R. Drever

CONTINUATION PROPOSAL
NSF GRANT NO. PHY-8803557

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

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October 1988

LIGO-M890008-00-M

TABLE OF CONTENTS

INTRODUCTION

This continuation proposal for NSF Grant No. PHY-8803557 requests support for a one-year continuation of research and development towards the establishment of a laser interferometer gravitational wave observatory (LIGO). The proposed work is part of a three-year program: "Caltech/MIT Project for a Laser Interferometer Gravitational Wave Observatory," as proposed to the National Science Foundation in December 1987, reduced in scope in April 1988, and approved by the National Science Board in May 1988. Initial support for this activity has been provided by NSF for the period 15 June 1988 through 30 November 1988. The project involves the joint efforts of scientists and engineers at the California Institute of Technology (Caltech) and the Massachusetts Institute of Technology (MIT). R. Vogt serves as project director, R. Drever and R. Weiss are heading the respective science teams at Caltech and MIT, W. Althouse heads the engineering team, and K. Thorne provides theoretical support.

Continued funding is requested for the 1 December 1988 through 30 November 1989 period at a level of about \$3.6 million, with the expectation that NSF will entertain a subsequent supplementary proposal of \$0.4 million, to support the project at the activity level of the April 1988 plan.

1. RECENT PROGRESS

This section covers progress since the start of the grant (June 15, 1988) on prototype research and development and on planning for a Laser Interferometer Gravity Wave Observatory (LIGO) by the Caltech and MIT science groups and the LIGO engineering team located at Caltech.

Areas of highest priority included:

a) Interferometer prototypes
   - i) sensitivity enhancements of prototypes
   - ii) development and testing for full scale LIGO interferometers

b) Conceptual design of LIGO

c) Buildup of project engineering team

A. Prototype Activities

1) 40-meter Prototype

A two-stage stabilization system now gives improved control of the frequency and phase of the light injected into the 40-meter interferometer system. The new design, incorporating a second, independently operating servo that stabilizes the phase of the light transmitted through an improved mode cleaner, has several advantages over the earlier, single-stage system in which one interferometer arm served as a wavelength reference: (1) the loop gain and consequent suppression of frequency noise are higher; (2) the mode cleaner has less mechanical noise because piezo elements have been eliminated; (3) the technique is appropriate for optical power levels planned for the LIGO; and (4) the design is extendible to the coherent addition of two or more lasers.

Recent work on this two-stage design has culminated in a system with adequate gain to suppress phase and frequency fluctuations from the laser to the level of shot noise. The principal challenge of this work was in improving the second stage, where the phase of the light coming out of the mode cleaner is corrected to match the phase reference defined by one of the arms of the 40-meter interferometer. This was achieved by ganging together several electro-optic and electromechanical transducers. The resulting system works robustly even though the operating conditions are adverse: the laser as supplied by the manufacturer (a Coherent Innova 100-20) is exceptionally noisy, and much of the critical beam path is presently still in air and subject to acoustically excited noise. Still, there is excess gain available. Though as yet operated only at low power (one watt laser output, 30 mW injected into the interferometer) there is adequate reserve gain to achieve shot-noise limited performance at the highest power available in the laboratory (ten watts from the sum of two lasers).

The first stage of stabilization, in which the laser wavelength is controlled to match the mode cleaner cavity, has been modified to improve the efficiency and increase the output power of the laser; the Pockels cell internal to the laser cavity (which is susceptible to radiation damage) has been removed, and high-bandwidth correction to the laser wavelength is now provided by a piezo-driven mirror. Combined with the high-gain second stage, this method for stabilizing the laser provides as much total gain as was achieved previously, but without the lossy intra-laser Pockels cell; consequently a factor of five higher power is available.

The capability for autonomous operation of the interferometer was improved significantly by increasing the dynamic range of transducers in the wavelength stabilizing servos. In the present configuration, the interferometer can easily run for one-hour stretches completely unattended, even during periods of peak traffic noise, and round the clock with minimal intervention. The principal drift is thermal expansion of the optical bench used to hold the laser-cavity mirrors, and a method for correcting this drift for completely unattended runs is available.

Experience acquired in rebuilding and testing the first of two Argon ion lasers was applied to the second, resulting in better mechanical stability and reduced fluctuation in the beam. The optics are arranged so either laser can be used with the interferometer, an arrangement that prevents down time during laser breakdowns. With further small modification, future experiments in coherent addition of lasers can be carried out.

The construction of a novel device to monitor the spatial distribution of amplitudes in interfering wavefronts was completed, and the device is being used to optimize the alignment and mode matching of the laser beam to the mode cleaner.

A new method for controlling test-mass alignment, based on autocollimator optics and pulsed visible-light laser diodes, was designed and tested on the bench; tests in the 40-meter system are underway.

A concept for bellows-encapsulated rubber, to be used in seismic isolation stages, has been elaborated into a design appropriate to the next upgrade of seismic isolation in the 40-meter interferometer. This is to be implemented after a 1.8-meter diameter central chamber (under construction) is installed.

2) 5-meter Prototype

A project decision was made to begin operations in the 5-meter facility with a stationary interferometer (stationary mirrors) assembled in the central tank as a prelude to a full scale prototype. The stationary interferometer will test two geometries for interferometric recombination of the light reflected by orthogonal Fabry-Perot cavities and will also be used to develop implementation schemes for the technique of light recycling. The experiment will be carried out to a level where the dominant limiting factor and noise term are understood.

Work has begun on installing the stationary interferometer in the central instrumentation chamber and the electromagnetic shaker and accelerometers in the instrumentation chamber dedicated to vibration isolation and suspension development. The prototype compound-test-mass suspension system using quadrant-diode position sensors and magnetic controllers has been under test in air. All the low-frequency normal modes of the system have been identified and successfully damped. The system is to be installed in the vacuum test chamber to measure the isolation transfer function and to determine the stability of the electrostatic control loop that positions and points the mirror. A decision on future uses of the system will be made after the vacuum tests have been completed.

The quadrant position sensors are undergoing further development and simplification by installation of vacuum-compatible low-power operational amplifiers made integral with the sensor heads. Sensor amplifier, matrix, and magnetic-driver electronics have been designed and tested.

The techniques developed at the 40-meter prototype for frequency stabilization of the Argon ion laser have been transferred to the 5-meter facility. An external Pockels cell and fast PZT mirror system are being installed in the Spectra Physics 2020 laser previously used on the 1.5-meter system.

Water and solvent outgassing from the inner assemblies of the instrumentation tanks has been diminished by air bakeout of these components. In general, we find substantial reduction in the water outgassing rates (factors of 10^2 to 10^4) of viton, teflon and epoxy components used in wiring and other electronics by prebaking in air. We expect that this procedure will be important in reducing the gas load in the instrumentation chambers of the LIGO.

3) Laser Development

Work is continuing on the development of a single-mode frequency-stabilized Nd:YAG oscillator/amplifier combination to develop 1 to 5 watts at 1.06μ. The system uses a commercially available diode-pumped monolithic-ring oscillator as a master oscillator followed by a colinearly diode-pumped amplifier rod. Most of the parts have been assembled for this system.

A demonstration experiment of intracavity frequency doubling in a single-mode ring geometry is being assembled. The power oscillator is a discharge-tube-pumped slab laser, on loan from GE.

A proposal from the MIT science team was written to NASA to support an enhanced program in Nd:YAG development. An emphasis in the proposed research is on the long-term frequency stabilization required for certain NASA programs. Although not essential in the LIGO initially, it may simplify some of the optical servo designs to tie the laser to an absolute reference. In later years, when the facilities are used for multiple searches, absolute frequency stabilization will be useful to reduce interference between different interferometers.

B. LIGO Development

Work continued on the planning and conceptual design for the Caltech/MIT Laser Interferometer Gravitational Wave Observatory (LIGO).

1) Sites

Investigations began on a potential LIGO site in Louisiana which was brought to our attention by the Louisiana State University (LSU) Experimental Relativity Group.

A contract was placed with LSU to carry out a preliminary seismic survey of the potential LIGO site near LSU. This work is under the direction of Warren Johnson of the Department of Physics and Astronomy and Don Stevenson of the Louisiana Geological Survey. Data were taken during the first two weeks of September at several locations and under a variety of conditions. These data are currently being analyzed; a report is expected in early October.

A proposed property description and two alternate LIGO layouts at Edwards AFB, California, were presented to Air Force personnel in July, and permission was obtained to conduct ground surveys and preliminary soil sample and geological studies. Ground surveys were carried out in August, and the soil and geotechnical work is currently underway. Upon completion of analysis of the soil and geotechnical data, one of the two layouts will be adopted and a detailed site plan will be submitted to the Air Force; this submission is currently planned for December 1988. In parallel with preparation of the site plan, archeological and paleontological surveys will begin in the areas to be disturbed by LIGO construction. The site plan review at EAFB is expected to be completed by April 1989; we hope to have environmental studies completed and an Environmental Assessment report prepared by then. The site plan review and the environmental assessment are the principal ingredients of an application for a formal site-use permit to the Air Force Systems Command. The AFSC requires four to six months for their review process, and the signature of the Secretary of the Air Force is required. Approval could occur about one year from now. Air Force personnel at Edwards have suggested that the process of review and approval at the System Command level would be greatly facilitated by having the NSF as the site-use applicant.

2) Vacuum System

The use of low-hydrogen-content ($\lesssim 1$ ppm) steel for the vacuum system housing the interferometers would allow attaining the desired vacuum levels of $\sim 10^{-8}$ torr without high temperature bakeout, thus significantly reducing cost.

A Vacuum Test Facility (VTF) for the accurate measurement of the outgassing rate from low-hydrogen-content steel has been assembled. Leak checking, bake-out and initial instrumentation calibration of the Vacuum Test Facility were completed, and connections were established to the LIGO computing facilities for data logging and analysis. The four test chambers made from specially manufactured low-hydrogen steel were completed, and initial pumpdown to begin outgassing measurements will take place in early October.

The VTF will also be used for testing the performance of ion pumps and, eventually, for measuring the outgassing of interferometer and other components.

3) Conceptual Design

Efforts are continuing on the conceptual design of the LIGO which will consist of L-shaped interferometer systems with 4-kilometer arms at two cross-correlated sites.

Work has progressed in areas of vacuum-system pumping strategy, mechanical design of vacuum chambers to accommodate test masses, suspensions and ancillary interferometer components, structural design and layout of enclosures (buildings), and LIGO power requirements. These ideas are currently being documented for internal review. A LIGO Design Handbook has been started to serve as a vehicle for collecting, collating, and disseminating this information in a controlled, coherent fashion.

A concept for a real-time monitoring, control and data logging system for LIGO has been developed. It is based on a distributed system compatible with the Unix-based Sun computers being installed at Caltech and MIT. The design is intended to serve as a basis for the future instrumentation system on both the 5-meter and the 40-meter systems and to be a prototype for the LIGO.

Other conceptual design work included proposed vacuum tests to determine the outgassing rate of water in the LIGO, a study of laser power requirements and how they influence the LIGO electrical and cooling requirements and operating costs, and a study of outgassing of feedthroughs and wiring with application to the LIGO. Conceptual design work also proceeded on layout and design of vacuum tanks, seismic isolation and orientation-control systems.

An important continuing study is the design of baffles to reduce scattered light in the LIGO vacuum pipes. Simple geometric constraints have been formulated; more detailed calculations which include the diffraction and scattering by the baffles and tube walls are in progress. Several members of both science teams have now taken on the analytic estimation of the noise due to motion of the baffles. The problem has been bounded. There is agreement that for frequencies above 100 Hz and strain sensitivities of 10^{-21}, for beams traveling near the center of the 4 km tubes, baffle motion driven by ground noise will not compromise the interferometer performance.

C. Other Progress

A productive three-day LIGO project meeting (7/26–28/88) was held at MIT, involving all senior scientific and project staff. One-year work plans for both science teams were discussed and adopted, and critical science and engineering issues were discussed.

Computing facilities for the science and engineering groups have been installed at Caltech and are operational. Compatible computing equipment at MIT has been ordered and is expected to be operational by the end of October.

Plans for interferometric measurements of wavefront distortion due to optical inhomogeneity and birefringence in thick samples of fused quartz have been made with industry. The tests on samples, now being polished, are scheduled to be completed by February 1989. The data are required for the design of full-size mirrors for the LIGO and to determine the limits imposed by these imperfections on the contrast of the interferometer and the ability to recycle light.

An analytical method for combining the output from three separated interferometers, resulting in precise phase and sky-location information for burst sources, was devised by

Y. Gürsel and M. Tinto. This technique, which has been validated by extensive numerical simulations, is analogous to phase-closure in radio astronomy. It will produce much more accurate sky maps of gravity wave sources than previously suggested methods.

D. Personnel Changes

Assistant Professor Fred Raab joined the Caltech science group in July. Visiting Associate Y. T. Chen completed his appointment and returned to Cambridge, U.K. Michael Zucker joined the LIGO staff after completing his Ph.D. with a thesis: "Experiments with a Laser Interferometric Gravitational Wave Antenna."

The LIGO engineering group added to its staff Fred Assiri, a Civil/Structural Engineer. A Mechanical Engineer is expected to start work in early October; meanwhile, Julius Jodele, an independent contractor, has been assisting with mechanical design. With the Vacuum Engineer, Computing Analyst, and Subcontracts Manager added earlier, this will bring the engineering staff to the presently funded level of six persons.

2. PLANNED WORK

The planned activities described here are part of those given in our December 1987 proposal, "Caltech/MIT Project for a Laser Interferometer Gravitational Wave Observatory."

Work planned for the one-year grant continuation beginning December 1, 1988 includes research and development of gravity wave interferometers towards ever higher sensitivities and towards the design of operational full-scale LIGO interferometers. We will complete the conceptual design of the LIGO and submit a proposal to the NSF for construction of the LIGO.

A. Prototype Interferometers

1) Work Plan for the 40-meter Prototype.

a. Laser Stabilization/Sensitivity Improvement.
The continuing work on improving the laser stabilization and interferometer sensitivity of the 40-meter prototype will emphasize operation at higher power. The efficiency of the lasers and other elements in the optical chain will be improved, and lossy elements such as the optical fiber will be eliminated. The goal of this work is to achieve shot-noise limited performance at power into the interferometer on the order of one watt.

b. Mode Cleaner into Vacuum.
A significant source of phase noise in the current configuration is in the path between the mode cleaner output and the interferometer beamsplitter, which includes several mirror mounts exposed to acoustic excitation, an air path of over one meter, and an optical fiber. Housing the mode cleaner in the main vacuum system will eliminate this path and reduce noise associated with it.

c. Six-foot Tank.
The fitting out of a 1.8-meter tank as a replacement for the currently used .8-meter central chamber will be completed. Modifications include addition of flanges and the construction and installation of an internal structure to support seismic isolation systems, optical components, and test masses.

d. Separate Suspension of Beamsplitter Components.
The mechanical arrangement of the beamsplitter and other components in the central chamber, which are currently mounted on a common suspended block, will be altered by separately suspending these elements and eliminating the block. This will reduce vibration of these elements and thereby the associated noise.

e. Alignment Control Improvements.
New techniques for sensing mass orientation with optical levers, including improved optical arrangements for increased stability and dynamic range, improved electronics, and the use of modulated visible- light laser diodes, will be implemented.

f. Automatic Alignment System.
The system for maintaining alignment of optical cavities by sensing phase fronts of the resonant beams will be implemented, first on the mode cleaner and later on the 40-meter interferometer.

g. Anti-seismic Suspension Point Interferometer.
The development of the interferometer sensing the motion of the suspension points of the test masses will continue, including its operation in a servo system to reduce low-frequency motion of the masses.

h. Coherent Addition of Lasers.
The outputs from two Argon-ion lasers will be added coherently to test techniques proposed for the LIGO, and to double the power available for the prototype interferometer.

2) Work Plan for the 5-meter Prototype

a. Stationary Interferometer.
The stationary interferometer designed to demonstrate recombination of light from two Fabry-Perot cavities will be completed and tested. Recombination will be first demonstrated by using in-line optical phase modulators and then by placing the modulators in side arms so they are not exposed to the full power of the laser. The system will also be used to demonstrate recycling, the technique of making the entire interferometer into a cavity to increase the stored light and thereby the sensitivity.

b. Suspensions.
The nested double suspension system will be tested in vacuum to measure its isolation transfer function and vibration characteristics. Research on vacuum-compatible passive-isolation stages, including bellows-encapsulated rubber, will also be carried out.

c. 5-meter Prototype with Suspended Masses.
The stationary interferometer system will evolve into a prototype gravitational interferometer in stages. The mirrors and test masses will be suspended first, followed by suspension of the remaining optical components. New pointing controls and independently-suspended optical components, first developed on the 40-meter prototype, will be incorporated in the 5-meter system.

d. Optical Tests of Thick Fused Quartz.
Measurements of wavefront distortions due to optical inhomogeneity and birefringence of special quartz samples will be carried out with industry. This effort is part of a program to measure such optical properties as coating reflectivity and absorption, mirror figure, and scattering at small angles.

e. Instrumentation System.
An instrumentation system, which will be a forerunner of that required for the LIGO, will be developed jointly by the science and engineering groups and installed first in the 5-meter interferometer. The system will be used initially to monitor interferometer operation and eventually will become part of the active control of the interferometer.

B. Nd:YAG Laser Development

Development of an efficient and quiet light source for the LIGO based on Nd:YAG technology will continue. The two main parts of this work are; (1) development of a laser-diode-pumped oscillator to produce 1 to 5 watts of 1.06μ light, and (2) demonstration of frequency doubling using a slab laser pumped by discharge lamps.

C. LIGO Development

1) Conceptual design.
The conceptual design of the LIGO will be completed and will form the basis for a preliminary engineering design and cost definition. Key issues relating to the vacuum system, receiver-facility interfaces, and capability for multiple-use will be resolved (see the December 1987 proposal).

2) Sites.
Completion of environmental assessments, preliminary geotechnical work, and arrangements for site leasing or options to purchase will lead to a selection of two primary sites and designation of backup sites.

3) Vacuum Test Facility.
Tests to determine the outgassing of tubing made of low-hydrogen steel will be completed. Data from these tests will characterize the effects of surface preparation and cleaning techniques, bakeout procedures, and rates of outgassing as a function of time.

4) Preliminary Engineering Design and Cost Definition.
This effort focuses attention on the relatively expensive capital parts of the LIGO: vacuum chambers, tubes, valves, pumps and controls; buildings to house the vacuum chambers, tubes, and work areas; power supply and distribution; laser cooling equipment; supporting utilities; environmental monitoring; safety and security; communications and ancillary equipment; and access roads, erosion control, landscaping and related site development work.
The objective of the preliminary engineering design activity is to systematically conceive, evaluate and document the implementation aspects of the LIGO facilities to a level of detail sufficient for reliable cost estimates.

5) Construction Proposal.
We intend to submit a proposal for the construction of the LIGO in the fall of 1989. We will propose to enter into a contract with the NSF to provide all services and materials required to complete the engineering design, and to develop, construct, test, calibrate, and operate the LIGO facilities including the first interferometers. We will offer a plan to accommodate multiple users of the facilities from institutions other than Caltech and MIT. The construction proposal will include such technical, programmatic, cost, and supporting data as are required to permit an in-depth evaluation by the NSF.

3. RESIDUAL FUNDS STATEMENT

We anticipate no residual funds at the end of the current funding period.

4. PUBLICATION LIST

1. "LIGO Vacuum System Study," J. Livas and B. Moore, *15th Space Simulation Symposium*, November 1988.
2. "A Search for Gravitational Waves from Coalescing Binary Stars Using the Caltech 40 Meter Gravity Wave Detector," S. Smith, *Ph.D. Thesis*, Caltech, June 1988.
3. "Experiments with a Laser Interferometric Gravitational Wave Antenna," M. Zucker, *Ph.D. Thesis*, Caltech, July 1988.
4. "Developments in Laser Interferometer Gravity Wave Detectors," R. Drever, *Proceedings of the Fifth Marcel Grossmann Meeting, Perth*, August 1988.
5. "Astronomical Observations with Networks of Gravitational Wave Detectors. I: Mathematical Framework and Solution of the Five Detector Problem," M. Tinto (with S. V. Dhurandhar), *Mon. Not. R. astr. Soc.* (In press).
6. "Astronomical Observations with Networks of Gravitational Wave Detectors. II: Solution to the Four and the Three Detector Problem," M. Tinto (with S. V. Dhurandhar), *Mon. Not. R. astr. Soc.* (In press).
7. "Astronomical Observation with a Network of Detectors of Gravitational Waves," M. Tinto, *Proceedings of the Italian Workshop on Gravitational Wave Data Analysis, Amalfi*, 1988 (In press).
8. "Astronomical Observation with a Network of Three Wide-band Detectors of Gravitational Waves," M. Tinto, *Proceedings of the Italian Workshop on Gravitational Wave Data Analysis, Amalfi*, 1988 (In press).
9. "Gravitational Wave Astronomy: I. The Inverse Problem for Gravitational Wave Bursts," M. Tinto (with Y. Gürsel), *Proceedings of the Fifth Marcel Grossmann Meeting, Perth*, August 1988 (In press).
10. "Phase TV: Wavefront Analysis of an Optical Resonator," B. Lemoff, *SURF Paper*, Caltech, September 1988.