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QUARTERLY REPORT
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CONTINUED PROTOTYPE RESEARCH & DEVELOPMENT AND PLANNING FOR THE CALTECH/MIT LASER GRAVITATIONAL WAVE DETECTOR

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INTRODUCTION

This report covers the Laser Interferometer Gravitational Wave Observatory (LIGO) Project activities from January through March 1990, including work of the Caltech and MIT science groups and the engineering team located at Caltech. Principal foci of research and development activities were:

a) Interferometer prototypes
   i) development and testing of technologies needed for full scale LIGO interferometers
   ii) work towards reliability and sensitivity enhancements of prototypes

b) LIGO development

A team made up of NSF personnel and an NSF-appointed committee visited Caltech in February as part of the review of the LIGO construction proposal.

1. PROTOTYPE ACTIVITIES

A. 40-meter Prototype

Higher Power Operation. The dynamic range of the servo electronics in the 40-meter prototype has been increased to accommodate the maximum power available at the output of the optical chain. As a result, the interferometer now operates reliably with a total of 60 mW of bright-fringe power available at the two main photodiodes.

Suspended Mass Orientation Control. A new design for the servos controlling the orientation of the test masses was developed and tested on one test mass; the stability below 10 Hz is improved by a factor of 3.

Separate Suspension of Beamsplitter Components. A new servo system to control the beam splitter was tested. This system includes an optical lever and a magnetic transducer system that applies forces directly to the beam splitter to control its orientation in four degrees of freedom. Production of electronics to control five components that will be separately suspended as part of the rebuild of the beam splitter optics was started.

Monolithic Test Masses. Specifications were developed for the fused silica blanks which will serve as monolithic mirror/test masses in the 40-meter prototype. Calculations indicate that optical distortions due to heating from a beam passing through a 10-cm thick blank do not present a problem for this application.

Optics Development. Comparison of the storage time of fundamental and off-axis modes in the 1-meter mode cleaner indicated that the reflectivity of mirrors exposed to the resonant light had degraded, by approximately a factor of two, over a period of several months. The degradation, which was reversed by cleaning with solvents, appears to be attributable to "baking on" of the bonding material used to assemble the mode cleaner.

A detailed inspection of low-loss mirrors and substrates has revealed substrate contamination that can lead to defective mirror coatings. We are working with an optical-coating subcontractor to separate the effects of substrate imperfections from imperfections in the coating process.

B. Stationary Interferometer

Initial research with the stationary, recombined Fabry-Perot interferometer, using inline modulation, has been completed. Information learned can now be transferred to the 40-meter prototype as the first step in making it a recombined system. The sensitivity of the stationary interferometer, $2 \cdot 10^{-17}$ m/$\sqrt{\text{Hz}}$, is limited by shot noise at high frequencies and by thermal noise in the rigid mirror mounts.

In order to achieve this current performance, technical improvements in laser frequency stabilization and reduction in acoustic noise have been made. A "clean-room" technique has been developed to allow the continuous use of supermirrors in air without degradation.

Information of value in other interferometer designs and for follow-on research with the stationary system has been obtained. Superpolished mirrors (polished and coated by new vendors) have been installed and give 0.975 of the incident power reflected on resonance. Alignment techniques have been developed to couple 0.95 of the input power to the main cavity TEM_{00} mode and to achieve a 0.98 contrast in the recombined Fabry-Perot interferometer.

An intrinsic limitation of the inline modulation technique, the cancellation of the RF-modulation sidebands, has been identified experimentally and explained theoretically.

Theoretical and design work for a broadband recycled interferometer with external modulation has been completed. This system is a candidate for the initial LIGO interferometer and will be the next research program in the stationary interferometer.

C. Vibration Isolation and Thermal Noise Studies

Vibration Isolation. We have begun planning to develop and test a vacuum-compatible, multiple-stack vibration-isolation system for the initial LIGO interferometer and for use in suspended prototypes. The elements of the plan are:

1) The specification of isolation transfer function and drift.
2) Evolution of a damped spring design using either bellows-encapsulated elastomers or open elastomers and metallic springs.
3) A finite element, three-dimensional analysis using ABAQUS, a program that includes non-linear and frequency-dependent damping.
4) The construction of a full scale model.

5) Measurement of the isolation transfer matrix.

Thermal Noise. Studies on thermal noise in suspensions continue. The measurement of the dissipation, in flexure, of a variety of suspension materials (fused quartz, silicon, sapphire, tungsten) has led to the hypothesis that thermoelastic damping will dominate in thin members such as suspension wire and ribbons. The spectrum of the off-resonance suspension noise is predictable and decreases as $1/f^{2.5}$ at frequencies above the pendulum resonance. Currently, the dimensional scaling of thermoelastic dissipation is being measured in fused quartz fibers of different diameters. Theoretical work is being done to determine the feasibility of an experiment to measure the off-resonance thermal noise in a fused quartz mirror at frequencies below the first flexural resonance.

2. LIGO DEVELOPMENT

A. Sites

Owens Valley. LIGO engineers visited the potential LIGO site at Owens Valley Radio Observatory in January to gather additional data. The previously-discovered marshy area is somewhat larger in extent than previously thought and is an environmentally-sensitive area. There are no apparent special environmental concerns with the remaining area under consideration. Data on property boundaries and flooding potential were gathered. Adequate electrical power is already installed at the site. We have made minor adjustments to the potential LIGO layout to accommodate these considerations, and are preparing to approach the Los Angeles Department of Water and Power (sole property owner) for permission to conduct preliminary geotechnical and hydrological studies.

B. LIGO Interferometer Design and Optics Research

Optical Beam Alignment. A concept for initial alignment of interferometer beams and test masses, using fiducials in the building foundations, was developed. A low-power pilot beam could provide a reference for rapidly aligning successive interferometers, without mutual interference.

Test Mass Design. We have started the design of test masses for the LIGO. Measurements of inhomogeneity and birefringence in thick pieces of fused quartz were completed. Analysis of the data indicates that these imperfections will not be a limiting factor in monolithic test masses of the initial LIGO interferometer. A preliminary assessment of industrial manufacturing capabilities is underway.

Numerical Simulation. We have acquired a numerical optical-simulation code (GLAD V) which will be used to verify interferometer configurations, and to generate final optical specifications for the test masses and other optics. This computer program is being tested on the Caltech LIGO computer network. After initial familiarization and testing/verification, we expect to acquire a second license for the MIT LIGO computer network.

C. Experiments with the Vacuum Test Facility (VTF)

We are continuing to learn more about the dependence of outgassing rates on bakeout time and temperature. Earlier VTF data suggested that lower bakeout temperatures and longer bakeout times might achieve acceptably low water vapor outgassing rates with less change (increase) of hydrogen outgassing rates from the low-hydrogen steel. Accordingly, we have baked Chamber #3 (which had been steam-cleaned) at 90°C for $\sim$ 700 hours. Measurements of water-vapor and hydrogen outgassing rates are now being made.

D. LIGO Beam Tube Investigations

We plan to demonstrate several key aspects of the proposed construction strategy for the LIGO beam tubes. We will fabricate $\sim$ 80 m of spiral-welded tubing from a fresh production run of low-hydrogen steel, assemble a long test section into a vacuum setup, and bake out the test section using the planned technique for the LIGO beam tubes. Primary objectives are: 1) to demonstrate that the low-hydrogen steel is reproducible; 2) to show that the spiral-welding process introduces no surprises; 3) to show that the baked tubing meets LIGO outgassing-rate requirements. Because integrity of the mechanical design of the LIGO beam tubes is not an issue (the proposed baseline employs standard pressure vessel design practices), the test tubing will be made 2 feet in diameter (rather than the 4 feet proposed for LIGO). The tube sections thus are suitable to be installed in the 40-m prototype after completion of the tests. A coil of low-hydrogen steel was ordered in February, and we expect to have the test section set up and pumped down by mid-summer.

E. Materials Testing for Vacuum Compatibility

A program for systematic testing of the vacuum compatibility of materials and components for use in the LIGO interferometers is being planned. The program is organized into two major areas: tests of properties which affect the pressure (vacuum) performance of the LIGO, and tests of properties which affect mirror performance (contamination). A test-apparatus design and testing procedures will be developed during the next quarter.

F. LIGO Procurement Documents

Procurement schedules for the major LIGO subcontracts (facility Architectural & Engineering (A&E) design, facility construction, vacuum equipment design and construction, and beam tube design and construction) have been developed and critical dates identified. Documentation requirements for Request-for-Proposal (RFP) packages have been identified. Drafts of proposal instructions, statements of work, and technical specifications are in preparation. We expect to be ready to release RFPs for A&E design work and vacuum-system elements by early summer.

3. OTHER PROGRESS

An NSF site visit to Caltech was conducted on February 22 and 23, 1990. NSF personnel and an NSF-appointed review committee were given a presentation on the LIGO construction proposal which had been submitted during the last quarter of 1989. Special emphasis was placed on the LIGO Concept and on LIGO Implementation, Schedules, and Cost. The visitors also toured the laboratory of the 40-meter prototype.

Monthly LIGO Project Status Reviews were resumed at Caltech in January. Usually one or more project members from MIT will attend these meetings.

Project personnel are working with the Caltech Public Relations office to prepare a brochure on LIGO. A LIGO "fact sheet" has been written. These activities are conducted with Caltech private funds.

A theoretical study of light scattering, "Internal Scattering in Fabry-Perot Cavities," was submitted in January, 1990 for publication by Andrej Čadež (now at the Kardelja University in Ljubljana, Yugoslavia).

4. PERSONNEL CHANGES

Dr. Andrew Jeffries has left the LIGO project (MIT) to take a job developing new X-ray imaging techniques at San Francisco State University.

Dr. Peter Saulson has resigned as a Principal Scientist at MIT and left the LIGO project to take a research position at the Joint Institute for Laboratory Astrophysics (JILA) in Boulder, Colorado.

Peter Fritschel received the Wolf Graduate Fellowship to support his work on the LIGO project.

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