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QUARTERLY REPORT
NSF COOPERATIVE AGREEMENT NO. PHY-9210038
THE CONSTRUCTION, OPERATION, AND SUPPORTING RESEARCH AND DEVELOPMENT OF A LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

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I. INTRODUCTION

This report summarizes the Laser Interferometer Gravitational-Wave Observatory (LIGO) Project activities from June through August 1993.

The report incorporates a number of changes over past versions, intended to give a more complete picture of the project progress and status. A section summarizing the project status compared with the baseline plan has been added. This section includes four tables: a schedule summary using significant milestones; funding and obligation to date by WBS element; a listing and status of programmatic issues involving Caltech and NSF; and project staffing against plan. A second section has been added to document collaborative efforts and interactions with the scientific community.

II. TECHNICAL ACCOMPLISHMENTS

This summary includes work of the Caltech and MIT science groups and the engineering team located at Caltech. The principal areas of activity are:

- LIGO development, including sites, facility design and development of the initial interferometers.
- Prototype laboratory activities aimed at improved understanding of interferometer noise sources or at development of key interferometer techniques.

A. LIGO DEVELOPMENT

1. Sites

Livingston Parish, Louisiana. Louisiana State University (LSU) has made progress in negotiating a purchase agreement with the principal landowner, Cavenham Industries, but Cavenham remains concerned about the hydrological impact of LIGO. We have furnished a draft hydrological study of the site and preliminary drainage design to LSU for discussion with Cavenham. Cavenham is presently reviewing the drainage plan.

LSU reports that all issues regarding the acquisition of the second, smaller parcel of land have been resolved and the transfer is complete.

Site investigation work continues to be on hold, awaiting clearing of the forested area by Cavenham after completion of the land transfer arrangement.

Hanford, Washington. The DOE/NSF land use permit and MOU are reported to be satisfactory to all parties concerned. We are awaiting signed copies so that we can proceed with securing engineering support services from the DOE on-site contractors, as authorized in the MOU.

Drafts of the Environmental Assessment (EA) report and Finding of No Significant Impact (FONSI) prepared by our contractor, Battelle Pacific Northwest Laboratories, were submitted to NSF for review and approval on August 20.

Engineering work for plans, specifications and a cost estimate for the rough grading of the site is proceeding smoothly. It is expected to be completed by September, and will allow construction to begin at the Hanford site upon approval of the EA and FONSI.

2. Industrial Design Subcontracts

A contract for the design and qualification testing of the LIGO beam tube modules was awarded to Chicago Bridge and Iron, Inc. (CBI). Contract award was delayed 5 weeks while awaiting NSF approval to proceed. The effective start date was August 17. The initial review of project plans scheduled for 30 days after award will be delayed two weeks to accommodate personnel schedules, and, since CBI is not authorized to proceed with work until after the initial plan review, this schedule slip will add to the earlier delay in contract award. The total delay will be reflected in all subsequent planned review and deliverable dates.

B. PROTOTYPE ACTIVITIES

1. 40-Meter Interferometer

Assembly of the Mark II 40-m interferometer in its new vacuum system has been completed. After installation of all in-vacuum interferometer components, the vacuum system was pumped down. The interferometer was aligned and preliminary locking was achieved. Since that original pumpdown, the interferometer has been kept under vacuum continuously.

After initial locking of the interferometer was achieved, the process of shakedown and debugging was started. Many of the servosystems require fine tuning to minimize their contribution to interferometer noise, and all parts of the system must be characterized to ensure that their operation is understood. One improvement which was immediately noticed is that the addition of the new seismic stacks has reduced the excitation of the test mass suspensions at very low frequencies (near 1 Hz); although this does not directly affect the interferometer noise in the LIGO frequency band, it does reduce the dynamic range demands on many of the servosystems.

2. Suspended-Mirror Mode Cleaner

Completion of the Mark II 40–m interferometer assembly has allowed resumption of work on the suspended-mirror mode cleaner. Construction of the mode cleaner in its vacuum system has been completed. The mode cleaner has been aligned under vacuum and the laser has been locked to it (although not in the final servo configuration). Shakedown of the servosystems has begun.

3. Stationary Interferometer

The goal of stationary interferometer research is to investigate the two candidate modulation and optical topology schemes that may be used in the initial LIGO interferometer. The project will make a decision on the LIGO initial interferometer modulation and topology in October 1993. The decision is required for the next steps in the research program leading to the initial LIGO interferometer; in particular, the design of the recombined interferometer in the Mark II 40–m system and the design of the interferometer to measure the phase noise in the 5–m system. The information necessary to make this decision is being collected from the experimental results of the stationary interferometer prototypes and through optical and servo modeling:

- Research on the external modulation topology in the past quarter has concentrated on: (1) measuring the closed loop transfer functions of the various servosystems in the interferometer, and (2) investigation of leakage of the subcarrier, used to lock the Michelson recycling cavity into the arm cavities.
- Modeling of the interferometer topology with asymmetric Michelson arms has progressed. The optical response of the interferometer to motion of the mirrors along the optical axes at arbitrary frequencies has been analyzed, and modeling of the response of the servosystem at relevant signal frequencies has begun. Experiments to validate these calculations are underway. An effort to model interferometer lock acquisition has begun.

4. Interferometer Alignment

The research is directed to providing a means for alignment of the LIGO initial interferometers.

Data for the alignment discriminants on reflection of a stationary double cavity have been taken. The signatures for angular misalignments of each of the three mirrors while the system is maintained in longitudinal resonance have been obtained. A comparison with the analytical model developed previously is underway; some additional complexity in the analytical model (the explicit addition of sidebands and a change of basis) has been necessary.

Work has continued on the demonstration of the alignment technique on a suspended cavity. Two mirrors have been suspended and electronically damped, and a cavity formed of these two mirrors has been servo-controlled on resonance. The ambient seismic noise in displacement and angle has been characterized for short (50 cm) and long (5 m) baselines to aid in servo design.

5. Suspension Development

Investigation of techniques for suspending test masses to achieve the high mechanical Q values in the different vibrational modes required to reduce thermal noise to acceptable levels continues. This quarter, we have concentrated on measurements of Q values of the internal vibrational modes of a monolithic test mass (9 cm diameter by 10 cm thick). A Q of 10^7 has been achieved; this value exceeds the requirement for the initial interferometer and demonstrates that the optical polishing and coating processes for manufacture of the LIGO test masses are compatible with thermal noise requirements. Investigations of losses introduced by the attachment of magnets to the test masses are underway.

III. PROJECT STATUS

A. Schedule

Fully integrated schedules for the total project, for the facilities and equipment development and for interferometer development were provided to NSF during this quarter. These schedules have been adopted by the Project as the baseline schedule and will be used to guide the work.

Significant milestones have been identified in the Project Management Plan and will be used henceforth to report the schedule status of the project. Table 1 gives a summary of current and near-term milestones and their status.

Table 1

SIGNIFICANT MILESTONES

Milestone	Baseline Date	Completed Date	Expected Date	Comment
Past-Due				
No Past-Due Milestones				
Due During Reporting Quarter				
No Milestones Due This Quarter				
Upcoming				
Select Interferometer Optical Topology	10/01/93		10/01/93	On schedule
Initiate Site development at WA site	10/14/93		10/14/93	Depends on NSF approval of EA and FONSI
Release Vacuum Equipment RFP	12/10/93		12/10/93	
Select Building Design Contractor	1/04/94		1/04/94	
Beam Tube Final Design Review	1//24/94		3/10/94	Delay of beam tube contract start resulted in schedule slip

B. Cost

As part of the project management plan, we have adopted a new level 3 WBS. The new WBS is based on the one used in the proposal but updated to reflect some changes in the way we envision managing the work. Henceforth, funding and obligations will be reported against the new WBS. Cumulative funding and obligations are given in the following table:

Table 2

Cooperative Agreement No. PHY-9210038 Financial Status as of 7/1/93 ($K)		
Cumulative Funding to date		19,100 K
Cumulative Obligations to date:		
WBS 1.1	Site Plans	34.4 K
1.2	Buildings	7.8
1.8	Site Investigations	636.8
4.1	Management and Administration	1253.3
4.2	Technical Staff	4185.3
4.3	Travel	201.8
4.4	R&D Equipment	1642.6
4.5	In-house Operations Support	923.3
	TOTAL	8885.3

C. Programmatic Issues

A list of programmatic issues involving LIGO and NSF is given in Table 3.

Table 3

PROGRAMMATIC ISSUES — CALTECH / NSF RESPONSIBILITIES

No.	Issue	Responsible	Due Date	Status / Comment
1	Appoint External Advisory Committee	LIGO	11/01/92	No agreement with NSF on committee charter
2	LIGO FY 1993 Funding	NSF	12/01/92	R&D authorization received 9/01/93
3	Submit Management Plan to NSF	LIGO	9/15/93	On schedule
4	Completion of DOE/NSF land use permit and MOU for WA site	NSF	10/14/93	Awaiting DOE signoff
5	Approval of CBI Subcontract	NSF	7/17/93	Completed 8/16/93
6	Approval of EA and FONSI for WA site	NSF	10/14/93	Need planning completion date from NSF

D. Staffing / Personnel Changes

Gerhard Stapfer has joined the Project as Deputy Chief Engineer. He moves to LIGO from the Jet Propulsion Laboratory where he has been for the past 30 years. Most recently he was Assistant Program Manager for the SP-100 Project, a $650M DOE/NASA program. He will join the LIGO management team with particular responsibility for the oversight of the large facility and equipment subcontracts.

Dr. Peter Fritschel has accepted the position of a research scientist on the LIGO project at MIT beginning in September 1. He will work primarily on the phase noise measurements on the 5–m interferometer. For the past year, he has been working with the VIRGO Project in Orsay.

Denise Durance has accepted a position as an Associate Scientist at Caltech starting September 1. She will take over the day-to-day responsibility for the care and maintenance of the 40–m interferometer and will assist the science team in investigations with it.

Tim Howard, an engineer with the Project since 1991, has left to take a position in industry. The following table compares the actual current LIGO staff with the staffing goal for this period given in the Project Management Plan.

Category	Management Plan Goals	Actual
Scientists	14	14
Engineers	11	10
Graduate Students	9	9
Technicians	6	6
Administration	5	5

IV. INTERACTIONS WITH OTHER SCIENTISTS

A LIGO/VIRGO joint workshop was held in Lyon and Orsay on July 19–21 to discuss the specification, manufacture, and testing of large diameter optics and coatings. At the end of technical discussions, working groups were formed on specific topics to collaborate on development of the core optics (test masses, beam splitters, etc.) for the LIGO and VIRGO interferometers. D. Jungwirth, F. Raab, D. Shoemaker, R. Weiss, and S. Whitcomb represented LIGO at the meeting.

A paper ("Thermal Noise in the Test Mass Suspensions of a Laser Interferometer Gravitational-Wave Detector Prototype" by A. Gillespie and F. Raab) was published in *Physics Letters A*, **178**, 357–363.

A paper, summarizing a talk by F. J. Raab to be given at the November Laser and Electro Optics Society meeting in San Jose, CA, was submitted for inclusion in the conference proceedings.

R. Weiss presented a talk on LIGO at Brookhaven National Laboratory on July 27.

Visitors to LIGO during this quarter included:

- Carlo Bradaschia (Pisa) and Alain Marraud (Orsay), both from the VIRGO Project, August 2–4, for discussions about stainless steel outgassing results, requirements, and plans for vacuum pumping, and requirements and plans for civil construction.
- David Blair (University of Western Australia), August 12–13, for discussions about seismic isolation approaches and results and exploration of areas for collaboration.
- Matt Husman (Stanford), August 13, to discuss possible directions for research at Stanford in suspensions or seismic isolation.

V. CONCERNS

Two concerns have arisen during this reporting period.

- The NSF held a technical review of the project from June 7-10 at Caltech. The review panel consisted of 27 panel members; six NSF staff also attended. Two of the four days involved three parallel sessions to investigate specific technical areas of the project. This was a very demanding task for the LIGO team, including for example, the preparation of over 600 viewgraphs for the formal presentations. Although reviews are a necessary component of a project of this size, we wish to alert NSF to the fact that a review of this magnitude in a team as lean as LIGO causes a significant disruption to the ongoing activities, with significant impact on cost and schedule.
- Communications between NSF and the Project are inadequate and occur via too many non-project channels. It is urgent to establish effective, direct communication channels between NSF and the Project.

Pasadena, September 3, 1993

R. Vogt, P.I./P.D.