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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 October through December 1988, including work of the Caltech and MIT science groups and the engineering team located at Caltech. R. Vogt is providing overall project direction as P.I., R. Drever (Caltech) and R. Weiss (MIT) are heading their respective science teams, and W. Althouse is heading the engineering team. 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

Prototype research efforts on the 40-meter facility at Caltech have been directed toward developing optical systems in the 40-meter interferometer, both to improve its performance and to test LIGO designs. A series of experiments using high-power cavities and new methods of controlling the phase of the input light and the motion of test masses has led to a redesign of critical elements of the beam-injection optics and electronics. Construction now underway of new optical arrangements—including significant transfers of optics from air into the vacuum system—will make many features of the prototype much closer to proposed LIGO designs.

The two-stage laser stabilization system, in which the laser wavelength tracks a standard cavity (mode cleaner) and the phase of the cavity output light is controlled to match one of the interferometer arms, was refined by increasing the gain and range of both stages.

The system can now operate without the electro-mechanical control of optical phase that was required previously. This enhancement reduces spurious beam deflection and obviates the need for mechanical transducers of optics within the vacuum system.

A method for controlling the interferometer arm lengths symmetrically—applying precisely matched forces to both end masses—was developed and tested. This common-mode compensation reduces the sensitivity to fluctuations in the phase of the input light without affecting the response to the differential motion caused by gravitational waves. Measurements show a reduction in phase noise by a factor of 300 due to this technique.

Taken together, these enhancements provide assurance that laser stabilization will remain adequate to achieve shot-noise limited sensitivity for the next phase of operations (described below), in which the power will be increased and the available servo range will be reduced.

Tests of a pulse-encoded laser diode autocollimator, used to control the orientation of two masses simultaneously, have demonstrated the promise of this device as a substitute for the gas-laser optical levers now in use. The optical arrangement of the autocollimator is simpler than, and the measured noise ($3 \cdot 10^{-8}$ rad/$\sqrt{\text{Hz}}$) is comparable to, that of the old system.

Investigation of seismic isolation materials disclosed a promising two-component RTV rubber having good vacuum properties and low compliance. This rubber is incorporated into isolation stacks now being assembled.

A series of tests of the power-handling capabilities of optical cavities show distortion of wavefronts when the power circulating between the mirrors is on the order of one kilowatt. This effect depends on absorption loss in the mirror coatings, thermal properties of the substrate, and geometry of the cavity. Analytical calculations and computer modeling have identified the temperature variation of the substrate index of refraction as a critical parameter. Experiments now underway will test mirrors with up to 10 kW circulating power—comparable to the power in LIGO interferometers with recycling.

A new mode cleaner has been built, using proven mechanical design and mirrors selected for lowest loss. Construction of parts to allow a reconfiguration of the vacuum system, in which the mode cleaner will be adjoined to the beamsplitter chamber, is complete, and assembly is underway. This arrangement eliminates the optical fiber from the optical chain, and will inject a stable beam directly into the interferometer. Furthermore, the elimination of lossy components will result in much higher optical power—approximately one watt input. With slight modification, the vacuum and optical systems can be reconfigured to accommodate an input mode cleaner approximately 12 meters long.

Preparations are well underway for the next major modification to the interferometer, in which the beamsplitter mass—currently comprising many optical components in addition to the beamsplitter—will be separated into individually suspended components. The beamsplitter and associated components will remain in the corner chamber, and two additional satellite vacuum chambers (presently under construction) will hold the test masses that now share the chamber with the beamsplitter. Sensors and feedback transducers for magnetic control of the separated components have been designed, and prototypes are being tested. The optical layout, including a provision for beam recombination, has been designed, and special parts, including large-diameter beamsplitters and large-aperture Pockels cells, are on order.

B. 5-meter Prototype

Prototype research efforts on the 5-meter facility at MIT have been directed primarily toward developing a stationary Fabry-Perot interferometer to test recombination and recycling geometries and as a prelude to a full-scale prototype.

The internal wiring, safety support posts and the auxiliary hoists for the vacuum chambers of the 5-meter facility were installed. The stationary interferometer has been assembled in the central chamber, while a prototype compound suspension system has been placed in the suspension test chamber.

Frequency stabilization of the Spectra Physics Argon laser, previously used on the 1.5-meter prototype, has been carried out with the techniques developed at the 40-meter prototype. The laser is presently locked to an external cavity with a finesse of 300 by using fast and slow PZT actuators on the laser mirrors and an external Pockels cell. When used with the interferometer, this frequency reference will be one of the Fabry-Perot cavities in the recombined interferometer arms.

Vacuum-compatible parts for the static interferometer, using a recombination system with in-line Pockels cells, have been assembled. The system is placed on a vibration-isolated aluminum optical table in the central chamber with the optic plane of the interferometer raised so that the same layout can be used later with suspended cavity mirrors. The laser is coupled to the interferometer through a single-mode optical fiber using graded-index matching lenses. The optical efficiency of the fiber feed is 60%. The initial cavity configuration uses standard commercial mirrors having an anticipated finesse of several hundred. The cavity input mirrors have a 3% transmission. Higher quality "super-mirrors" are expected to arrive in January 1989.

The electronics for photodetection, fringe modulation, RF phase detection and mirror servo control have been assembled and tested. The stationary interferometer is being aligned and will initially be operated in air.

The suspension test chamber was instrumented during this quarter. A prototype compound suspension was installed in the chamber during November. Initial measurements indicate that the mass-damping servo loops behave satisfactorily in vacuum. Measurements of the isolation transfer function using an external electromagnetic shaker are planned for January.

C. Laser Development

A collaboration to develop higher power Nd:YAG lasers, pumped with laser diodes, was begun with Professor Byer's group at Stanford. Initially the collaboration involves information exchange and will evolve into joint development and testing of laser-diode-pumped Nd:YAG slab lasers and techniques for laser frequency stabilization.

Spectra Diode Corporation has provided us with 10 additional 1/2-watt laser diodes for pumping the Nd:YAG laser/amplifier combination that is designed to develop approximately 1 watt of single-mode, frequency-stabilized power at 1.06μ.

2. LIGO DEVELOPMENT

A. Sites

Louisiana State University (LSU) delivered a report on a preliminary seismic survey of the potential LIGO site in Louisiana. This work was carried out under the direction of Messrs. Warren Johnson of the Department of Physics and Astronomy and Don Stevenson of the Louisiana Geological Survey. The report revealed that an oil pipeline crossing the property is a source of low-frequency (< 10 Hz) seismic noise; this may restrict alignments of the LIGO at this site. A site plan with two possible alignments is being prepared for discussion with the property owner.

A preliminary soil and geotechnical exploration of the LIGO site at Edwards Air Force Base, California, was carried out in October, and the report of these studies was completed. These results are being evaluated. A hydrology study and a biological survey of the site are in progress with reports due January 5 and January 20, respectively. A detailed site plan is in preparation for submission to the Air Force.

B. Vacuum Test Facility (VTF)

Calibrations of the VTF were completed and the first two stainless-steel test chambers have been pumped down. Measurements indicate that the special low-hydrogen stainless steel being tested has hydrogen outgassing rates well within acceptable values. Water outgassing data have been accumulated for > 1350 hours after pumpdown (there are no previously published data beyond 100 hours). No significant difference in water outgassing rate between the uncleaned test chamber and one cleaned with hot water and detergent has been observed. The hydrocarbon outgassing rate of the cleaned chamber is a factor of 20 below that of the uncleaned chamber, consistent with expectations. Measurements of ion-pump speeds for different gas constituents at different pressures of interest in the LIGO application have also been made.

C. Conceptual Design

A two-phase concept of a vacuum-system configuration was developed and documented. The two phases allow us to identify and separate the early and long-term needs of the LIGO installations and permit us to concentrate resources on the initial configuration while providing for long-term needs in our planning. Configuration details of several types of vacuum chambers have been worked out and documented, and are being reviewed. A draft Vacuum System Specification was prepared and is being reviewed before circulation to industry. Schematic layouts (floor plans) of vacuum system enclosures (e.g., buildings), offices and shop areas, along with plans documenting the flow of personnel, materials and equipment, were prepared and circulated within the LIGO team for review and comments. A study of LIGO electrical power requirements was prepared and circulated internally for review and comments. Engineering studies are continuing in the areas of vacuum tube fabrication and tube cover design.

Studies in support of LIGO conceptual design included analyses of the following topics; wind-induced vibrations in the LIGO beam tubes, the vibration transfer function of metal bellows, the effect of non-level beam tubes, dust contamination on mirrors, thermal requirements on the beam tubes, site requirements, man-made noise at the sites, requirements on the building structures, vacuum-pressure requirements, and operations scenarios.

Calculations of light scattering in the beam tubes continue using analytic techniques. A computer code to carry out phase-retaining propagation of waves in complex optical geometries has been found (GLADV) and is being evaluated at the University of Arizona. A first order recommendation on the baffle and tube design to reduce the influence of scattering is expected to be made by the end of December.

3. OTHER PROGRESS

In November we began monthly Project Status Review meetings. The purpose of these meetings is to convene members of the LIGO Project Office, the engineering group, and both science groups to review the current status and plans for developing the contents of the construction proposal.

Preparation for tests of the transmission of slowly-annealled fused quartz to determine the wavefront distortion that may occur in LIGO scale mirrors is progressing. The two thick fused-quartz blanks to be tested for optical inhomogeneity and birefringence have been polished to $\frac{\lambda}{50}$. A test procedure has been established to determine the spatial scale and amplitude of the optical inhomogeneity. Techniques to measure the optical birefringence of the samples have been discussed with ZYGO Corporation. The measurements are expected to be carried out in the last week of December.

A Sun 4/260 and 4/110 distributed computer system was installed at MIT. The system enhances as well as unifies the computing environment across the LIGO project. Most of the general purpose software for the system has been installed and members of the MIT research group are making the transition from the VAX/VMS (associated with the old DEC system) to the UNIX operating system.

Computer analysis of simulated gravity-wave signals continued, concentrating on extracting source location and polarization information from coincident detection of bursts in three or more detectors. Preliminary results obtained with the San Diego supercomputer facility indicate that the information from three detectors, each recording bursts with signal-to-noise ratios on the order of 5, spans approximately 80% of the sky.

4. INTERNATIONAL COOPERATION

Initiatives to interest some of our European counterparts in meaningful collaborative efforts have been unsuccessful.

5. PERSONNEL CHANGES

The LIGO engineering group in October added Larry K. Jones to its staff as Mechanical Engineer. Jeffrey C. Livas, who has been a member of the MIT science group, left the project in December.

Pasadena, 20 December 1988

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