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

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INTRODUCTION

This report covers the Laser Interferometer Gravitational Wave Observatory (LIGO) Project activities from January through March 1989, 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 sensitivity enhancements of prototypes

b) Conceptual design of LIGO

1. PROTOTYPE ACTIVITIES

A. 40-meter Prototype

An improved configuration for beam-injection optics and electronics in the 40-meter prototype, started near the end of the previous quarter, is now complete and about to be tested. In the new arrangement the critical elements of the beam-conditioning chain up to and including the main beamsplitter—mode cleaner, mode matching lenses, primary modulation, phase correction, and final beam steering—are contained in a contiguous vacuum envelope. The elimination of the air path and optical fiber between the mode cleaner and beamsplitter is expected to improve performance. Significantly higher power (at least 0.5 Watt) is available at the beamsplitter. In addition to modifications to the vacuum system, the reconfiguration required motorizing many of the adjustments that were previously hand-controlled; the 14 added motorized positioners have been successfully used for aligning and mode matching. These changes bring the prototype closer to LIGO designs.

A newly developed laser-diode based autocollimator was used to control the alignment of one arm of the prototype for a three-day span. The drift and noise of this one-beam system is less than or equal that of the four-beam He-Ne laser based alignment system used to date.

An improved design for optical-sensing, magnetic-forcing transducers to control the position and orientation of suspended components ("shark detectors") has been tested on the bench, simultaneously controlling three degrees of freedom of a suspended mass. The devices are compact, low-noise, and general-purpose. The displacement noise above 3 Hz is less than 7×10^{-11} meters/$\sqrt{\text{Hz}}$. The construction of tens of these devices and their associated electronics is underway in preparation for the next major modification to the prototype apparatus, in which the beamsplitter mass will be subdivided into several separately-suspended components, and the beams from the interferometer arms will recombine at the beamsplitter. Many of the components needed for this modification—including new vacuum chambers—have been designed, and machine shop construction is underway.

B. Stationary Interferometer

Substantial progress was made during the past quarter in the development of the stationary interferometer at the 5-m facility.

The first recombination configuration has been undergoing tests. The principal elements of the interferometer configuration are two 50-cm Fabry Perot cavities as optical storage elements (each with a finesse of 100), a beam splitter, and two inline Pockels-cell phase modulators. Three servo loops are used in the interferometer: the first performs a frequency lock of the laser to one of the Fabry Perot cavities, the second loop locks the other Fabry Perot cavity to the laser and the third loop phase locks the Michelson interferometer formed by the beam splitter and the two Fabry Perot input mirrors. The error signals to lock the first two loops are derived by cavity-reflection techniques. The cavity-reflection signals are sampled by low-reflectivity beam splitters to minimize the loss of power in the main interferometer. The third loop derives an error signal at the anti-symmetric output of the recombined interferometer which is the principal output of the system. The interferometer is illuminated by light from a single mode optical fiber.

The system has come into full operation recently. Initial measurements of the interferometer performance in air with an input power of 30mW are: an optical efficiency of .3, fringe contrast of .95, an output phase noise of 5×10^{-7} radians/$\sqrt{\text{Hz}}$ and a displacement noise of 1.3×10^{-16} meters/$\sqrt{\text{Hz}}$ at frequencies above 20kHz. The noise amplitude is at present a factor of 100 larger than shot noise and is strongly correlated in the three servo loops. These are initial results taken during the first run when the entire system was finally locked. Work is now in progress to reduce the common mode noise which is believed to be due to frequency and amplitude noise in the laser.

The system has not yet been operated in vacuum although all parts to enable this have been constructed and tested. The current experimental strategy is to define and reduce the obvious noise sources with the instrument still easily accessible in air.

C. Other Experimental Work

The nested suspension system is being tested at the 5-m facility in the suspension test vacuum chamber. Research during the last quarter has established that: the normal mode analysis of the system is confirmed by experiment in vacuum, the damping system using shadow quadrant position sensors and magnetic controllers is successful in both air and in vacuum, the vibration isolation as determined by external excitation of the system while under vacuum obeys the anticipated $1/f^4$ dependence at frequencies up to 80 Hz. Work is in progress to measure the isolation at higher frequencies and to determine the ultimate Q of the suspension system.

Tests of power-handling ability of low-loss mirrors of the type used in the 40-m prototype show distortion effects occurring at a power threshold of approximately 0.2 watts loss of light per mirror. Analytical modeling has shown this threshold to be consistent with theoretical expectations and numerical simulations. The distortion is due mainly to temperature-dependence of the index of refraction of the fused silica substrates and degrades the properties of beams transmitted through them. Alternative substrate materials that should be capable of handling more power have been identified. A major R&D effort in optics, directed at a broad spectrum of present and future optics issues, including the above, is being initiated.

Tests for optical birefringence and inhomogeneity in fused quartz blanks on a scale appropriate for LIGO mirrors were completed at ZYGO Corporation. The results are being analyzed.

D. Theoretical Studies

A technique has been developed to estimate rigorously the thermal noise in a complex mechanical system. The importance of this lies in part in its utility in directing the experimental effort to reduce the influence of thermal noise in the LIGO suspension systems. An analysis of the effect of photon shot noise in various recombined interferometer designs has been completed; a similar analysis for the cavity-reflection locking system has also been carried out.

2. LIGO DEVELOPMENT

A. Sites

Green Bank, WV

At the request of the NSF, the LIGO Project explored the feasibility of building a 4-km LIGO installation at the National Radio Astronomy Observatory (NRAO) site near Green Bank, West Virginia. We visited the site, collected and evaluated available data, and identified two possible LIGO alignments. We concluded that it is technically feasible to build a LIGO at Green Bank, although the site is topographically more complex than other sites we have studied. A series of reports containing details and conclusions were submitted to the NSF.

Edwards AFB, CA

Reports of preliminary hydrological, biological, and cultural impact surveys were received and are being evaluated. A review of the earlier preliminary geotechnical survey yielded the conclusion that, because of the instability of the lake bed soils in the area, it would be necessary to support the LIGO installation on piles driven to a depth varying between 60 and 120 feet. The cost impact of these piles partially offsets the very low earthwork costs at this site, but Edwards remains a relatively low-cost potential site for the LIGO.

Owens Valley, CA

We have initiated a preliminary inquiry into the feasibility of a 4-km LIGO at the site of the Owens Valley Radio Observatory (OVRO). The 1983 Stone & Webster survey concluded that there was insufficient space for a 5-km LIGO, but recent analysis shows that a 4-km installation will fit. The site possesses many positive attributes of a good LIGO site: a well-developed infrastructure, very flat topography, stable soil conditions, and a single, private landowner with whom Caltech has maintained excellent relations.

B. Vacuum Test Facility

Long-term hydrogen and water outgassing tests continue, with data to 4000 hours on one test sample. Based upon the long-term data from the first two samples, the attempt to produce low-hydrogen steel inexpensively at the steel mill has been an unqualified success. No high temperature bakeout will be required to meet the very low hydrogen partial pressure requirements of the LIGO, even if the beam tubes are uninsulated. We are continuing to explore the less demanding problem of driving off the water on an acceptable time scale.

C. Conceptual Design

Late in the last reporting quarter, a significant problem was identified in the area of vacuum-system requirements for the beam splitter, input and output beam-conditioning optics. Additional scientific manpower was added to the conceptual design effort, dedicated to the task of systematically evaluating the limits of the geometry of these optics; this required temporary suspension of work on the 40-m prototype. Although the results of this effort required scrapping much of the earlier engineering work on vacuum chambers and building concepts, including release of the Vacuum System Specifications for review by industry, we now have a much clearer picture of the realistic demands which these key areas place on the facility concept, including a broad range of uncertainty which must be accommodated. We are developing a modular vacuum-system concept which permits the installed hardware configuration to adapt economically to specific demands as they arise in the course of LIGO evolution.

A study of light scattering in the 4-km beam tubes, including major contributions by K. Thorne, was completed and evaluated, resulting in specific recommendations for baffles in the beam tubes. This major problem is now considered solved.

Additional conceptual-design topics in which significant progress was made include:

- Quantification of the role of mid-stations in the LIGO, and evaluation of the tradeoffs in their placement.
- Evaluation of tolerable vibration levels of LIGO optical components.
- Development of facility environmental requirements.
- Identification of auxiliary physical parameter measurement requirements.
- Specifications for the allowed levels of dust contamination in the LIGO.
- Development of an initial operations scenario for the LIGO.
- Evaluation of LIGO control/data acquisition and data analysis requirements.
- Identification and partial evaluation of interface requirements between LIGO interferometers and LIGO facilities.
- Evaluation of LIGO support-facility requirements, including both campus facilities and special on-site facilities (such as long baseline mirror testing).
- Detailed calculations of sensitivity to residual gas and specification of allowable pressures.
- Theory of the outgassing of the LIGO vacuum system.
- Site requirements.
- Analysis of the effect of slope on the LIGO performance.
- The influence of temperature variation on the LIGO baseline and beam tubes.

3. OTHER PROGRESS

The Sun 4 computer system installed at MIT in the last quarter has been brought on line.

4. INTERNATIONAL COOPERATION

R. Vogt participated in a February 14 meeting in Paris, France, which had been convened upon initiative of and chaired by the NSF. Representatives of all major European gravity-interferometer research groups and their funding agencies attended. A principal focus of the discussion was the exploration of possibilities for international collaboration in the development of gravity wave interferometry, and several technical and scientific working groups were established.

5. PERSONNEL CHANGES

Paul Linsay, who was half time on the LIGO project, has left the LIGO project as planned, and taken a new position at the MIT Fusion Research Center.

Pasadena, 24 March 1989

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