CALIFORNIA INSTITUTE OF TECHNOLOGY

Laser Interferometer Gravitational Wave Observatory (LIGO) Project

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Subject: LIGO Quarterly Report - Draft

A draft copy of the LIGO Quarterly Report (end of February 1995) is attached for you review. Please provide any comments you may have as soon as possible to permit me to include them in the submittal to NSF.

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Quarterly Report

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

NSF COOPERATIVE AGREEMENT No. PHY-9210038
March 1995

CALIFORNIA INSTITUTE OF TECHNOLOGY

Contents

1.0 Introduction

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, 1994 through February 28, 1995.

The Quarterly Report as defined in the Cooperative Agreement and the Project Management Plan[2] includes a summary at the third level of the WBS of actual obligations com-

1. Cooperative Agreement No. PHY-9210038 between the National Science Foundation, Washington, DC 20550 and the California Institute of Technology, Pasadena, CA 91125, dated May 1992.
2. LIGO Project Management Plan, LIGO-M950001 rev. B, February 1995.

pared to baseline estimated costs and graphs at level 2 of the WBS comparing actual obligations with planned obligation profiles. Schedule reporting is to include an evaluation of earned value to the third level of the WBS (where appropriate). The cost and schedule status information presented in this Quarterly Report is based fully upon the LIGO Cost Book and the Level III costs have not been changed. The Cost Book is currently being used to develop an integrated performance measurement baseline. This information will be presented to NSF during the next quarter and will be available for available cost and schedule status reporting in the next Quarterly Report. The allocation of costs and to the new Work Breakdown Structure (WBS) is presented in section 3.0.

2.0 Summary of Work Accomplished

2.1 Facilities and Vacuum System (WBS 1.1)

2.1.1 Vacuum Equipment (WBS 1.1.1)

The Vacuum Equipment Request for Proposals (RFP) was reviewed on December 2, 1994 by the Vacuum Equipment Review Panel, revised to incorporate suggestions, and then released to industry on December 8, 1994. The RFP was sent to 40 companies. Roughly one third of these companies were potential prime contractors. The rest were primarily component suppliers with an interest in the Vacuum Equipment procurement. A bidders conference was held at Caltech on December 16 with approximately 24 companies in attendance. Following the meeting, at the request of several contractors, the proposal due date was extended from January 23 to February 10, 1995, at which time 4 proposals were received. The Proposal Evaluation Panel has began the process of evaluation and is prepared to make a recommendation to the Review Panel and the Source Selection Board early in the next quarter. Following completion of the source selection, LIGO staff will visit NSF headquarters to present both the history of the Vacuum Equipment procurement and the results of the source selection. Plans are to initiate the Vacuum Equipment Design competition (Phase A) on March 23, 1995 with a down-selection to a single contractor in June 1995.

2.1.2 Beam Tube (WBS 1.1.2)

The Beam Tube Qualification Test is in progress with completion scheduled early next quarter. A discovery during cleaning of the beam tube sections prior to the qualification test resulted in a special study to evaluate cleaning performance. This added two months to the beam tube schedule. Cleaning was completed and the beam tube sections were welded together along with an expansion joint to form a 43 m long prototype assembly. The assembly was mounted on fixed supports at both ends and a guided support was provided at the expansion joint at the center of the assembly.

A pumping and measurement system using turbomolecular pumps, metal-sealed valves, liquid nitrogen cold traps and a residual gas analyzer was cleaned, assembled and connected to the pump port on the beam tube prototype. This system was separately baked under vacuum to minimize its contribution to the beam tube outgassing. The complete system was pumped down on January 18. Pre-bake measurements were made of outgassing rates and an air signature test confirmed that the prototype leak rate was acceptable (see table below). There is no specified requirement for the pre-bake outgassing levels, except for hydrogen, which is expected to be below 1 x 10^{-13} $t{\cdot}l/s{\cdot}cm^2$.

Item	Pre-bake Measurement
H_2 Outgassing	2.9 x 10^{-14} $t{\cdot}l/s{\cdot}cm^2$
H_2O Outgassing	2.3 x 10^{-11} $t{\cdot}l/s{\cdot}cm^2$
CO Outgassing	< 2 x 10^{-13} $t{\cdot}l/s{\cdot}cm^2$
CO2 Outgassing	< 3 x 10^{-13} $t{\cdot}l/s{\cdot}cm^2$
Maximum leak, from Air Signature	< 1 x 10^{-9} $t{\cdot}l/s$ Note: < 1 x 10^{-7} $t{\cdot}l/s$ req'd.

Thermal insulation was installed and the complete system was baked at 140 C under vacuum to duplicate the 30 day bake planned to remove water from the beam tube modules in the field. Direct I^2R heating was applied using nine welding machines flowing an average current of 2500 amps through the prototype tube wall to provide uniform, resistive heating. At the end of this quarter, the bake was in its 26th day.

The Qualification Test Review is scheduled for April 17 & 18, 1995.

2.1.3 Beam Tube Enclosure (WBS 1.1.3)

The Beam Tube Enclosure design activities are address under WBS 1.1.4, Facility Design, below.

2.1.4 Facility Design/Construction (WBS 1.1.4)

Hanford, Washington. The rough grading at the Hanford site was completed within the budged cost by Seland Construction Co. Dames & Moore performed the geotechnical field monitoring activities associated with the rough grading. The firm of the JUB Engineers, Inc. performed the construction management task for the above contract. Close-out reports have been received from all three companies.

The ground noise measurements were completed by Battelle Pacific Northwest Laboratories. A preliminary report has been received for evaluation.

Livingston, Louisiana. The lease agreement between LSU and NSF has been signed for the Livingston property. The issue of the access road to the site is still not resolved. According to LA Department of Transportation the project is only partially funded, and the construction cannot begin until full funding is available. Caltech has initiated efforts to resolve this issue.

The time for response to the public notice for the environmental assessment elapsed on March 10, 1995. NSF is expected to issue the Finding of No Significant Impact (FONSI) soon. This will complete environmental issues for the Livingston site.

The Final Report for the Geotechnical Investigation was completed by Woodward-Clyde. The report describes in detail the sub-grade characteristics of the soils at the Livingston LIGO site and recommends the type of foundations to be used for the beam tube and buildings.

Property boundary staking was completed to identify the scope of the site clearing effort.

Six proposals/bids for site clearing have been received and evaluated. A request for an adjusted bid was issued to all bidders, directing them to use on-site borrow material because of the high costs that were proposed associated with the use of off-site borrow material. The revised bids are scheduled to be submitted on March 24, 1995.

Facility Design & Construction Management. The Ralph M. Parsons Company was awarded the contract for the design and construction management of the LIGO facility including the beam tube enclosure. Parsons is proceeding with the conceptual design phase of the contract. There has been extensive participation by LIGO staff to define the science requirements for the facility. This quarter Parsons has submitted the Design Configuration Control Document (30% completed) and the Beam Tube Enclosure Conceptual Design Report for our review and approval. LIGO project management has participated extensively in the review of the above activities.

2.2 Detector (WBS 1.2)

Activities of the newly-organized Detector Group shifted from "planning only" to implementation this quarter with the approval of the Detector Implementation Plan in early January. Detector activities are organized according to the LIGO WBS as follows:

WBS 1.2.1 - Interferometer (IFO) System, which is organized into subsystems:

- Seismic Isolation (SEI)
- Prestabilized Laser (PSL)
- Input/Output Optics (IOO)
- Core Optics Components (COC)
- Core Optics Support (COS)
- Alignment Sensing/Control (LSC)
- Length Sensing/Control (LSC)
- Suspensions Design (SUS)

WBS 1.2.2 - Control and Data Systems (CDS)

WBS 1.2.3 - Physical Environment Monitor (PEM) System

WBS 1.2.4 - Support Equipment

In addition, there is a Detector System Engineering/Integration activity (SYS).

Activities performed under WBS 1.2.1 and 1.2.2 are reported below. There are no activities planned during FY 1995 for WBS 1.2.3 and 1.2.4.

2.2.1 Interferometer (WBS 1.2.1) Design Activities

Seismic Isolation. The current baseline seismic isolation design is a scaled-up (approximately by a factor of two) version of the seismic isolation system used in the 40-m interferometer. Design of the LIGO seismic isolation systems will be deferred until the beginning of 1996 so that limited manpower can be applied to more urgent issues (the baseline schedule can (and will) be readily adjusted to accommodate this delay). Meanwhile, an engineering study will be conducted using an outside contractor (High Technology Engineering Services) to optimize the basic design concept, with emphasis on lighter weight and superior spring properties. A prototype will be fabricated and tested as part of this study. This work will begin in the next quarter.

Prestabilized Laser (PSL). Design activities for the PSL commenced on schedule. The PSL conceptual design and performance requirements were documented and a Design Requirements Review (DRR) was conducted including the requirements for the PSL portion of CDS. The PSL preliminary design was initiated. A PSL prototype, using an existing prestabilized laser modified with LIGO PSL features and CDS electronics and software, will be assembled, and testing will begin during the next quarter. After completing laboratory tests, the PSL prototype is scheduled to be installed on the 40-m interferometer so that full-sensitivity testing can be performed and long-term operational experience can be gained.

Input/Output Optics (IOO). Design requirements and a conceptual optical layout are being developed. The IOO design requirements and conceptual design are scheduled for review in the first quarter of 1996.

Core Optics Components. A prototyping activity was initiated to investigate and characterize industrial capabilities for polishing and coating full scale optics suitable for LIGO. A plan and specification for polishing and coating were drafted, reviewed and approved, and RFPs for polishing and coating were issued. Blanks for this purpose had been procured previously. Two of the blanks were furnished to two "superpolishing" vendors (superpolishing is the process used for all low-loss mirrors used in the 5-m and 40-m interferometers, which use smaller diameter optics) to determine if that process can meet the LIGO specifications (these are "best effort" subcontracts). The remaining blanks will be polished by two competitively selected companies who bid to our specification. The polished blanks will then be coated by the coating contractor. The plan is to have all polished blanks measured to our specifications by an independent metrology house both before and after coating. This work is proceeding on schedule.

Alignment Sensing/Control. A facilities study was performed to determine the mechanical stability of LIGO building floors. This generated new insulation requirements for the building foundation (inputs were furnished to the Facility Design and Construction Management company) and led to the conclusion that the building floors are sufficiently stable to be used as a directional alignment reference for short periods of time (tens of minutes) only. This conclusion reduces the redundancy inherent in our alignment concept, and increases reliance on the planned "wavefront" alignment system which uses spatial phase errors in the main interferometer beam to correct alignment errors.

Work began on documenting the ASC conceptual design and performance requirements, with emphasis on the optical levers used to initially acquire alignment and maintain it for short periods.

Length Sensing/Control. The design of the length control system for LIGO will rely heavily on computer modeling. As a step towards developing a full model of the LIGO interferometer to aid in the design of the lock acquisition scheme, a non-linear optical response and servo model of a single Fabry-Perot cavity was completed. The model's output was compared and seen to agree with data from the 40-m interferometer. Furthermore, the model was used to develop a faster lock acquisition servo for the 40-m interferometer (details found in the R&D report). This success gives confidence that the full model will enable the design of a locking servo for LIGO.

The next step is the development of a model for two coupled Fabry-Perot cavities, a configuration which contains much of the complexity of the LIGO interferometer. To date, the optical response model and computer code has been completed, but not yet checked against a simpler linear-response code. This verification is underway. It is possible that the study of the coupled cavity system will be delayed in favor of the study of the lock acquisition of a recombined, non-recycled interferometer. This decision will depend on the progress of the 40-m interferometer.

The task of defining the interfaces of the LSC subsystem with the other interferometer subsystems began. This will be a major activity in the next quarter.

Suspension Design. The effort to document the suspension conceptual design, performance requirements and interface requirements started. Because engineering resources have been limited, the short-term schedule has been rearranged to advance the conceptual design and requirements documentation for all suspension types before proceeding with preliminary design activities.

2.2.2 Control and Data System (CDS) (WBS 1.2.2)

Development of controls for the Prestabilized Laser (PSL) is a major effort for the CDS in FY 95 which requires that an existing design for the PSL electronics be modified, upgraded and improved to make the entire PSL as LIGO-like as is possible (see PSL report under Interferometer, above). The requirements collection and conceptual design phase for the PSL controls was completed and the Design Requirements Review (DRR) was conducted during this quarter. The preliminary design and prototyping phase started.

This phase will be approximately three months in duration and will result in a fully functional PSL and PSL controls prototype system.

Scheduled activities in other CDS areas progressed. This included purchasing prototype hardware components for the Timing System and developing the conceptual design of the Global CDS. The Vacuum Feedthrough and Cabling activities have been delayed because available resources were allocated elsewhere. These activities have sufficient schedule float, and will be picked up next quarter.

2.3 Research and Development (WBS 1.3)

2.3.1 40-m Interferometer Investigations

Studies in support of the R&D and detector program continued on the 40-m interferometer.

The next major development of the 40-m is to modify the optical configuration to give a direct optical recombination of the light from the two arms, instead of the electronic comparison of the arms now used. This will permit higher power operation and is required before recycling can be implemented. To accommodate the optical recombination scheme desired for LIGO, the vertex test masses had to be moved to introduce an asymmetry between the paths from the beam splitter to the two arms. This modification was successfully accomplished and tested. The actual reconfiguration of the optics will take place next quarter.

The most likely limitation to the 40-m sensitivity in the intermediate frequency band (near 400 Hz) was determined to be due to electronic noise in an amplifier in the servosystem which holds the second arm in lock. A new, lower-noise amplifier has been designed and built. It will be tested as soon as the optical recombination investigations permit.

A smart lock acquisition system was implemented and tested on the 40-m interferometer. This system samples the signal on second arm as the test mass swings through one of the fringes; a computer program calculates the velocity of the test mass and applies an impulsive force to stop the mass and send it back to the fringe with a low velocity so that the analog servo can acquire lock. This system successfully damped the test mass and reduced the lock acquisition time by an order of magnitude.

A moderate duration data run was made with the 40-m interferometer in November 1994. The goal of this run was to acquire data for use in developing data analysis tools and for characterizing the noise performance in the time domain. The data are being analyzed for short bursts and chirp-type sources. A total of 40 hours of running time were recorded; the current data analysis is concentrated on the 13 hours with the best performance.

2.3.2 Suspended Mode Cleaner

A 12 meter long mode cleaner using separately suspended mirrors is being developed as a

LIGO prototype. This mode cleaner is currently being characterized off-line in preparation for its transfer to the 40-m interferometer later this year. Testing had been delayed in the second half of 1994 because of problems with the laser; these problems have now been resolved and characterization is continuing. Highlights of testing during this quarter include:

A preliminary measurement of the mode cleaner's ability to remove beam jitter was made. The measurement gave a lower limit of a factor of 200 for the suppression of beam jitter, in agreement with the predicted value of 700. The sensitivity of this experiment is being improved to give a firm measurement.

Data were taken which can be used to set the requirements for the amplitude and phase stability of the master oscillator for the modulator used in the length sensing servosystems in LIGO. Analysis of these data is underway.

The experimental setup for setting an upper limit to residual frequency noise after the light is passed through the suspended mode cleaner was assembled, and checkout is underway.

2.3.3 Suspension Development

Much of the improvement in the 40-m interferometer sensitivity is a direct result of experiments performed using a separate apparatus which investigated the Q's of the various mechanical resonances in test masses and their suspensions. This simple apparatus was assembled to measure the Q's of both the internal test mass modes and the modes of the suspension wires of a suspension similar to that in the 40-m interferometer, permitting the effects of alternative designs to be evaluated quickly.

The apparatus used for these investigations is now being rebuilt to permit testing of full size LIGO test masses. A larger vacuum system has been designed and built. The electrostatic drive for exciting the internal modes of the test mass has been enlarged and improved. A new suspension tower for safely holding 25 cm diameter test masses has been design and built. The new apparatus is currently being assembled and tested.

Once it has been checked out, this apparatus will be used to test full size LIGO test masses and to verify the predicted performance of LIGO suspensions. It can also be used to investigate alternative suspension techniques without interfering with the operation of the 40-m interferometer.

2.3.4 Phase Noise Research

To make very high precision position measurements, the LIGO interferometers must make a very precise measurement of the optical phase of the light (10^-10 rad/rHz). Because of the scaling of different noise sources with interferometer length, it is necessary to separately demonstrate the position sensitivity (described above for the 40-m interferometer) and the optical phase sensitivity needed for LIGO. This research effort is designed to develop and demonstrate the technology for the shot-noise limited interferometer operation at initial LIGO power levels to achieve the required phase sensitivity using the 5-m facility at MIT. Considerable progress on the construction took place this quarter.

The two seismic isolation stacks, including the top plates for mounting the interferometer components and the support structure which penetrates the vacuum, were installed on schedule.

A beta version of the Barry Controls active isolator system (STACIS) was delivered to the lab and installed underneath the stack support structure as the first layer of seismic isolation. Engineers from Barry Controls are working in the MIT lab to characterize the system and customize the installation with the objective of an operating system at the time the first phase of the interferometer is installed.

The process of installing and balancing a suspended mirror was investigated using a newly designed suspension tower and a mock mirror. A procedure was developed which results in reproducible mirror balancing. The control of the mirror orientation was tested. New OSEM heads were delivered by the LIGO Caltech electronics shop. The mirror suspension task remains on schedule.

The laser has been stabilized in amplitude and frequency. This involved constructing a reference cavity and mounting it in a vacuum chamber, preparing the intermediate optics between the laser and the reference cavity, and assembling and tuning the phase detection and servo electronics. The initial frequency stabilization was completed on schedule; some fine-tuning of the system is required before the laser will be ready to illuminate the interferometer.

Soft-wall clean room enclosures are being installed around the vacuum system to provide a clean environment when the interferometer parts are installed in the system (similar to the concept for LIGO). This installation is behind schedule (due mostly to incorrectly sized parts), but a delay of the installation of the suspended optics is not anticipated.

The three inch diameter by one inch thick optics for the interferometer were completed (polished and coated) and delivered by REO.

The mechanical components for mounting the in-vacuum interferometer input optics were all fabricated and have been checked for fit. They now need to be vacuum prepped, assembled, and installed.

The schedule calls for ‘first light’ in a simplified interferometer in April, and this goal appears feasible.

2.3.5 Interferometer Alignment Investigations

This research effort is directed toward providing a system for alignment of the LIGO initial interferometer. A test of the target wavefront sensing system has been initiated on the MIT fixed mass interferometer, where the discriminants at all interferometer ports will be measured and compared with the semi-analytical model. This test will be the first prototype to employ the modulation and configuration system which has been selected for the initial LIGO (building on the research now concluded at both MIT and CIT), and a careful reconfiguration is underway to avoid the shortcomings of the earlier fixed mass interferometer experiments where possible.

The construction phase of this experiment is scheduled to continue through the first two quarters of this fiscal year. During the quarter just completed, most of the effort was dedicated to the preparation of the modulated, frequency-stabilized beam which will be used to interrogate the interferometer.

A new optical table was installed for the laser source. Purge systems, cabling trays, optical fiber protection conduit, laser cooling water and electricity were put in place. The previous Fixed Mass Interferometer was disassembled.

An existing laser was installed. New transducers for the frequency control were fabricated and characterized. An electronic control system from the LIGO Caltech electronics shop was installed and tuned for the individual characteristics of the laser and the transducers.

The Acousto- and Electro-optic modulation system which will provide a new 'subcarrier' frequency and apply phase modulation sidebands and the main carrier was assembled. The single-mode optical fiber was put in place and coupling lenses installed.

2.4 Project Office

2.4.1 Project Management (WBS 1.4.1)

Personnel. The LIGO staff currently consists of 65. Of these, six are contract employees. During the quarter LIGO added the following personnel:

TABLE 1. New LIGO Employees (December 1994 - February 1995)

Irene Baldon	Administration
Felix Fernandez	Cost/Schedule Controls - Contract Employee
Trish Mast	Cost/Schedule Controls - Contract Employee
Mark Patlan	Cost/Schedule Controls - Contract Employee
Rita Torres	Administration
Linda Turner	Document Control - Contract Employee

Fifty LIGO staff are located at CIT including five graduate students. Fifteen are located at MIT including seven graduate students.

Schedule Status. In accordance with milestones proposed during the NSF review in June 1994, a LIGO Project Performance Measurement Baseline is being prepared and will be completed by the end of April 1995. This Performance Measurement Baseline will include a cost estimate maintained to reflect approved change actions and actual cost experience, an integrated project schedule, and a time-phased budget based on estimates assigned to individual tasks in the project schedule. The LIGO Project is currently preparing the Integrated Project Schedule (IPS). The status of major IPS milestones will be discussed in future quarterly reports.

As of the end of the reporting period, all significant milestones can be achieved. However, the date for the Complete Beam Tube Qualification Test milestone listed in the Project Management Plan slipped by one month to March 1995 because modifications of the cleaning process were required. The Qualification Test Review (QTR) will be held in April 1995. The status of the significant milestones identified in the Project Management Plan is summarized in Tables 1 and 2

TABLE 2. Status of Significant Facility Milestones

Milestone Description	Late Date		Completion Date	
	Washington	Louisiana	Washington	Louisiana
Initiate Site Development	03/94	08/95	03/94	
Beam Tube Final Design Review	04/94		04/94	
Select A/E Contractor	11/94		12/94	
Complete Beam Tube Qualification Test	02/95		Projected 03/95	
Select Vacuum Equipment Contractor	03/95			
Complete Performance Measurement Baseline	04/95			
Initiate Beam Tube Fabrication	10/95			
Initiate Slab Construction	10/95	01/97		
Initiate Building Construction	06/96	01/97		
Accept Tube and Cover	03/98	09/98		
Joint Occupancy	09/97	03/98		
Beneficial Occupancy (Accept Buildings)	03/98	09/98		
Accept Vacuum Equipment	03/98	09/98		
Initiate Facility Shakedown	03/98	09/98		

TABLE 3. Status of Significant Detector Milestones

Milestone Description	Late Date		Completion Date	
	Washington	Louisiana	Washington	Louisiana
BSC/TMC Seismic Isolation Final Design Review	11/96			
Core Optics Support Final Design Review	11/96			
HAM Seismic Isolation Final Design Review	12/96			
Core Optics Components Final Design Review	01/97			

TABLE 3. Status of Significant Detector Milestones

Milestone Description	Late Date		Completion Date	
	Washington	Louisiana	Washington	Louisiana
Detector System Preliminary Design Review	01/97			
I/O Optics Final Design Review	06/97			
Prestabilized Laser Final Design Review	08/97			
CDS Networking Systems Ready for Installation	09/97			
Alignment Final Design Review	11/97			
CDS DAQ Final Design Review	04/98			
Length Sensing/Control Final Design Review	05/98			
Physical Environment Monitor Final Design Review	06/98			
Initiate Interferometer Installation	07/98	01/99		
Begin Coincidence Tests	07/00			

Performance Status. In accordance with milestones proposed during the NSF review in June 1994, a LIGO Project Performance Measurement Baseline is being prepared and will be completed by the end of April 1995. This Performance Measurement Baseline will include a cost estimate maintained to reflect approved change actions and actual cost experience, an integrated project schedule, and a time-phased budget based on estimates assigned to individual tasks in the project schedule. The LIGO Project will combine cost and schedule data to create the Performance Measurement Baseline during the months of February and March, 1995. Subsequently we will present cost and schedule performance data relative to that baseline in the monthly progress report.

Contingency Allocation. No contingency allocations in excess of $1 million were made. Prior to completing the LIGO Performance Measurement Baseline by April 28, 1995, no contingency requests will be approved.

2.4.2 Project Controls (WBS 1.4.2)

Document Control. A Document Control Administrator joined the LIGO staff in January. Since that time, systems have been established to organize, store and track internal and external LIGO documentation. Systems have also been established to facilitate the review of and response to documents that are required to be submitted by subcontractors. During the first two month of operations, over 500 documents have been logged into the Document Control Center (DCC), and efforts have begun to collect and log LIGO related documents previously published.

Cost/Schedule Control Systems. A contract has been issued to Applied Integration Management Corp. to provide support developing performance measurement based project reporting and control systems. Early in the second quarter an integrated project schedule will be prepared and the baseline cost estimate will be time-phased in accordance with the schedule to prepare a performance measurement baseline. LIGO plans to begin measuring progress against the schedule and reporting earned value in April. A review of the management systems by the NSF is scheduled for May 22-24, 1995.

Actual Costs. The conversion of the financial systems to the new work breakdown structure (WBS) began in December. Most costs are now being accumulated against the new WBS. Conversion of historical costs is in progress. Actual cost data is presented by major WBS element in section 3.0.

2.4.3 Systems Engineering (WBS 1.4.3)

Integration. Work on the System Specification and Science Requirements Document was initiated. Outlines of the documents have been prepared and are under internal review.

Beam tube baffling strategies and concepts were discussed and reviewed at a meeting hosted by LIGO at Caltech in early January and attended by representatives from the GEO and VIRGO projects. As a consequence of this meeting, several aspects of the LIGO baffle baseline design were altered. These included the number, the spacing, and the light scattering characteristics of baffles.

The VIRGO group presented an approach to baffle placement which minimizes the number of baffles by locating baffles at points corresponding to the limit of the geometrical shadow of a previous baffle, located closer to a cavity mirror. This scheme provides for the fewest baffles at the midway point between cavity mirrors and thereby minimizes contributions to phase noise by diffractive scattering.

Measurements during the Beam Tube Qualification at the contractor facilities (CBI) showed that beam tube backscatter (BRDF) was two orders of magnitude higher than expected. This led to a decision to baffle the first 100 m of beam tube near the test masses to preclude direct viewing of the beam tube by the cavity mirrors. In addition, it was decided to coat the steel baffle material with a diffuse blackening agent to further reduce the backscatter.

LIGO placed a contract with Breault Research Organization to conduct a survey of available blackening agents with acceptable performance. LIGO will have to evaluate candidate materials for suitability under high vacuum environments.

The LIGO Integration Group will oversee the conceptual definition of the baffles using acceptable blackening agents.

Interferometer Baseline Configuration Definition. As a result of the Quarterly Integration and Science Meetings on February 9 and 10, the Integration Group initiated a set of tasks, to be performed throughout 1995, aimed at rigorously defining the optical configuration of the LIGO interferometers. This task is a follow-on from the September 30, 1993 meeting at which key topological aspects of the LIGO interferometers were determined.

At the meeting, it was decided to use sub-carrier frequency modulation to sense and control cavity lengths; it was also agreed to use recycling to enhance effective laser power within the cavities; it was also decided not to exploit polarization as a means of encoding or extracting information.

Unanswered questions which will be addressed in the course of the present effort include:

- the location and type of signal taps (i.e., mirrors) needed within the interferometer to sense the length degrees of freedom which need to be controlled;
- the location of the frequency carrier and subcarriers;
- the sensitivity of these frequencies to potentially interfering higher-order cavity modes;
- the complete end-to-end sensitivity of GW signal for the completely defined interferometer configuration.

Multi-layer, thin dielectric coating analysis. In support of defining optics quality and performance requirements for the Pathfinder Program, a software program was developed to determine the sensitivity of LIGO core optics to slight imperfections in the high-reflection (HR), low-loss coatings required for the cavity mirrors. The work performed resulted in several key findings relevant to pathfinder and these results were published in a LIGO Internal Technical Document, T95008A-E (author: Dr. Hiro Yamamoto). These findings include a way of specifying the contribution to total wavefront error arising from the contribution of coating imperfections; an analysis of inferring performance of a coating at the Ar+ laser wavelength (514.5 nm) by measurements performed at the more common metrology wavelength of the HeNe laser (632.8 nm); and an estimate of tolerable coating errors of several different types of coating imperfections which are commonly encountered in the fabrication of high-performance coatings.

Design of HR and AR coatings for dual wavelength operation. Preliminary results from ongoing efforts at Stanford University aimed at developing scientific and commercial versions of diode-pumped NdYAG laser technology indicate that frequency-doubled solid state lasers operating at CW power levels needed for LIGO interferometers may be available at about the time LIGO is scheduled to begin operations.

Unfortunately, the LIGO core optics specifications and optics procurement will need to be in place earlier than it will be possible to assess whether NdYAG laser technology can be routinely available in time to adopt the technology in the initial interferometer design. However, a prudent risk-reduction approach would be to provide, if technically feasible, the capability of operating LIGO lasers at either of the two laser lines (Ar+ @ 514.5 nm and NdYAG @ 532.0 nm).

The same coating modeling program developed for HR coating specification development (discussed above) is being used to assess the feasibility of dual-wavelength operations. Analysis has shown that the high performance HR coatings can perform equally well at either wavelength if the coatings are designed to have optimal performance at the midpoint wavelength of 523 nm. We are presently assessing requirements for the anti-reflection (AR) coatings that also are needed in the core optics. AR coatings consist of fewer layers and are generally less forgiving because the spectral dependence of their reflectance properties varies dramatically over narrow changes of wavelength. The Systems Engineering Group is working with the Detector Group to fully define the performance requirements of AR coatings and to assess whether these can be met at the two wavelengths separated by 18 nm.

LIGO End-to-End Simulation and Analysis Environment. The Systems Engineering Group has completed a four-month long trade study to identify, compare and select a unified programming environment to be used throughout the LIGO project. Systems Engineering is working to provide a platform for analysis and simulation for LIGO scientists which will be a productive tool. The goals of the trade study were to identify state-of-the-art modeling tools based on graphical user interfaces, object-oriented, modular programming, and UNIX-based multi-platform distributed processing.

Eight initial options were studied, and these were reduced to two candidates for further evaluation. The two candidate systems were the the KHOROS system, developed at the University of New Mexico under the aegis of DARPA and the NSF, and the Advanced Visualization System (AVS), a commercially available product with all the same features of KHOROS.

The final decision involved a trade between the need to support (by hiring additional in-house staff) a public domain software package which is not rigorously maintained and the need to invest in commercial software. In the end, it was estimated that selecting AVS would be the more cost-effective approach for LIGO. LIGO has negotiated a group licensing structure with AVS to enable both LIGO and the developing LIGO Users Community to take advantage of AVS's generous volume and academic/educational discount. LIGO is in the process of obtain its first set of licenses. These will be shared with three theory groups which are beginning to develop software tools directed at performing analysis of LIGO signals when the detector comes on-line. One of the groups is at Caltech, under Prof. Kip Thorne. Prof. Bruce Allen, of the University of Wisconsin at Madison is interested in developing data analysis tools and will obtain an AVS license. In addition, Prof. L. Sam Finn of Northwestern University, is also planning in active participation in LIGO data analysis.

2.4.4 General Computing (WBS 1.4.4)

FrameMaker has been adopted as the new desktop publishing software standard. A modem pool was installed which supports remote access for traveling staff members. ISDN telephone lines have been installed to increase the data bandwidth for telecommuting contractors and staff. The ligo ethernet has been expanded to new offices to accommodate new staff members.

3.0 Financial Status Report

Actual cost through the first quarter of FY 1995 have been allocated to the new LIGO

Project WBS and are summarized in Table 3.

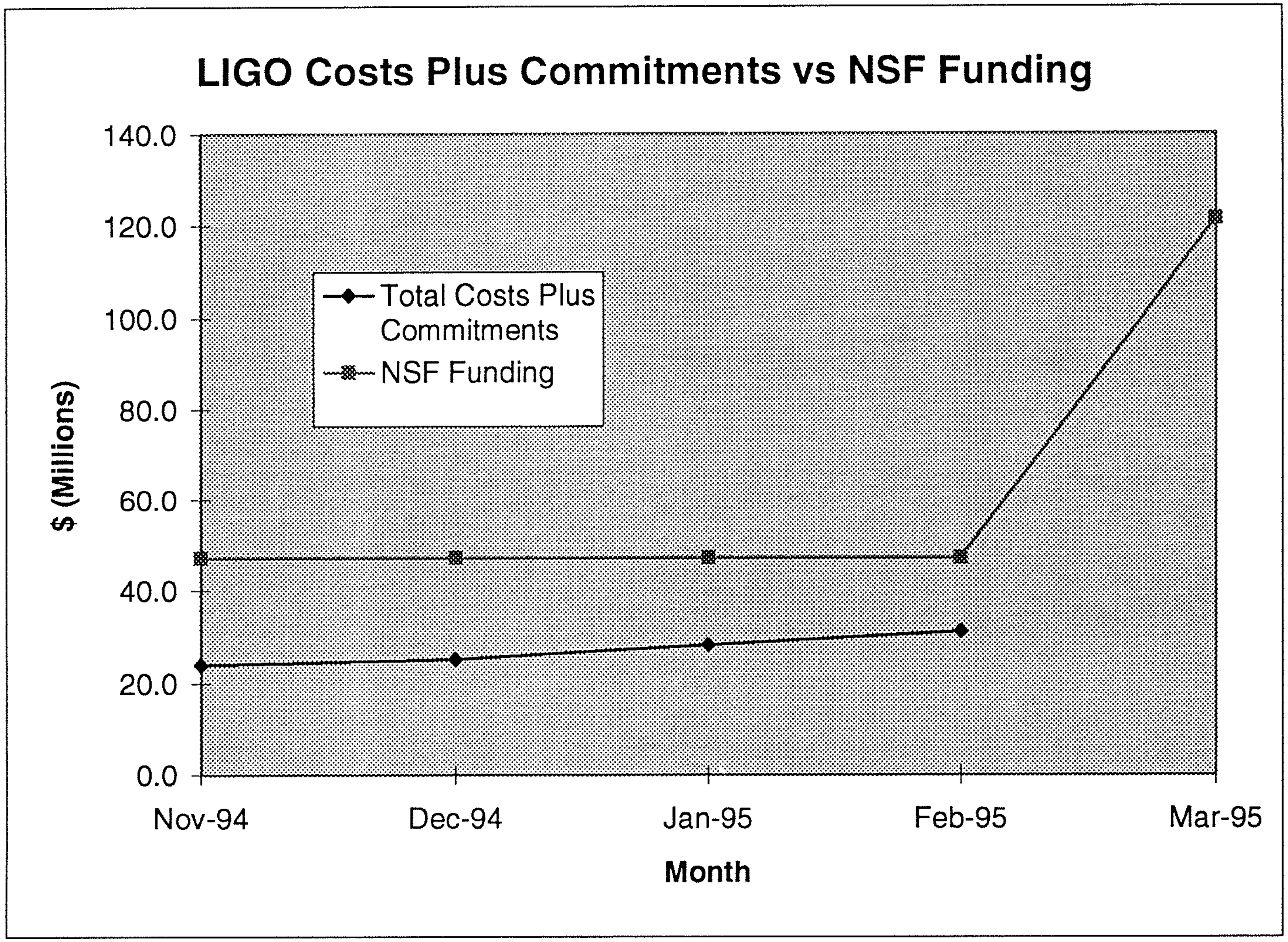
Table 4: Actual Costs (Through February 1995)

WBS	Description	Allocation of Costs through November 1994	Dec 1994	Jan 1995	Feb 1995	Cumulative Costs through February 1995
1.1.1	Vacuum Equipment	$487,273	$18,160	$11,632	$21,540	$538,605
1.1.2	Beam Tubes	$1,339,077	$32,026	$20,129	$572,615	$1,963,846
1.1.3	Beam Tube Enclosures	$8,149	$0	$5,874	$3,263	$17,286
1.1.4	Facility Design and Construction	$3,284,754	$94,321	$473,948	$182,468	$4,035,491
1.2	Detector	--	$194,093	$203,633	$202,087	$599,814
1.3	Research and Develop-ment	$10,407,161	$276,568	$170,789	$215,200	$11,069,719
1.4	Project Office	$4,729,283	$302,593	$283,606	$313,610	$5,629,091
*	Unassigned	$1,670	$205	$354	($974)	$1,255
1.0	Total Project Costs	$20,257,368	$917,967	$1,169,964	$1,509,810	$23,855,108
	Cumulative Project Costs	$20,257,368	$21,175,334	$22,345,298	$23,855,108	
	Open Com-mitments	$3,531,398	$3,834,948	$5,751,393	$7,221,014	
	Costs Plus Commit-ments	$23,788,766	$25,010,282	$28,096,691	$31,076,122	
	NSF Funding	$47,088,935	$47,088,935	$47,088,935	$47,088,935	

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

4.0 Change Control

A change control system will be initiated in FY 1995. Future Quarterly Reports will provide a status of change activity.


LIGO Costs Plus Commitments vs NSF Funding
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
$ (Millions)
Total Costs Plus Commitments
NSF Funding
Nov-94
Dec-94
Jan-95
Feb-95
Mar-95
Month