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 1994. It includes technical accomplishments, project status, and a summary of interactions between the LIGO Project and the rest of the scientific community. The section on technical accomplishments has been reorganized in accordance with the new Work Breakdown Structure (WBS) which was adopted at the beginning of this quarter.

II Accomplishments

WBS 1.1 Facilities and Vacuum System

WBS 1.1.1 VACUUM EQUIPMENT

A Vacuum Equipment RFP has been written and is in the process of being reviewed. A draft Vacuum Equipment Technical Specification which will become part of the RFP has been completed. This specification was reviewed by the LIGO science team on August 31. Review comments will be incorporated and the RFP is scheduled for release during the next quarter.

WBS 1.1.2 BEAM TUBES

The review committee for the beam tube module Final Design Review, held last quarter at Chicago Bridge and Iron (CBI), issued its report and recommendations. All of the recommendations were accepted by the project and are being implemented. Fabrication of the Qualification Test Module is in progress. Tubetech, a subcontractor of CBI, has successfully completed the fabrication of the spiral welded tubes and CBI (Houston) has completed the welding of the stiffening rings. The fabricated tubes have been shipped to CBI (Plainfield) for final assembly, pump down, bake out and leak test. Outgassing measurements, one of the key objectives of the Qualification test, are scheduled for November.

Steel samples from the coils processed for the Qualification Test Modules have been tested and evaluated to validate the baking process of the coils. As CBI had not yet completed their sample test facility, the measurements were done at Caltech. The results indicated that the outgassing rate for these samples was

near the lower end of the anticipated range. This confirms the validity of the steel bake process which CBI had followed.

WBS 1.1.3 BEAM TUBE ENCLOSURE

A small design contract has been issued to Concept in Concrete, which had proposed the concept of pouring the beam tube cover in-situ. At the present, this design, modified to consider pre-casting of the cover, is nearing 30% completion and will be evaluated in September. The design will be of sufficient detail to provide an updated cost estimate for the construction of the beam tube enclosure. A competing design effort by CBI is being considered and CBI has been asked to submit a cost estimate.

WBS 1.1.4 FACILITY DESIGN / CONSTRUCTION

Livingston, Louisiana

All of the issues in the lease agreement between LSU and NSF have been resolved and both parties are ready to sign the agreement. LSU has completed the title search of the Cavenham property and expects title to transfer from Cavenham to LSU shortly, at which time the lease agreement can be executed.

A permit to clear the center line of the two arms has been issued by the U. S. Army Corps of Engineers. After re-staking was completed, the center strip was cleared to provide access for the drilling equipment and the geotechnical investigation of the site has been initiated. A draft report describing the geotechnical findings is expected to be completed and issued by November.

All formal responses to the section 404 permit have been received by the Corps of Engineers. Their initial review indicates no significant comments or objections. We anticipate a permit to be issued by mid-October.

The final Hydrologic and Hydraulic report has been completed by Gulf Engineers & Consultants Inc. The report finalizes and confirms the preliminary drainage recommendations. This report is a key document required for the design of the Livingston site.

Hanford, Washington

A formal ground breaking ceremony was held at the Hanford site on July 6. In attendance were local and state government representatives, members of NSF, MIT and Caltech as well as a number of contractors.

The rough grading at the Hanford site, performed by Selland Construction, has proceeded at a slow pace. The progress had been adversely impacted by the limited amount of available water which was exacerbated by the severe drought condition experienced in the area. A second well was initiated, but produced no useful flow rates until a depth of 2000 feet was reached. At this level, a high capacity aquifer allows a minimum of 500 gallons per minute of water to be pumped. This capacity, combined with a second holding pond, allows the rough grading to proceed at its originally anticipated daily rate. It is expected that the rough grading will be completed by mid-November.

Industrial Design Contracts

A number of qualified Architect-Engineer (A-E) contractors responded to the Commerce Business Daily announcement. In accordance with the established procedures, the respondents were evaluated and a selection of the three most qualified firms was reviewed by the A-E review panel which unanimously concurred with the selection. An RFP has been prepared and issued, requesting the three selected firms to submit their proposal by September 23. The selection process for the A-E contractor should be completed by the end of October, and the contract is expected to start by the end of November.

WBS 1.2 Detector

Planning for the detector design and fabrication effort was accelerated in preparation for the September NSF review. The detector includes the interferometers, the control and data system, the physics monitoring equipment, and the support equipment. A draft detector implementation plan has been prepared and, once finalized, will be used to manage the detector work.

WBS 1.3 Research and Development

40–Meter Interferometer

The work on the 40–meter interferometer this quarter has focused on the installation of monolithic test masses (fused silica masses with mirror surfaces polished and coated directly onto the front surface). Thermally excited vibrations of the older compound test masses, which had mirrors optically contacted to them and exhibited Q values as low as 10^3, had been a candidate for noise in the frequency region near 500 Hz. Three of the four new test masses have been installed, with effective Q's ranging from about 3×10^5 to about 7×10^6. Preliminary data indicate that the noise at frequencies near 500 Hz has been reduced. The replacement of the fixed mass should reduce the thermal noise budget for the interferometer by more than an order of magnitude.

To achieve the highest possible Q values for suspended test masses, the size of magnets attached to the masses and the method of attachment have been systematically varied. Such changes not only affect the thermal noise contribution, but also affect the stability and the lock acquisition characteristics of the interferometer. These aspects of interferometer behavior are being modeled and compared to experimental data.

Phase Noise Demonstration

This research effort is designed to develop and demonstrate the technology for the shot-noise limited LIGO interferometer fringe readout using the 5-m facility at MIT. A project design review of the research program took place this quarter. The experiment is now well into the construction phase. Space changes, underwritten by MIT, have been completed. The existing vacuum system has been disassembled and is being cleaned and tested. The laser source has been purchased and is being installed. Design and detailed drawings for the mechanical and electronic systems have been completed and submitted for bids; optics have been ordered.

Optics Modeling

Analytic and numerical modeling of the large aperture optics continued this quarter as input to the optical pathfinder process. A series of calculations using the Fourier Transform Propagation Code explored the envelope of tolerable defects

in both the mirror surface and the substrate inhomogeneity for the initial LIGO interferometer configuration. The wavefront perturbations applied to the model were derived from measurements of mirrors and substrates with the same aperture as those to be used in the initial LIGO interferometer. The mirror data was kindly provided by the Hughes Danbury Corp. from surfaces that had been developed as calibration flats in the AXAF project. The mirrors and substrates satisfy the requirements for the initial LIGO interferometer. The remaining issues to investigate are the wavefront perturbations from the large aperture coatings.

Control Modeling

A task order has been given to JPL to continue the work on modeling the servo control and lock acquisition of the initial interferometer. The current effort is to extend previous single optical cavity models to coupled cavities as a prelude to the full initial LIGO interferometer model.

Interferometer Alignment

The research is directed to providing a system for alignment of the LIGO initial interferometer. The primary activity this quarter was the demonstration of the automated alignment of a suspended 5-meter baseline Fabry-Perot cavity. A phase-front sensing system was used employing RF detector systems prototyped in the previous quarter. A real-time computer servo system was developed to correctly translate the sensor signals to control signals. Predictions from the semi-analytic modal decomposition model for the signals were confirmed, and the subsequent analysis of the experiment has refined the plans for both the further prototype efforts and the design of the LIGO alignment system.

Attention is now focussed on preparing the MIT Fixed Mass Interferometer to serve as a test bed for further studies of the alignment system. 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 careful planning is underway to avoid the various shortcomings of the earlier FMI experiments where possible. Prototyping of angle readout sensors, needed for quantitative alignment data, has started.

Suspended-Mirror Mode Cleaner

Work on the suspended-mirror mode cleaner has concentrated on tuning and debugging of the servo loops for the mode cleaner length control and for laser frequency stabilization servo.

Optics Testing and Development

Experimental evaluation of a cleaning procedure that may be suitable for large aperture optics was begun. This procedure, known as the "RCA-1" cleaning process, is commonly used in surface physics and in the semiconductor industry, but little is known about its applicability to ultralow-loss optical surfaces and coatings. The process has now been successfully tested on about a dozen mirrors in separate trials. The surfaces are successfully cleaned at the molecular level as evidenced by interference bands that are visible when homogeneous water films are grown onto the mirror surfaces. Optical losses were either unaffected or improved on most of the mirrors tested, but the losses for one batch of mirrors was observed to degrade, indicating that further work is needed.

WBS 1.4 Project Office

The reorganization of the project management continued this quarter. A new WBS and a parallel organization structure were selected. An updated cost estimate, using the new WBS, was made, with the responsible managers of the major WBS elements preparing the cost inputs. This estimate was presented to NSF management. U.S. Cost has constructed a database using these cost inputs which will produce a total project cost roll-up. This cost estimate will be reviewed by an NSF-appointed panel at Caltech September 20–23.

The recruiting effort for the remaining key positions in the enhanced project management (Project Control Manager and lead Systems Engineer) have continued. Written offers have been made to the leading candidates.

III Project Status

A. Schedule A new set of milestones are being defined as preparation for the September NSF review. Future schedule status will be assessed against these milestones in future quarterly reports.

B. Cost In preparation for the NSF review scheduled in September, an updated cost estimate for the entire project has been prepared. This estimate improves on the original proposal because of improved understanding of the detector, the selection of definite sites (rather than the generic ones that were used in the proposal), and the further definition of the vacuum system design. It also includes the enhanced project staff which will be built up over the next year. Once this budget is approved by NSF, it will be used to track future costs for this report.

C. Staffing/Personnel Changes Gary Sanders has joined LIGO as Project Manager. He comes to LIGO from Los Alamos National Lab where he held a similar position working on the GEM Detector for the SSC.

Mike Zucker (senior staff scientist) has moved from Caltech and joined the MIT Science group.

Graduate students Martin Regehr (Caltech) and Joe Kovalik (MIT) have completed their degrees. Martin has left the project to begin his new position; Joe will begin his new position later this year. Two new graduate students (Jim Mason and Malik Rakhmanov) have joined the project at Caltech.

IV Interaction with Scientific Community

R. Weiss gave a colloquium on the LIGO Project on June 15 at the Princeton University Plasma Lab.

An invited talk entitled *The LIGO Project: Progress and Prospects*, was given by F. Raab at the First Edoardo Amaldi Conference on Gravitational Wave Experiments, June 14–18, in Frascati, Italy.

R. Weiss gave a talk on surface hydrocarbon contamination measurements at the American Vacuum Society Seminar on Surface Measurements, June 14, in Burlington, Massachusetts.

An invited talk *The LIGO Project – A Progress Report*, was given by R. Spero at the 6th Asian Pacific Conference, July 4–8, in Brisbane, Australia.

The following contributed talks were given at the Marcel Grossman meeting at Stanford, July 25–29:

- *Status of the LIGO 40-Meter Interferometer* by R. L. Savage, Jr.
- *Seismic Isolation in the LIGO 40-Meter Interferometer* by L. Sievers and R. E. Spero

- *Shot Noise Limited Sensitivity of the LIGO 40–Meter Interferometer* by R. E. Spero
- *Measurement of Optical Path Fluctuations due to Residual Gas in the LIGO 40–Meter Interferometer* by M. E. Zucker and S. E. Whitcomb
- *Sensitivity of the LIGO Interferometer to Mirror Misalignment and How to Align It* by Y. Hefetz
- *Update on the LIGO Project* by S. E. Whitcomb

R. Weiss organized a workshop on gravitational-wave detection at the Summer Study on Particle and Nuclear Astrophysics and Cosmology in the Next Millenium, June 29-July 14, at Snowmass, Colorado. A. Abramovici, B. Barish, D. Shoemaker, K. Thorne, and S. Whitcomb also participated.

Visitors to LIGO during this quarter included:

- Jean-Marie Markowski (Lyon), A. Brillet and C. Nary-Man (Orsay), and A. Giazotto (INFN, Pisa) all members of the VIRGO project, working in collaboration with LIGO on development of large scale optics, visited the LIGO project at Caltech on August 1–3.
- D. Mc Clelland and J. Sandeman (Australian National University), members of the AIGO collaboration, visited the lab at Caltech for a period of one week each in July for discussion of possible future collaborative efforts.
- K. Danzmann (University of Hannover), A. Rudiger (MPI, Garching), and J. Hough, J. Logan, D. Robertson, S. Rowan and H. Ward (University of Glasgow) all members of the GEO collaboration visited the lab at Caltech.
- A number of visitors from Japan including K. Kawabe, K. Kuroda, K. Tsubono, and M. A. Barton (Tokyo University); N. Kawashima and H. Mizuno (Institute of Space and Astronautical Science); H. Shinkai, N. Sakai, T. Tachizawa, and T. Hirai (Waseda University); M. Araya and M. Ohashi (National Astronomical Observatory); J. Hirao (Daitoh-bunka University); and Y. Koyama (Communications Research Laboratory) visited the lab at Caltech.
- B. Mours and R. Morand, members of the VIRGO project, visited members of the LIGO Control and Data System Group for discussions on August 1-2.
- G. Gorini (INFN, Pisa), a member of the VIRGO project, visited Caltech from July 26-30 for discussions which will lead to construction of a

fixed-mass interferometer at the INFN that is similar to the Caltech interferometer used for optical topology studies.

- D. Blair, H. Peng, E. Ivanof, and A. Luiten (Perth, Australia) visited the LIGO lab at MIT on June 3 and gave talks on the bar antenna at Perth.
- W. Johnson from Louisiana State University toured the MIT lab on June 7 and discussed coordination with LIGO.
- P. Hariharan from the University of Western Australia and CSIRO visited the LIGO group at MIT on July 19 for discussions on optical metrology and fabrication.
- K. Skaldon and D. Robertson of the Glasgow group/GEO-600 visited MIT on August 5 for discussions of alignment and a laboratory tour.

The following papers were published this quarter.

- "Mirror-orientation noise in a Fabry-Perot interferometer gravitational wave detector," by S. Kawamura and M. Zucker, *Appl. Opt.*, **33**, 3912-3918, 20 June 1994.
- "Suspension losses in the pendula of laser interferometer gravitational-wave detectors," by A. Gillespie and F. Raab, *Physics Letters A*, **190**, 213-220, 1994.

The following paper was accepted for publication in *Applied Optics*.

- "Measured Limits to Contamination of Optical Surfaces by Elastomers in Vacuum," by A. Abramovici, T. Lyons and F. Raab, January 1994.

Pasadena, September 1, 1994

S. Whitcomb