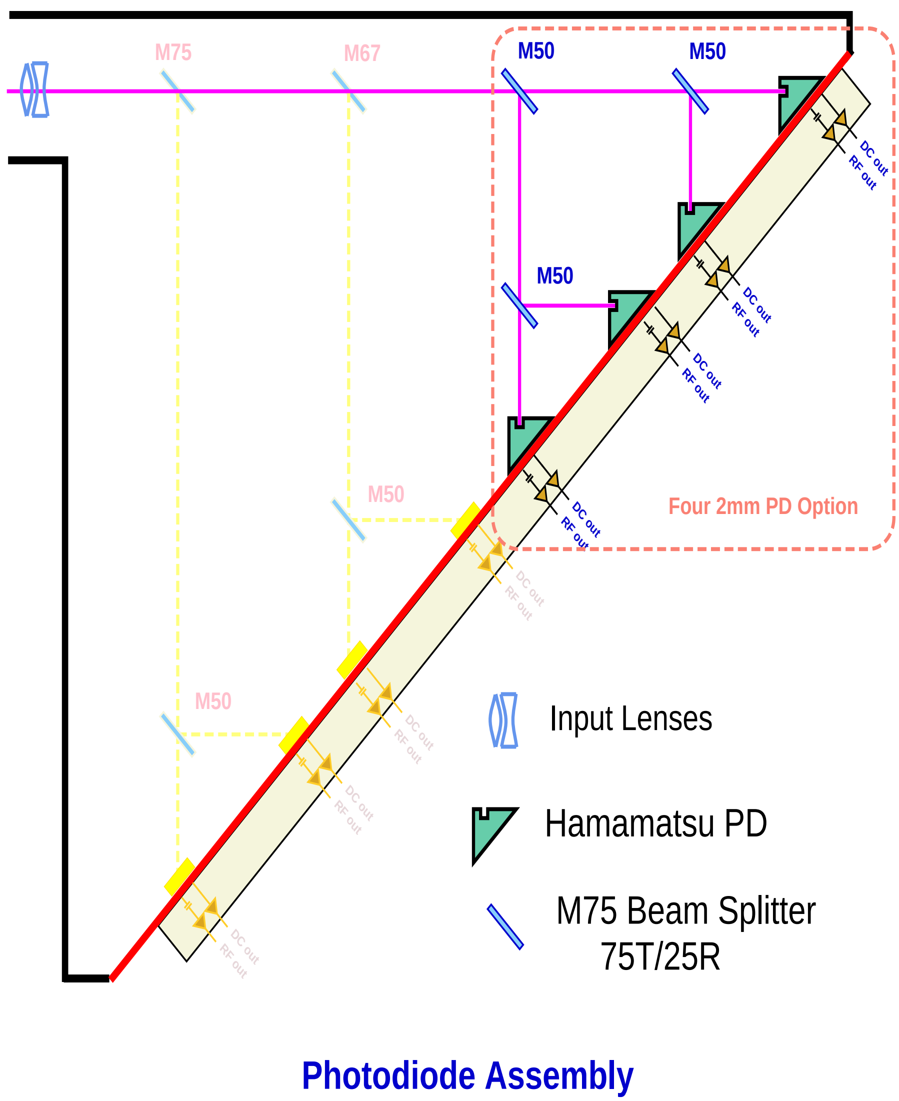

Figure 23. Photodiode Assembly Layout with Full Implementation.
(8 photodiodes). The 4-diode implementation is shown in the dashed box.

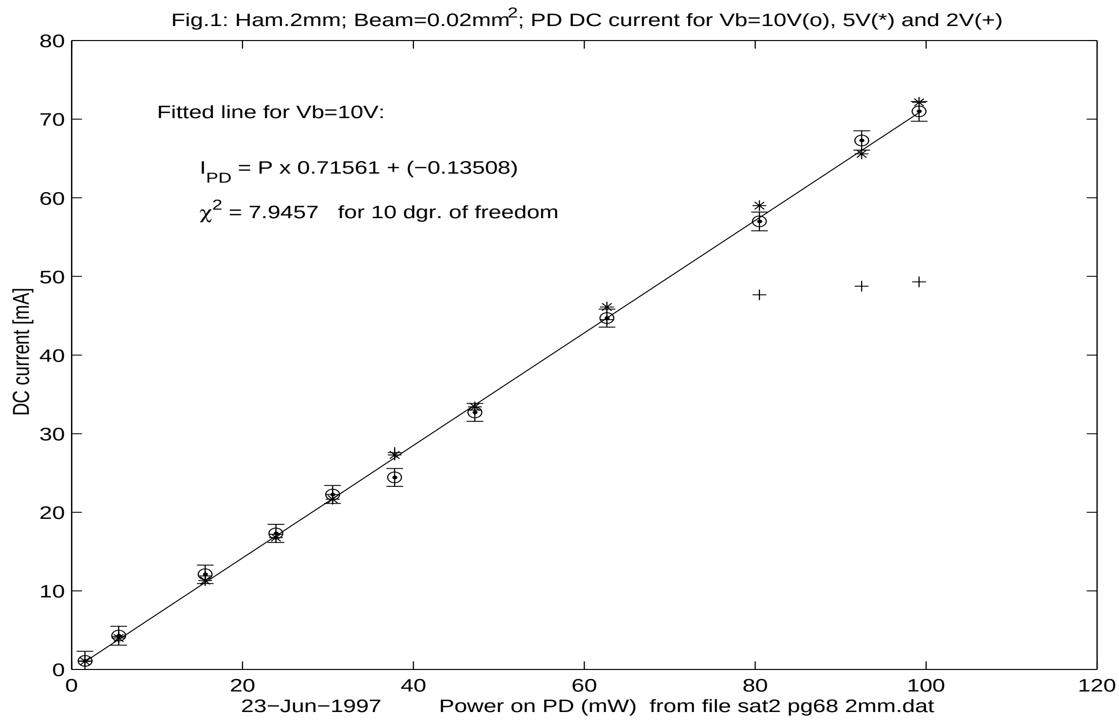

Figure 24. DC Response of the 2mm Photodiode as a function of incident intensity for various bias voltages.

Work planned to be accomplished during the next quarter:

- Alignment Sensing/Control. Complete work on Initial Alignment.
- Length Sensing/Control. Continue Final Design activities.

7.4 Detector System Engineering/Integration

Significant accomplishments this quarter:

- Completed contamination test setups.
- Used the integrated layout to resolve several design issues.

The effort to qualify in-vacuum materials and processes for their optical contamination properties made considerable progress this quarter. Two measurement setups were completed: first a very clean vacuum system instrumented with a Residual Gas Analyzer (RGA) and having equipment for calibration, bake, and control of the pumping speed; and second, a system for direct optical measurement using high-finesse Fabry-Perot cavities in initially very clean vacuum chambers, with a precision measurement of the change in the storage time or the shift in higher-order spatial modes (due to direct absorption). In either experiment, samples of possible contaminants are introduced after establishing a baseline performance. Qualification with empty vacuum systems is underway as the quarter closes.

The development and use of the integrated layout drawing set including the optical layout continued this quarter, ensuring interface consistency. The Core Optics Support telescopes and baffling were introduced, and the detailed Input Optics design executed in this context.

In the general systems engineering domain, special purpose meetings concerning modulation approaches, diagnostics, and control system top-level design were held. Refinement of the Detector Subsystems Requirements and documentation continued.

Work planned to be accomplished during the next quarter:

- System Preliminary Design. Continue the Preliminary Design coordination and review.
- Contamination. Qualify the first critical materials for interferometer design (cabling and suspension sensors/actuators) for contamination.

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

Significant accomplishments this quarter:

- Completed and tested the Vacuum Controls hardware and software.
- Conducted Preliminary Design Reviews of the Data Acquisition and Suspension Control Systems.
- Reviewed the Design Requirements of the Length Sensing/Control system.
- Installed Vacuum controls system at Hanford and supported vacuum system commissioning. Completed fabrication of Livingston equipment racks.

Work on the vacuum controls is ending with final operator interfaces, test specifications, and as-built drawings in place. Surveys of the Hanford site with detailed plans of cable runs and placement of CDS equipment were performed.

Support for interferometer subsystems: The design for the suspension actuator driver was prototyped and met the model predictions for dynamic range and noise performance. The Preliminary Design Review of the CDS Suspension electronics was held on August 21, 1997. The CDS Length Sensing/Control Design Readiness Review (DRR) was held with the Detector Preliminary Design Review, and the preliminary design effort planned.

Global System and Data Acquisition: The Preliminary Design Review of the Data Acquisition system was held on August 8, 1997. The review team included internal and external reviewers. The Final Design is now underway. Diagnostics development continued; a coordinated effort of to start the actual coding and test of procedures was planned and started.

R&D support: The Recycling Mirror and Beam Splitter Servo Modules for the 40 meter Recycling experiment were built and tested. The initiative to implement wavefront sensing alignment on the 40 meter also continued.

Work planned to be accomplished during the next quarter:

- Interferometer Controls. Complete the Input Optics and Pre-Stabilized Laser Design Requirements Reviews and begin production of first-article electronics. Continue Alignment and Length Sensing preliminary design. Fabricate the prototype suspension controller. Conduct the Physics Environment Monitor Preliminary Design Review.
- CDS integration and global systems. Complete the Final Design Review for Global Controls and place orders for equipment.
- Data acquisition. Continue Final Design.
- Vacuum system controls. Fabricate Livingston hardware.
- Interferometer Diagnostics. Continue the Preliminary Design.

7.6 Physics Environment Monitor (WBS 1.2.3)

Significant accomplishments this quarter:

- Continued design. Work in this subsystem advanced less quickly than anticipated due to other demands on resources. There is no impact on system-level milestones.

Working drawings of mounting systems and mechanical interfaces were developed, specifications were prepared for hardware, and details of electrical and software interfaces developed with the Control and Data System group.

There was progress characterizing the sites with the development of a high-sensitivity magnetic field sensor and the configuration of portable data acquisition systems. The objective is to measure several parameters of interest at the two sites simultaneously and with GPS time stamps to see what correlated noise sources will be significant.

Work planned to be accomplished during the next quarter:

- Conduct the Final Design Review.
- Make On-site measurements of possible inter-site correlated environmental effects.

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 this quarter:

- Completed debugging and repair activities in the 40 meter Interferometer.
- Completed of the first phase of the 1064 nm Phase Noise Interferometer.

40-meter Interferometer Investigations. A significant fraction of time this quarter was dedicated to the identification and repair of failed hardware components of the 40 meter interferometer. Our original goals for this quarter (locking the recombined interferometer and obtaining a calibrated power spectrum, venting to install recycling hardware, and commissioning the recycled interferometer) were severely delayed by these failures. However, we did succeed in repairing the apparatus and operating it in a stable locked state in its present recombined configuration at the very end of the quarter.

The most difficult of our hardware problems involved the erratic performance of the argon ion laser. This was ultimately diagnosed as a degradation in the laser tube itself; however its intermittent symptoms (occasional multi-mode operation, unstable laser power), interspersed with periods of satisfactory operation, made this diagnosis difficult. The root problem was a deterioration of the metal cathode within the laser tube which sagged as it fatigued, inducing the observed problems. Two successive replacement tubes proved to be defective (both tubes had gas seals which quickly failed causing the argon to vent within a day of initial operation). The service response time of Spectra Physics (the manufacturer of the argon ion laser) was especially slow because they had coincidentally suspended production of argon tubes in July due to manufacturing problems they were experiencing. The failure of our second replacement tube was linked to these production problems. In total, we worked from the end of June until nearly mid-August before these problems were finally resolved.

Further problems were discovered with the laser power supply (a faulty current controller board), a Pockels cell high voltage supply, a VME power supply, a phase shifter module, and a failed suspension controller. A 12 Hz signal which was apparent once the system was starting to operate was diagnosed as due to an error in the alignment of the suspensions sensors with respect to the optic-mounted magnets, and required one additional venting. As a result of this discovery, the LIGO installation procedure has been rewritten to include the precision alignment procedure which used to address the problem encountered in the 40 meter.

Vacuum was re-established on August 29, and extended periods of data were acquired during the closing days of the quarter. It appears that at present the noise floor of the apparatus is dominated by electronic noise. The source of this is under investigation.

The wave front sensing electronics which were shipped from MIT have been checked out and prepared for installation on external optical tables. Progress was made on the customization of the sensors and servo-loop for 40 meter.

Development of Data Acquisition and Analysis Techniques. The software was upgraded and backup utilities installed. The data acquisition system was used as a tool to aid in the locking and initial characterization of the interferometer.

Phase Noise Research. The first phase of the research using the Phase Noise Interferometer with Nd:YAG Infrared light was concluded this quarter. The system consisted of the 700 mW pre-stabilized laser (resembling closely the configuration planned for the LIGO Pre-Stabilized Laser), and two suspended in-vacuum masses forming a quiet reference Fabry-Perot to allow sensitive tests of the laser. Final measurements have been made with this configuration, and the performance of the laser (and thus the overall system) is very good. In Figure 1, the frequency noise of the laser measured using the separate suspended cavity is shown. This level is satisfactory for the final phase of the Phase Noise Interferometer. During the next phase measurements will be made of the phase noise, at LIGO sensitivity, on a recycled suspended Michelson interferometer. The data also shows that the stabilization technology is in place for LIGO.

The additional optical components (the beamsplitter and second Michelson mirror) were prepared for in-vacuum suspension (attachments, suspension balancing, and vacuum baking), and the suspension controllers accurately diagonalized (ensuring that the sensors indicate and actuators deliver pure translations). A modest data acquisition system was set up. Sensors and feedback for additional degrees of alignment freedom were installed. An Indium Gallium Arsenide photodetector-amplifier was prepared which will be used to sense the light in an early prototype test for the LIGO Length Sensing/Control photodetector. At the end of the quarter, all equipment was installed and ‘first light’ in the complete system was achieved.

Work planned to be accomplished during the next quarter:

- 40 meter Interferometer:
  - The remaining recycling hardware will be installed: suspended input mirror and associated components, suspension control electronics, cabling.
  - The power recycled system will be commissioned, beginning with the power recycled Michelson configuration, then adding the Fabry-Perot arms.
  - The alignment sensors will be installed and tested, and the signals will be used to aid interferometer characterization.
  - The capabilities of the data acquisition system will be enhanced, and the system will be exercised.
- Phase Noise Demonstration. Measurements using the final configuration will be carried out. Additional aspects of the Length Sensing/Control system will be tested

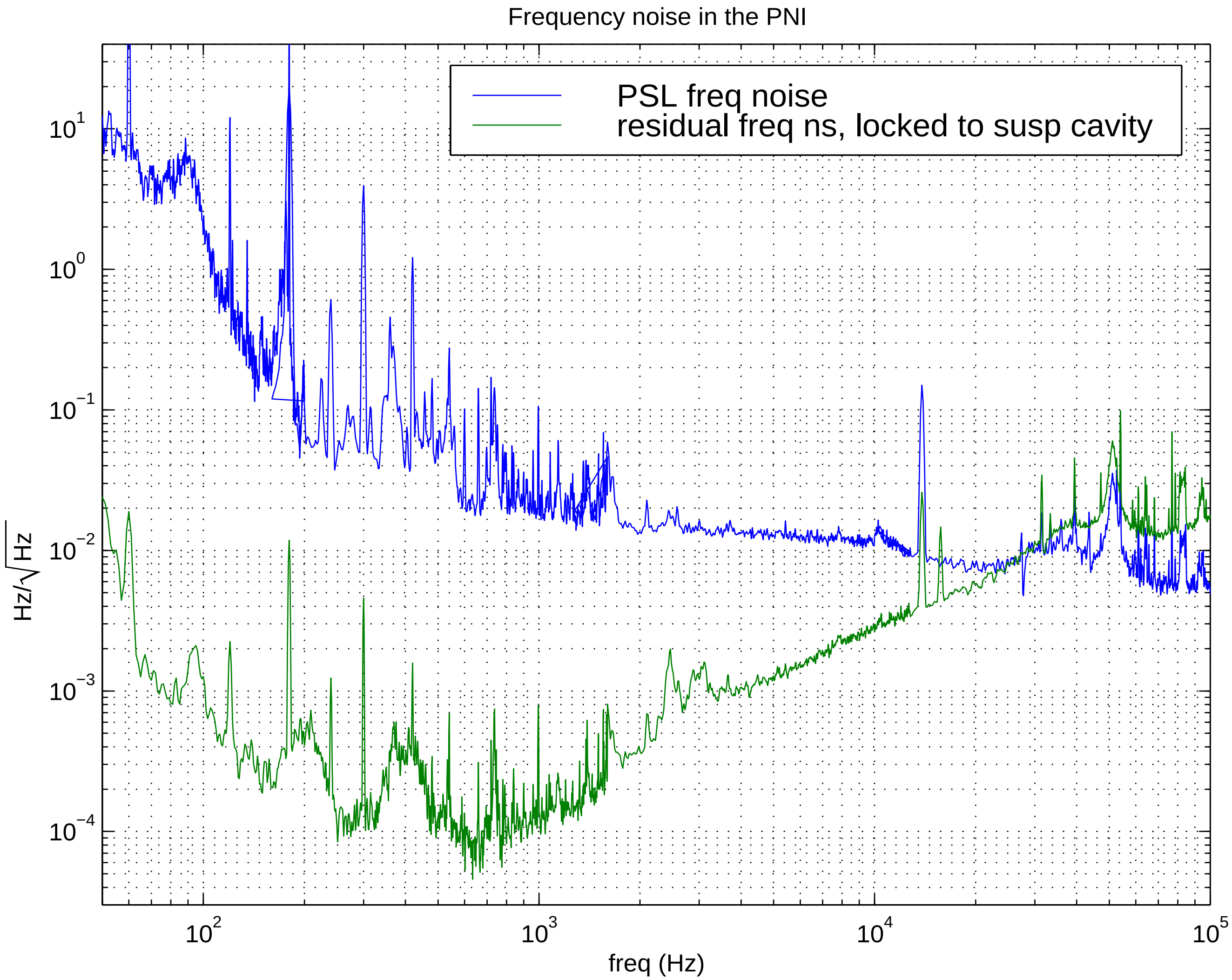

Figure 25. Frequency Noise of the 700 mW NPRO Pre-Stabilized Laser.

As characterized using a suspended cavity Fabry-Perot. The top curve is the pre-stabilized laser frequency noise as measured by the suspended cavity, and the lower is the error signal of the suspended cavity loop that incorporates feedback to the laser. This shows the effect of the additional loop gain and gives an estimate of the level for the residual frequency noise after the second level of stabilization.

9.0 Systems Engineering (WBS 1.4.3)

9.1 Integration (WBS 1.4.3.1)

Significant accomplishments this quarter:

- Completed a Preliminary Design Review for the Beam Tube bake task.
- Prepared final drafts of Interface Control Documents (ICDs): Beam Tube--Civil Construction; Vacuum Equipment--Civil Construction Completion; Beam Tube--Vacuum Equipment.
- Approved and formally released the Reliability Program Plan.
- Issued drafts of the Suspension Reliability Prediction Report and the Physics Environment Monitoring Reliability Prediction Report.
- Supported the development of the 10W laser system by conducting research on laser diodes to identify operating characteristics, application standards, and device availability. A reliability plan was also developed in which quality audits, laser diode screening and the implementation of a reliability improvement warranty were suggested.
- Updated the Washington Laser and Vacuum Equipment Area (LVEA) Integrated Layout. Revised "as built" representations of all signal and power stub-ups.

Discussion of accomplishments and work in progress:

Integration Planning. A schedule for integrating the 2Km Vertex Michelson at the Washington site has been started. This schedule tracks planned delivery dates, need dates, work teams, laboratory space, test equipment, and fixtures. This planning is being performed jointly with the Hanford Observatory staff.

Beam Tube Bake. A Preliminary Design Review (PDR) for the Beam Tube Vacuum Bake task was held this past quarter. Design requirements for the bake were identified, documented, reviewed and approved. Design analysis and preliminary design work for bake insulation, electrical heating and control, vacuum pumping, and monitoring instrumentation, data acquisition and logging were completed. Final design and specifications for Beam Tube insulation were completed. An Invitation for Bid was released for insulation work to begin at the Washington site in October (with completion scheduled next year). Remaining equipment needed for the bake of the first Beam Tube module at the Washington site was ordered. Washington site staff dedicated to the vacuum bake activities has been recruited.

Reliability Support. The draft of the Data Acquisition System (DAQ) Reliability Prediction Report is in process. Each subsystem reliability prediction report provides reliability predictions and allocations to subsystem equipment and availability predictions indicating the contribution of the subsystem to the top level LIGO availability requirements. Subsystem Reliability Prediction Reports will continue to be performed on the remaining LIGO subsystems as preliminary design information becomes available.

Mock-up Development. Development of the vacuum equipment chamber mock-ups is continuing at Caltech. These chambers will be used by the Detector subsystem teams to validate installation and integration approaches before the hardware is staged at Hanford.

A five foot by six foot Newport optical table and support structure has been installed in the Horizontal Access Module (HAM) chamber mock-up. Mock-ups of Seismic Isolation (SEI) components excluding the isolation stack have been fabricated and set up outside and within the HAM chamber. Two 84 inch diameter access doors were fabricated and delivered for the chamber. Fabrication of one 60 inch diameter access door each for the HAM and Beam Splitter Chamber (BSC) was started. A 49 inch diameter, non-sandwich design, optical table with its internal support structure was fabricated and delivered for the BSC chamber. Preliminary design has started on the balance of BSC Seismic Isolation structural components.

Integrated Layout Drawing. The Hanford, Washington Laser and Vacuum Equipment Area (LVEA) integrated layout drawings have been updated to reflect as-built details for the Process Systems International (PSI) vacuum chambers and the civil construction details. Work is proceeding on the Vacuum Equipment Area (VEA) layouts for the mid- and end-station buildings. The routing of Control and Data Systems (CDS) cabling along the beam manifold has been laid out and the design specifications for cable trays are being written.

Work planned for the next quarter:

- Continue work on mock-ups. This includes: attaching all four access doors to respective chambers; designing, fabricating and installing SEI components on the BSC; designing, fabricating and installing clean booths around the chambers; specifying, procuring and installing tables required for simulated testing; fabricating and installing a cosmetic bellows coupling between the HAM and BSC chambers.
- Issue final revisions of the Beam Tube-Civil Construction, Vacuum Equipment-Civil Construction, Vacuum Equipment-Beam Tube Interface Control Documents (ICDs) and write drafts of the Detector-Vacuum Equipment and the Detector-Civil Construction ICDs.
- Complete the schedule for the integration of the Washington 2-Km Vertex Michelson Interferometer. Support Detector integration planning by identifying installation sequences needed to be checked with the mock-up facilities. Identify support equipment, fixtures, etc., needed for component installation.
- Complete the draft Reliability Prediction Reports for the Suspension Systems, the Physics Environment Monitoring Systems, and the Data Acquisition Systems. Continue development of subsystem fault trees and reliability predictions as Preliminary Design Review information becomes available.

9.2 Simulation, Modeling and Data Analysis

Significant accomplishments this quarter:

- Drafted a common data format specification in collaboration with VIRGO. The specification, "*Specification of a Common Data Frame Format for Gravitational Wave Detection*", LIGO-T970130-01-E and VIRGO-SPE-LAP-5400-102, has been accepted by both the LIGO and VIRGO organizations. A beta version of a software library was released in July 1997. The specification has been made available to GEO 600 and TAMA 300 for their review. This document is important for establishing a common data format for the international gravitational wave detection community.

Discussion of accomplishments and work in progress:

- Work on the End-to-end model continued. The format has been revised to simplify the input data format. The software has been analyzed using a profiler and the internal data passing method is being revised to improve speed. A digital filter algorithm has been developed for improved accuracy. The front-end modeler has been revised to simplify customizing for different kinds of analysis. Validation of existing modules continues.
- Data recently taken for single-cavity operation of the recombined 40 meter interferometer are being compared to the time-domain model within the End-to-End model. Model validation using the 40 meter data had been delayed because the machine was not locking stably.
- VIRGO and LIGO are collaborating on an update of the frame format library. It will be converted to an object oriented design for better maintainability and extensibility. LIGO has begun to develop a C++ Frame I/O library which meets the data format outlined in the specification. The Preliminary design of C++ classes has started and actual code development will begin next quarter.
- The specification of LIGO data analysis software will began this quarter. The document, "*LIGO Data Analysis Software Specification Issues*" (LIGO-T970100-0A-E), was released in July.

Work planned to be accomplished next quarter:

- Draft the LIGO Data Analysis Software Specification. This document will specify the components and connectivity of software used for LIGO data analysis. The first draft will be delivered in September 1997.
- Complete the LIGO data acquisition modeling software. This model will provide simulated data streams in the common data format for use in LIGO data analysis software development.
- Design a C++ version of the Common Data Format I/O library with VIRGO. This will require collaboration with VIRGO before a beta release of the software can be made in late 1997 or early 1998.
- Add data compression algorithms to the Common Data Format. This could potentially double the speed of data analysis. A version of the Frame Library with compression will be delivered by late November 1997.
- Design the C++ classes and their interfaces for the LIGO Data Analysis Software. A first cut at these classes is planned by the fall of 1997 with documentation and implementation by spring 1998.
- Begin implementing of the C++ classes into an alpha version of the LIGO Data Analysis Software System during the C++ class development.

10.0 REFERENCES

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

2. *The Construction, Operation, and Supporting Research and Development of a Laser Interferometer Gravitational-Wave Observatory,* proposal submitted to the National Science Foundation, December 1989.

3. *Technical Supplement to the LIGO Construction Proposal (1989)*, dated May 1993.

4. *LIGO Project Management Plan*, LIGO-M950001, Revision B, April 24, 1996.

5. *LIGO Cost Book*, dated September, 1994.

6. *LIGO Project Management Plan*, LIGO-M950001, Revision C, October 1997.