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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 July through September 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) LIGO development
c) Preparation of the LIGO construction proposal

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

1. PROTOTYPE ACTIVITIES

A. 40-meter Prototype

Measurements of the prototype performance using the fixed-length mode cleaner installed in the previous quarter revealed that this configuration is limited by residual phase noise in the light incident on the beamsplitter. The application of common-mode correction forces to masses in each interferometer arm succeeded in suppressing this noise by a factor of 1300, but only for impressed c.w. test signals.[1] The overall performance was limited by second-order effects, probably nonlinearities associated with the correction forces, that resulted in a suppression of broadband noise by a factor of only 120.

[1] Combined with the measured frequency noise from the mode cleaner of $0.04\frac{\mathrm{Hz}}{\sqrt{\mathrm{Hz}}}$, these factors combine to allow sensitivity of better than $3 \cdot 10^{-18}\frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}$, in the absence of second-order effects.

A new variable-length mode cleaner using PZT-mounted mirrors has been constructed. Early tests indicate that the length adjustment will not introduce noise or in other ways limit performance. The purpose of the new mode cleaner is to eliminate the need for forces applied to the masses, thereby relaxing the requirements on linearity of the optical and electromechanical response of the interferometer.

Generalized high-gain amplifiers appropriate for use in different stages of laser stabilization were designed, and a breadboard version was built. Precise and long overdue measurements of the response of critical optical and electronic elements of the prototype interferometer were made possible following the acquisition of a new rf network/spectrum analyzer.

B. 5-meter Prototype

Work has continued on a stationary recombined Fabry-Perot interferometer to test concepts for the design of the initial LIGO interferometer.

The recombined Fabry-Perot stationary interferometer has demonstrated performance within a factor of 3 of the shot noise limit at frequencies above 90 kHz using inline Pockels cells but with only 5 mW of optical power in the bright fringe. This corresponds to a position sensitivity of $1.6 \times 10^{-16}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at frequencies above 90 kHz. The noise at the antisymmetric port and the two cavity sampling ports is not strongly correlated at 90 kHz indicating that the limiting noise is no longer a common mode source as it was during the last quarter. The effort is now dedicated to improving the performance at lower frequencies ($f > 10$ kHz) and to increasing the optical power.

Steps have been taken to increase the power of the laser and to reduce the open loop frequency noise of the laser in the 10 to 100 kHz band. A single line output coupler was installed in the laser to replace the prism. The etalon and aperture were mechanically isolated from the laser bed to reduce noise from water cooling of the laser. The cooling system has now been replaced with a recirculating system tied to the chilled water line. The laser now emits 600 mW in a single mode.

C. Other Laboratory Research

1. Suspensions

A new position and angle sensing and control system was tested for the first time on a suspended mirror. The measurements confirmed that drift and noise are acceptably low for use in prototype interferometers. Observed peak drift over two days of in-vacuo operation in a lab with poor temperature regulation was $< 1 \cdot 10^{-5}$ radian. The controller uses shadow sensing and magnetic feedback combined in a compact head. It is designed to simultaneously monitor and control all 6 degrees of freedom of suspended components; so far it has been tested with 4 degrees of freedom.

The research on a model double-suspension system using electrostatic and magnetic controllers continued during the past quarter and will be brought to a conclusion during the coming one. The system has demonstrated isolation that varies as $1/f^4$. Work this quarter has concentrated on establishing the transfer functions for control of the mirror as would be needed in a suspended interferometer. A control vector using both electrostatic and magnetic drives to minimize the mirror rotation associated with translation has been modelled and is being tested. The final step is to establish the transfer function and control vectors needed for pointing. This will complete the characterization of the system and allow it to be evaluated as a component of a suspended interferometer.

Research to predict and to reduce the off-resonance thermal noise in LIGO suspension systems continued this quarter. The internal losses of several tungsten fibers in flexural normal modes at different frequencies have been measured. Although the internal dissipation is sample dependent, with the highest Q's measured around 3000, it is now clear that in tungsten the losses in the gravitational wave frequency band of the LIGO are a mixture of viscous and Coulomb friction giving a mode Q which varies slowly with frequency. The significance of this is that we have overestimated the thermal noise above resonance in tungsten fiber suspensions in some of the earlier projections being made for the LIGO.

Measurements of Q in insulators are now being made. A sample fused-quartz fiber has exhibited a Q around 10^6 at a frequency of 613 Hz. The frequency dependence of the dissipation is now being measured.

In the course of this research a technique was established to fabricate low-dissipation fiber clamps which will prove useful in the LIGO.

2. Optics Testing

The analysis of the vector wavefront distortion in a double pass transmission of polished thick pieces of fused quartz of the size scale of LIGO mirrors is still in progress. Preliminary results show that the scalar wavefront distortion in a blank 9 cm thick, with a hole in it, has an rms amplitude corresponding to 9×10^{-3} green wavelengths and a correlation length between 1.5 to 2 cm. In a 4 cm thick blank, without a hole, the rms scalar distortion was measured as 1.6×10^{-2} green wavelengths. The birefringence of the thick piece corresponds to a vector retardation of 3.5×10^{-4} green waves with an rms fluctuation of 1.4×10^{-2}. The spatial distribution function of the birefringence fluctuation is still being analysed. The preliminary results indicate that birefringence fluctuations will be the limiting optical imperfections in thick fused-quartz pieces.

A program has been started to measure the total and small angle scattering of superpolished substrates with sputtered coatings. The scattering measurements of uncoated substrates are in progress. This will be followed by measurements of scattering and total loss of the same substrates with coatings.

A program of systematic inspection and measurement of low-loss optics, intended in part to evaluate the quality of products from competing manufacturers, was initiated. Transmission measurements on a stock of 50 super-mirrors showed uniformity variations ranging from less than 2% to greater than 15%.

D. Laser Development

We have begun a collaboration with the research group of Professor Robert Byer at Stanford University to develop high-power solid-state lasers for LIGO. We will provide technical and scientific assistance and participate in biannual technical reviews to help insure that the laser work is consistent with the requirements of the LIGO project.

2. LIGO DEVELOPMENT

A. Sites

We have continued an 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 more recent analysis shows that a 4-km installation will fit. The site possesses many attributes of a good LIGO site: a well-developed infrastructure, very flat topography, stable soil conditions, and a single landowner with whom Caltech has historically excellent relations. Two alignments that avoid a recently discovered marshy area at the site have been identified.

We are responding to a request from the NSF to investigate another potential site located at Fort Dix, New Jersey.

B. Vacuum System

The Vacuum Test Facility (VTF) has been used to bake out a stainless steel test chamber and to measure water outgassing as a function of time and temperature. The rate of water outgassing with temperature is consistent with the literature and residual water after baking is lower than needed for the LIGO. The amount of water that outgassed during the VTF bakeout test corresponds to about 300 monolayers. The post-bakeout outgassing rate for water was measured to be approximately 10^{-14} torr liters $sec^{-1}cm^{-2}$. The maximum temperature used was 240°C. Most of the water came off below 120°C; this temperature will be used for bakeout of a second test chamber.

Preliminary calculations have been made on an idea for cost-saving piecemeal bakeout of the LIGO beam tube that would involve leaking argon or nitrogen into the tube at an appropriate rate (and pressure) to carry removed water away from the de-gassed end of the tube.

Corrugated tubing is being investigated as a possible lower-cost alternative to straight-wall tubing for the 4-km LIGO arms. A mechanical test of a section of corrugated tubing (2 ft diameter, 20 ft length) to measure stress/strain relationships and cross-coupling of modes as a check on calculations has been conducted. The measurements indicate the tubing is stiffer than predicted. Deflections are less than calculated by factors of 1.3–3.8.

C. Conceptual Design

During the past quarter we have been completing an extensive conceptual design process for the LIGO facilities. The purpose of this effort has been to translate the scientific requirements for the facilities into technical solutions and provide the basis for costing the construction of the facilities. In this process we have studied the interactions between solutions to various technical problems and clarified certain design criteria which were previously ill-defined.

A significant reduction in scope occurred in July as a result of discussions with the NSF. This led to the concept of constructing the LIGO in stages. Phase A, which incorporates two interferometers at Site 1 and one at Site 2, will be the first stage and will form the basis for the LIGO construction proposal.

3. LIGO CONSTRUCTION PROPOSAL

Preparation of the LIGO construction proposal, which was begun in May, has been the major activity for this quarter. Although the reduction in scope occurred in the middle of this quarter, most of the proposal has now (September 1989) been written in draft form and reflects the new configuration. Staged construction of the LIGO will be proposed. The construction proposal, to be submitted in the fourth quarter of 1989, will request funds for the first of these stages.

4. OTHER PROGRESS

The performance of two or three gravitational-wave detectors operating in coincidence in a search for burst sources was analyzed. The case of mismatched sensitivity, as would result from one of the detectors being half-length, was included. Simulations yielded the optimum setting of local thresholds in the (likely) case where separated detectors are subject to spurious uncorrelated signals. The sensitivity of a set of three detectors, two full-length and one half-length, was found to be reduced by at most a factor of 1.20 compared to three full-length detectors. The implications for LIGO design are under review.

A PhD thesis on signal processing by T. Joo under the supervision of Prof. A. Oppenheim was completed at MIT. The thesis investigated different methods of analyzing gravitational wave detector data for periodic sources. The thesis showed that the Z-transform is a flexible way to recover the signals from Doppler-shifted sources and is no more computationally intensive than resampling methods. The thesis also shows that the statistical concepts of average and semblence of transformed spectra can be used together to give a statistically robust estimate for the probability that a particular set of records includes signals from a periodic source.

5. PERSONNEL CHANGES

Peter Saulson of the LIGO science group at MIT has taken a leave of absence to become a Visiting Fellow at JILA for the Fall term. David Shoemaker joined the LIGO science group at MIT in September 1989.

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