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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 October through December 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 reliability and sensitivity enhancements of prototypes
b) LIGO development
c) Completion of the LIGO construction proposal

Work on the LIGO construction proposal again monopolized the attention of key project members at the expense of laboratory progress.

1. PROTOTYPE ACTIVITIES

A. 40-meter Prototype

The variable-length mode cleaner constructed in the previous quarter was installed and successfully operated as part of a new configuration for the 40-meter interferometer. New laser stabilization circuitry provides increased gain (the unity-gain frequency is 2 MHz) and improved overload tolerance. Additional circuitry now automatically reacquires lock without operator intervention if the servo loop is interrupted.

The ability to control the mode cleaner length via PZT-mounted mirrors allows a large reduction in the forces fed back to the primary cavity test masses, eliminating a potential source of noise. Above 500 Hz, the feedback to the test masses has been reduced to a level much less than the shot-noise equivalent displacement.

The secondary cavity servo was improved by increasing its bandwidth and by the addition of an active notch filter to cancel the effect of the test mass mechanical resonance at

28 kHz. The unity-gain frequency was doubled, to approximately 4 kHz. These improvements have resulted in a robust system that recovers within a few seconds from mechanical or other disturbances.

Low-loss matching networks for RF phase modulation were constructed and installed. The maximum electrical power required for optimum modulation is reduced by approximately a factor of 3, to 1 watt. New RF power amplifiers were designed, constructed, and installed.

B. Stationary Interferometer

Research has continued with the stationary recombined Fabry-Perot interferometer to test concepts for the design of the initial LIGO interferometer.

This interferometer, using in-line phase modulators, has operated within 10% of the shot noise limit in a 10% bandwidth near 300 kHz with a power of 5 mW on the bright fringe. The shot noise limit corresponds to a displacement noise of 10^{-16} meters/$\sqrt{\text{Hz}}$.

A resonant filter is used in the laser frequency control feedback loop to achieve adequate loop gain at the high frequencies where the stationary interferometer is not perturbed by mechanical noise. In the band around 30 kHz the sensitivity is now primarily limited by the quality of the mirrors. These are to be replaced soon with superpolished, low-loss coated mirrors. Techniques to keep the new mirrors clean while the system is operated in air have been developed.

C. Suspension Research

Research on the double suspension system with magnetic and electrostatic controllers has come to a conclusion. Measurements confirm $1/f^4$ isolation up to 130 Hz, all the normal modes have been damped electronically, and calculations show that the system would be stable in interferometer operation. Except for two resonances near 30 Hz from vertical isolation springs, cross-coupling between horizontal modes does not compromise the isolation.

Research to predict and to reduce the off-resonance thermal noise in LIGO suspension systems continued this quarter. Flexure losses in unloaded tungsten, fused quartz, sapphire, and silicon fibers have been measured. Fused quartz has the smallest measured loss of the materials tested for frequencies between 30 Hz and several hundred Hz. The thermoelastic damping theory of Zener is a reasonable predictor of the losses in all of the materials when formed into thin flexural members. This is an important conclusion for evaluating the thermal noise from the pendulum in the suspensions and allows more accurate predictions of the effect on gravitational wave sensitivity in the LIGO. Materials with small thermal conductivity, large heat capacity, and small thermal expansion coefficient are favored. The low-frequency, off-resonance behavior of the thermal noise in large systems such as test masses and mirrors must still be evaluated because it does not seem to follow the Zener theory.

D. Optics Testing

The analysis of the effects of vector wavefront distortion in double pass transmission of polished fused quartz blanks has advanced. The phase distortion amplitude and correlation lengths derived from measurements of two blanks have been used in computer simulations of LIGO scale mirrors. The simulation shows that interferometer contrast will lie between .994 and .999 if only limited by wavefront distortion due to transmission through the inhomogeneous mirror media. The effect of birefringence inhomogeneities are still being analyzed.

A significant effort has gone into working with and evaluating new vendors for super-polished substrates and low scatter coatings.

New procedures for inspecting and testing substrates and mirrors, including microscope examination and cavity ring-down measurements, were developed and applied to the super-mirror inventory.

An apparatus to measure calorimetrically the optical power absorption of cavity mirrors was developed. Preliminary tests and calibrations have been completed.

2. LIGO DEVELOPMENT

A. Sites

Fort Dix, NJ—We received USGS maps of the Ft. Dix area with four proposed alignments for the LIGO, together with site photos, weather and flood data, and soil information. A LIGO Team member (Mike Burka) also visited the site and provided additional information on the general condition of the site.

We reviewed the four proposed alignments and only alignment #4 seems worth further consideration. The soil and flood data received are very general and do not cover site-specific issues of importance. We are in the process of obtaining additional site-specific information and data.

B. Experiments with the Vacuum Test Facility

A second test chamber was baked out as part of a continuing effort to quantify the process of reducing water vapor outgassing by baking. Chamber #4 (which had been cleaned with cold water and detergent) was baked at a low temperature ($\sim$ 115 °C) for an extended period ($\sim$ 300 hr), in contrast with the more conventional (240 °C, 6 hr) bake applied to Chamber #2. The total amount of water outgassed from Chamber #4 was 1/3 of that from Chamber #2, and the post-bake water vapor outgassing rate was measured at 10^{-16} $\text{torr}\cdot\text{L}\cdot\text{s}^{-1}\cdot\text{cm}^{-2}$ (chamber #2 yielded 10^{-14} $\text{torr}\cdot\text{L}\cdot\text{s}^{-1}\cdot\text{cm}^{-2}$; the LIGO beam tubes require an outgassing rate of $< 2\cdot 10^{-15}$ $\text{torr}\cdot\text{L}\cdot\text{s}^{-1}\cdot\text{cm}^{-2}$ to achieve the "goal" pressure levels of $< 10^{-10}$ torr H_2O). Hydrogen outgassing after the bake increased by a factor of $\sim$ 30 to 10^{-13} $\text{torr}\cdot\text{L}\cdot\text{s}^{-1}\cdot\text{cm}^{-2}$, still well within the LIGO needs.

C. LIGO Beam Tube Investigations

A number of fabricators of corrugated tubing were contacted to learn about manufacturing capabilities, processes, and design options for the LIGO beam tubes based upon corrugated fabrication techniques. We found that only two U. S. companies routinely weld corrugated tubing, and only one of those companies was willing to discuss process details with us. That company employs a welding technique which solves the mechanical problems associated with welding corrugated tubing but which has never been used, to our knowledge, for vacuum applications. We have requested a sample of tubing welded with this technique for evaluation.

D. LIGO Design Documents

We have started the preparation of a Facility Design Document. This document will provide specific requirements, guidance, criteria, and scope for the design of the LIGO facilities.

A preliminary draft of a Vacuum System Specification has also been prepared.

E. LIGO Construction Proposal

The major effort during the past quarter was directed toward completion of the LIGO construction proposal. This proposal, "The Construction, Operation, and Supporting Research and Development of a Laser Interferometer Gravitational-Wave Observatory," was submitted to the NSF on 12/14/89 and has been assigned Proposal ID No: PHY–9005154, dated 12/22/89, by the NSF.

3. OTHER PROGRESS

While calculating the performance of a network of detectors in a search for a stochastic background, Christensen (MIT graduate student) has discovered an error in Schutz and Tinto's calculations for the optimal relative orientation of interferometric detectors. The result is significant for large separations such as a United States and Asian baseline.

An analysis of the limiting noise from electrostatic and magnetic controllers for the test masses has been made. Results show that it is important to reduce the rms vibrational motion of the test masses for either system and that electrostatic controllers are better for low frequency applications.

An analysis of recycling with finite contrast in interferometers, with external and internal RF phase modulation, has been carried out. One of the results of the analysis is that the two systems have comparable performance but that external modulation may be more robust in practice.

4. PERSONNEL CHANGES

Richard A. Prout joined the LIGO engineering group in November 1989 as Optical Systems Engineer.

Pasadena, January 16, 1990

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