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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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 periods 15 June 1988 through 30 November 1988 and 1 December 1988 through 30 November 1989. 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 principal investigator and project director, R. Drever and R. Weiss are co-investigator members of the science teams at Caltech and MIT, respectively, W. Althouse heads the engineering team, and K. Thorne provides theoretical physics support as a co-investigator.

Continued funding is requested for the 1 December 1989 through 30 November 1990 period at a level of about $4.0 million, with the expectation that NSF will entertain a subsequent supplementary proposal of $0.2 million to support the project at the activity level of the April 1988 plan.

I. RECENT PROGRESS

This section covers progress since the last continuation proposal (October 1988) on prototype research and development and on planning for a Laser Interferometer Gravitational Wave Observatory (LIGO) by the Caltech and MIT science groups and the LIGO engineering team located at Caltech.

Areas of highest priority included: (1) conceptual design of LIGO, (2) interferometer prototypes, (3) preparation of the LIGO construction proposal.

A. LIGO Development

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

1. Sites

Louisiana State University (LSU) delivered a report on a preliminary seismic survey of a potential LIGO site in Louisiana. This work was carried out under the direction of Drs. 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 has been prepared.

A preliminary soil and geotechnical exploration of the LIGO site at Edwards Air Force Base, California, was carried out in October 1988, and the report of these studies was completed. A review of this preliminary 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.

A hydrology study and a biological survey of the Edwards site were completed in January 1989. The biological survey of one of the potential LIGO sites there was submitted to, and accepted by the Air Force. A preliminary archeological/paleontological survey (Phase 1) was submitted to and accepted by the California State Historical Preservation Office. This survey brings together existing records and surveys, and recommends additional survey work in several regions of "cultural significance," as defined by the National Historic Preservation Act of 1966.

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.

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 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.

2. Materials Testing

We have constructed a Vacuum Test Facility (VTF) and used the facility to evaluate outgassing properties of steel samples that are candidate materials for construction of the LIGO vacuum system. Data from the VTF have been used in conjunction with theoretical modelling to design the vacuum pumping strategy for LIGO. The VTF measurements were required because there was no adequate data base on the outgassing properties of steel subject to very-long-term vacuum exposure. VTF results indicate that at least one supplier can deliver 304L stainless steel with sufficiently low hydrogen content to achieve the requisite hydrogen outgassing rate without high-temperature bakeout. We have also identified adequate cleaning and other procedures (including low-temperature bakeout techniques for water vapor) to reduce all other contaminants to sufficiently low outgassing rates.

3. Conceptual Design

During the past year we have conducted an extensive conceptual design process for the LIGO facilities. The purpose of this effort was 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 studied the interactions between solutions to various technical problems and clarified certain design criteria which were previously ill-defined.

a. Identification of scientific functional requirements:

A major effort was conducted during the past year to specify and document the scientific functional requirements for the LIGO. This process required unification and rationalization of previous work done by the Caltech and MIT teams as well as formulation of requirements for many specifications which were not yet well defined. Over one hundred internal working papers and reviews were written covering the following broad topics:

- Site requirements.
- Vacuum studies.
- Noise source analysis.
- Interferometer design requirements.
- Environmental requirements.
- Auxiliary physical measurements.
- Data and control system requirements.
- Scientific requirements for operations.

b. Formulation of operations scenario:

In addition to scientific specifications, the scenario for how the LIGO will operate plays an important role in defining the facilities to be built. We have defined such a strategy and analyzed its implications for the design of the LIGO. We have decided to pursue a phased construction approach to deliver at the earliest date a system capable of discovering gravity waves and exploiting the initial discovery. The later phases of construction will enhance the scientific capabilities of LIGO and allow broader participation by others in the new field of gravity wave astronomy. We have identified the need for a simultaneous search and development capability, with minimum interference between these missions, as the optimum strategy to ensure successful LIGO operation. This has defined the need for three distinct detector units (observation, development, and special investigation detectors), and a flexible modular vacuum system capable of supporting simultaneous operation of multiple interferometers. Finally we have developed a plan for early use and later evolution of the LIGO facilities.

c. Development of vacuum system concept:

i. Beam tubes:

A concept for the LIGO beam tubes which specifies physical characteristics, environmental requirements, and construction implementation was developed. Two possible construction implementations for the tube have been evaluated:

smooth wall tubing with periodic reinforcement, and corrugated tubing. Construction and maintenance scenarios have been formulated.

ii. Vacuum chambers:

The LIGO concept requires a flexible vacuum system. We have conceptually defined four vacuum chamber types: test mass chambers types 1 and 2, diagonal chambers (which house the beamsplitter optics), and horizontal axis modules (for conditioning optics).

a) Test mass chambers:

The LIGO concept places strong demands on the test mass chambers (TMCs). These chambers house the critical test mass assemblies and Fabry-Perot cavity mirrors. These elements must receive the highest level of vibration isolation. The chambers need to accommodate different sizes of test masses and possible different configurations of test masses while allowing optical beams from other simultaneously operating interferometers to pass through the chambers unperturbed. Most importantly, some of the chambers (TMC, Type 1) must accommodate removal and installation of entire test mass assemblies for a given interferometer with minimal disturbance to the vacuum system and other interferometers. We have developed a solution which employs an airlock chamber design.

For those chambers located at the ends which may be opened without disturbing the remaining vacuum system and operating interferometers, a simpler and less expensive configuration, TMC Type 2, has been designed.

b) Diagonal chambers:

The diagonal chambers house the beamsplitter optics for the interferometers. While the diagonal chambers must accommodate vibration isolation systems similar to those employed in test mass chambers, a given diagonal chamber interfaces to only one detector. These chambers, therefore, do not require the complication of an airlock design.

c) Horizontal axis modules:

The conditioning optics chains at each interferometer input and output do not require the same degree of vibration isolation as test masses and beamsplitter optics. However, these optical chains have a high degree of complexity and will change more than other interferometer parts over the course of LIGO evolution. The corresponding vacuum chambers require the greatest degree of modularity, flexibility, and ease of access. We have developed a simple concept for these chambers in terms of modules which can be connected or stacked together in open-ended fashion. Removable endcaps on both sides of each chamber will allow convenient access to all internal components.

iii. Pumping and leak testing strategies:

We have developed strategies for pumping and leak testing the LIGO vacuum system. The pumping strategy involves specifying type, placement, and capacity of pumping stations, based on estimates of interferometer gas loads and vacuum system outgassing properties. The leak testing strategy for the beam tubes is based on pulsed exposure to He gas with recovery and compression in the pumping stations.

d. Interferometer conceptual design:

We have worked to develop a conceptual design for LIGO interferometers in general, to establish boundaries on the facilities which would be compatible with future evolution, and in particular have developed a more specific conceptual design for the initial LIGO interferometers. We have developed a vibration-isolation strategy which is based on stacks of metal spaced by encapsulated rubber springs, and which takes account of the level of isolation required for different classes of interferometer components. The design has an open-ended feature in that the primary isolation stacks rest on platforms which can be further isolated, if required, due to care taken in the design of the various vacuum chambers.

During the conceptual design of the input and output conditioning optics chains for the interferometers, we discovered that the level of complexity of this part of the facilities had been seriously underestimated in all previous planning for interferometric gravity wave detectors. In fact the requirements for conditioning optics drive key aspects of the facilities design and have significant impact on how the remote and campus facilities will be used in LIGO. The outcome of this work led to the requirement of a flexible modular envelope for the conditioning optics chains, using the horizontal axis modules described above.

e. Supporting equipment and facilities:

i. Laser power, cooling and electrical capacity:

We have developed a plan for allotting electrical power for the lasers, pumps, electronics and building functions. We have chosen to allot sufficient electrical capacity to operate one large-frame argon ion laser per interferometer in the facility. This power level will be sufficient to allow initial interferometers to be shot-noise limited at sensitivity levels adequate to conduct viable gravity wave searches. For advanced interferometers we anticipate the use of more powerful and efficient systems such as Nd:YAG lasers which are currently under development. Because such lasers should be more efficient by orders of magnitude than current ion lasers, the initial laser power capacity will be sufficient for operation of advanced interferometers. Power for lasers represents approximately half of the planned electrical capacity. The rest will be used for lighting, pumps, electronics and other building functions.

ii. Environmental specifications and auxiliary parameter monitors:

We have developed specifications for the laboratory environment required for LIGO and plans for implementation. This includes items such as power conditioning, temperature and air flow constraints, allowable mechanical noise, and drift and creep in structures. A significant problem which was identified is the cleanliness level of the lab environment. Measures were planned to ameliorate contamination of the optics and vacuum chambers. We have also formulated a plan for monitoring auxiliary physical parameters for the interferometers such as magnetic fields and line voltage, which will help to rule out spurious candidate gravity wave events.

iii. Interferometer/facility interfaces:

We have enumerated the mechanical, optical, and electrical interfaces between the interferometers and the facilities, and between separate site buildings. This work includes, for example, specifying the number and type of analog and digital signal lines which penetrate vacuum chambers, number and type of feedthroughs required, and possible levels of multiplexing.

iv. Data and control systems:

We have outlined the requirements for automated acquisition and logging of housekeeping data for the facilities, computer-assisted operation of control loops, and acquisition and logging of actual interferometer data. This includes enumeration of functions to be provided and estimation of signal bandwidths required.

v. Auxiliary and campus facilities:

We have identified auxiliary facilities to be provided at the LIGO sites and the campus facilities required to support LIGO operations. This has been done by developing scenarios for accomplishing various tasks associated with LIGO operations. For example, we have established procedures by which equipment is delivered to the sites, undergoes final assembly and testing, and is installed into the facility. From such scenarios we have identified what shop and storage facilities are required on site, and how quality and cleanliness controls are instituted. Similarly we have developed a concept of what type of tests, construction, etc., will be conducted at the LIGO sites, and which functions will be carried out on the campuses.

f. LIGO buildings and enclosures:

We have developed a conceptual design for buildings which will house the LIGO facilities and for an enclosure for the beam tubes. The building design seeks to provide an appropriate environment for LIGO activities while providing sufficient floor space and generality to accommodate future LIGO evolution. This need is especially important in the corner buildings at each site. The tube enclosure is required to reduce wind-induced motion of the beam tubes, thus making noise induced by scattered light inside the tubes a tractable problem. Simultaneously it provides a more temperature-stable environment and affords some protection from vandalism.

B. Prototype Activities

The best displacement sensitivity in the 40-meter prototype so far has been measured at 3×10^{-18} m/$\sqrt{\mathrm{Hz}}$. Assuming this sensitivity is primarily limited by displacement noise (random motion of test masses) and that LIGO interferometers would be dominated by the same noise source, a 4km baseline LIGO would exhibit a strain sensitivity of 8×10^{-22} /$\sqrt{\mathrm{Hz}}$, and would have a reasonable chance to discover gravity waves. However, this configuration of the 40-meter prototype could not be directly scaled up to an operating LIGO system. For instance, the frequency stabilization scheme was well suited for operation at low optical power levels but not at levels needed for the LIGO interferometers. Furthermore, the LIGO will require significant changes in the orientation and position control systems. During the current grant period we have emphasized the development of techniques which should not only lead to improved sensitivity in prototypes, but which can be directly scaled up to operating LIGO interferometers.

1. Development of a laser stabilization scheme consistent with LIGO power levels:

The Innova 100-20 large frame argon ion lasers at the 40-meter prototype have been tested at 7 watt single-mode output at 514 nm. The original stabilization scheme used an intracavity Pockels cell which required operation of the laser below 2 watt output power. In addition, an optical fiber used to inject light into the interferometer cavities, while providing reduction of fluctuations in laser beam geometry, severely limited the optical power that could be coupled into the interferometer.

We have constructed a new configuration for injecting light into the 40-meter interferometer. We have implemented a new two-stage frequency stabilization scheme. In the first stage, the laser is locked to a fixed length mode cleaning cavity. In the second stage, the phase of the light transmitted by this cavity is matched to one of the 40-meter cavities using a Pockels cell. We have extended the prototype's vacuum envelope to contain more of the conditioning optics, starting with the input mirror of the mode cleaner. This eliminates the optical fiber and any beam geometry perturbations caused by motion of the air path after the mode cleaner.

2. Development of the 5-meter facility:

Work began on the design of a 5-meter facility in 1986 and construction was completed near the beginning of the present grant period. The facility has 4 vacuum tanks. Three of the tanks are designed to house the 5-meter prototype. The fourth tank is configured to test suspensions. This tank is instrumented with an electromagnetic shaker to test vibration isolation of sample suspensions under vacuum.

At present, the central tank is dedicated to research on optical concepts in a stationary interferometer and the suspension tank is being used to carry out tests of a prototype suspension. The facility is adequate in scale to develop and test selected LIGO optical and suspension subsystems during the next 4 years.

3. Development of recombination techniques in a stationary interferometer:

Work was begun on a stationary (not suspended) interferometer to test an interferometer configuration in which the beams reflected by the Fabry-Perot cavities are recombined. Beam recombination is required in any LIGO interferometer using high optical power or recycling. Because the components of the stationary interferometer are held in standard mounts on an optical table, seismic, acoustic and thermal noise are not attenuated; consequently the interferometer can approach theoretical shot-noise limits only at frequencies $\gtrsim 10$ kHz. This frequency range is useful for testing optical concepts and for developing the servo systems and electronics. The interferometer is assembled on an optical table inside the central tank of the 5-meter facility.

The system is being used to study different servo-control concepts of holding the interferometer in lock and to test two different techniques of applying RF modulation to the light. The stationary interferometer will also be used to develop a recombination system in which the phase modulators are placed in sidearms to reduce the optical power in the Pockels cells, much as is planned for the initial LIGO interferometer. Finally, the system will be used to test broad-band recycling by adding a recycling mirror and associated phase control servos.

4. Development of orientation and position control systems suitable for very long baseline interferometers:

The position and orientation of many optical components must be controlled precisely for interferometer operation. The elements requiring the most critical control and adjustment are the test masses that bear the main interferometer mirrors. During the current grant period we have designed, constructed, and tested new control subsystems which are suitable for LIGO scale applications:

a. Prototype work on a more sensitive orientation and position control system:

We have designed and tested a new position and orientation control system, suitable for controlling test masses and other suspended components. This compact self-contained system uses shadow sensing and electromagnetic feedback local to the suspended component being controlled. The design allows for simultaneous control of up to six degrees of freedom per component.

b. Development of a new diagnostic tool for detecting errors in coupling light into cavities:

A new device, called a phase camera, has been developed to diagnose errors in mode matching an input laser beam to a Fabry-Perot cavity. The device produces three-dimensional images of the phase difference between the input beam and the cavity. It can be installed in front of any of the cavities in the system.

5. Optics research and development:

a. Investigation of heating effects in mirrors:

Advanced LIGO interferometers will have very high light levels in the Fabry-Perot cavities. During the current grant period we have investigated the power handling capability of fused silica supermirrors coated by Litton Guidance and Control Division. We have measured the throughput of high-finesse-transmission Fabry-Perot cavities of different length, mirror spot size, and ratio of length to mirror radius. In these preliminary studies we found that most of the cavities exhibited a saturation phenomenon when the power stored in the cavity exceeded approximately 1 kW. In the saturation regime, the throughput efficiency decreased and the output mode distorted. We have developed a model which attributes these effects to thermal lensing in the input mirror substrate. This model predicts that these thermal distortion effects will persist even in very long baseline cavities as are planned for LIGO.

We plan to institute a systematic research program to characterize the thermal distortion effects in cavities and to develop better mirrors in a cooperative effort with industry.

b. Developments toward improving optics test and characterization capabilities:

We are currently planning to expand our capabilities to test and analyze optical components. Recent activities include:

i. Investigation of radiometric mapping to determine temperature profiles of mirrors:

An infrared camera was used to make a radiometric image (using 10μ radiation) of the heating of a mirror coating by the absorption of laser light. The test showed that surface temperature increments as small as 0.1°K could be measured by this technique. This method promises to be useful for experimental studies of thermal distortion in optical components.

ii. Preliminary tests of homogeneity and birefringence on large, fused-silica substrates:

The LIGO mirrors will require a high degree of optical homogeneity and low birefringence in blanks which are much larger than those currently in prototype use. We have obtained slow–annealed fused silica blanks comparable in size to LIGO mirrors. These were ground flat to $\lambda/50$ and tested under our supervision at Zygo Corp. We collaborated on a modification to Zygo's phase mapping interferometer which allowed us to measure both homogeneity and birefringence of these thick substrates over a large aperture. The Zygo measurements are now being analyzed in part to determine the expected performance of thick substrates in a recycled interferometer.

iii. Development of improved experimental and analytical tools for scattering characterization:

The scattering angular distribution function for small angles is a key variable in estimating the noise due to scattered light in the LIGO. We have developed an apparatus which uses an optical fiber to map the scattered field in the region around the focal point of the mirror.

A substantial amount of analytic work was done to evaluate the effect of scattering in the LIGO beam tubes. The results of this analysis now form the basis for the design and placement of baffles.

6. Studies of vibration isolation and thermal noise:

a. Vibration isolation studies:

Research has continued on the development of a double suspension system in which the mirror is suspended from another object, the guard mass, which in turn is also suspended. This system should provide improved seismic isolation at frequencies below a few hundred Hz.

b. Thermal noise characterization:

Thermal noise in suspensions could limit the performance of high sensitivity interferometric gravitational wave detectors in the region of about 100 Hz. A new effort was begun to measure the internal dissipation of candidate suspension fiber materials in flexure at frequencies between a few hertz to several hundred hertz. The experiment in progress measures the Q, in vacuum, of the flexural resonances of suspension fibers clamped at one end. Once a short catalog of material Q has been established, the experiment will be used to measure the scaling of the loss with fiber dimensions.

C. Construction Proposal

Most of the work described in the preceding pages for this grant period was done in preparation for the LIGO construction proposal. This work has led to a design concept that serves as basis for an engineering design and cost estimate. A major effort on preparation of the construction proposal was started in May 1989.

Although a significant reduction in scope of the LIGO configuration occurred in July as a result of discussions with the NSF, most of the proposal has now (September 1989) been written 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.

D. Other Progress

In November we began a series of monthly Project Status Review meetings. The purpose of these meetings was 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.

A Sun 4/260 and 4/110 distributed computer system was installed and brought on line at MIT. The system is the same as that previously installed at Caltech and enhances as well as unifies the computing environment across the LIGO project. The system now has common software for engineering and scientific analysis at both locations.

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. 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.

An NSF/LIGO meeting was held at Caltech on April 10 and 11, 1989. LIGO design concepts, preliminary cost estimates, and management aspects were discussed.

E. International Cooperation

R. Vogt participated in a February 14, 1989 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.

As agreed at the Paris workshop, LIGO personnel have taken on the coordination of two international working groups: vacuum systems and control systems. The LIGO team also has assigned members to all other working groups coordinated by European scientists.

Full engineering and science briefings on the LIGO project were given, over the period of several days, to Drs. Hough and Leuchs, the respective leaders of the British and German gravity wave research groups. Similar courtesies were extended to Dr. Blair, who is organizing a new laser interferometer program in Australia.

Information on engineering advances also is being provided to Britain's Rutherford Laboratory on a continuing basis.

F. Personnel Changes

Jeffrey C. Livas, who was a member of the MIT science group, left the project in December 1988. Paul Linsay, who was half time on the LIGO project at MIT, left the project as planned. Richard Benford, who provided engineering and technical support to the MIT LIGO effort, left the project in Summer 1989.

The LIGO engineering group in October 1988 added Larry K. Jones to its staff as Mechanical Engineer. David Shoemaker joined the LIGO science group at MIT in September 1989.

II. PLANNED WORK

The planned activities described here are part of those presented 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, 1989 includes: (1) more detailed and more complete preliminary engineering design of LIGO facilities in anticipation of approval of the construction proposal; (2) research and development of prototype interferometers towards more reliable operation, higher sensitivities, and towards the design of full-scale LIGO interferometers; (3) the establishment of an optics testing facility; and (4) scientific and technical collaboration in the development of more efficient lasers.

A. LIGO Development

1. Conceptual Design:

The conceptual design of the LIGO will be reviewed, enhanced in depth, and supplemented where necessary. In particular, we will initiate further and detailed conceptual design work of LIGO interferometers and the LIGO data and control system. Additional work on buildings, vacuum systems, and beam tubes should result in increased definition and further cost tradeoffs.

2. Sites:

As soon as the NSF gives approval (presumably not before LIGO has been officially included in the FY'91 budget submitted to Congress), open discussions will be initiated with the owners of potential LIGO sites at the West and East Coasts in order to explore the possibilities for leasing or options to buy, and to secure permission to conduct the geotechnical and environmental work necessary for final selection.

3. Vacuum Test Facility:

Studies of the vacuum properties of materials slated for LIGO, of techniques to be used in LIGO, and of model setups of critical LIGO systems will be continued.

4. Preparations for Procurement of LIGO Engineering and Construction Contracts:

Preparations of materials (Requests for Proposal, etc.) necessary for the selection of industrial contractors for engineering, design, and construction of the LIGO facilities will begin as soon as approval of the LIGO construction proposal becomes highly probable. This advance preparation is necessary in order to assure that contractor selection and start of work can occur expeditiously as soon as construction funds become available.

B. Prototype Interferometers

1. 40-meter Prototype:

a. Servo system upgrades:

The current servo loops for stabilization of the laser using the mode cleaner and for phase correction of the light before it enters the main 40-meter cavities are the result of ad hoc evolution from previous schemes. We intend a comprehensive redesign and reconstruction of servo electronics and transducers to improve reliability stability and perhaps noise.

b. PZT mode cleaner:

We plan to install a modified mode cleaner with PZT driven mirrors to test for non-linear effects associated with the forces now applied to the test masses in the 40-meter cavities. This arrangement permits applying frequency correction to the mode cleaning cavity, as an alternative to applying common mode forces to the test masses. This step should also reduce the phase noise on the light entering the 40-meter cavities, thereby relaxing the requirements on linearity of the optical and electromechanical response of the interferometer.

c. Separately suspended mode cleaner:

We plan to install a 12-meter long input mode cleaner with separately suspended mirrors. This should further reduce frequency noise on the light entering the interferometer, because the deleterious effects of resonances can be reduced by the use of separate suspensions, and the cavity can be made longer than is feasible with mirrors on a spacer. Because we also plan the use of long suspended mass mode cleaners in the LIGO for other reasons, it is desirable to study their behavior in the prototype rather than develop the required interferometer phase sensitivity without them.

d. Separate suspension of beamsplitter components:

We believe that the low frequency behavior of the prototype is limited by resonances in the current composite beamsplitter mass. We intend to suspend the beamsplitter components separately to verify that this is indeed the cause of our current low frequency noise and to enable future work toward understanding the low frequency spectrum of the interferometer. This work will also test candidate position and orientation controls for the LIGO beamsplitters. This effort will result in direct replacement of optical functions in an envelope which will support later modifications to enable beam recombination.

e. Improved test masses and controls:

The initial LIGO interferometer design calls for monolithic test masses with control of 6 degrees of freedom whereas the 40-meter prototype uses optically contacted composite test masses with control of only 3 degrees of freedom. In particular, transverse mirror motion and possible noise generated in the optically contacted joint are potential noise sources in the prototype that are irrelevant to the initial LIGO interferometer.

We propose to install monolithic test masses in the 40-meter prototype with the 5-degree-of-freedom controllers developed for the suspended beamsplitter optics.

f. Beam recombination:

We now plan to recombine the beams in the 40-meter prototype as the next logical step toward reconfiguring the prototype in a LIGO configuration. We expect this step to increase the sensitivity of the prototype by improving cancellation of common mode noise, and to allow higher power operation with the later installation of low loss optics and eventual implementation of broadband recycling. We do not expect to complete this step during the next twelve months but we anticipate that preparation may start during this time. The scheme to be implemented will be determined by the results of the 5-meter recombination effort.

2. 5-meter Prototype:

a. Stationary interferometer:

Upon completion of current activities we will be converting the stationary interferometer from a system with inline phase modulators to one using sidearm modulators of the type being planned for the LIGO. This step requires two additional servo systems to control the position of the side arms, servo control of the cavity length and the location of the input mirror of one of the cavities to maintain the interferometer on a dark fringe at the antisymmetric port while simultaneously establishing the resonance condition in the Fabry-Perot cavity. The system with sidearm modulators will first be used with existing low quality mirrors and then be converted to a recycling system with superpolished mirrors having low losses.

The mirrors and coatings to be used in the recycling demonstration will be tested and qualified for scattering, loss and wavefront distortion before use. The recycling demonstration will, for the first time, set limits on the losses in superpolished mirrors with high (3%) transmission coatings of the type being contemplated for the LIGO. The coatings cannot easily be characterized in the existing ring-down apparatus.

b. Suspended interferometer:

When the recycling experiment has come to a satisfactory conclusion, the stationary interferometer will be converted by stages to a suspended interferometer. Initially only the 5-meter Fabry-Perot cavity mirrors will be suspended with minimal changes in the rest of the interferometer except for the mode-matching optics. This will require the installation of new suspension and beam pointing systems. We will incorporate the auto-alignment system developed for the 40-meter system on the 5-meter cavities at this step.

c. Development of an instrumentation system for the prototypes:

An instrumentation system, which will incorporate some of the requirements of the LIGO, will be developed jointly by members of the LIGO research and engineering groups. The system will initially be installed on the 5-meter facility and grow in capability by stages. The initial function is to monitor the state of the prototype by displaying such parameters as the position and orientation of the masses, the servo signals in the optical control loops, and other signals needed to diagnose the operation of the system. It will also be configured to accept data from diagnostic instruments such as special-purpose spectrum and network analyzers and in effect become an archive for prototype performance. In later stages the system will become part of the active control of the interferometer. During the proposed grant period we expect to accomplish only the initial function of state monitoring and data archiving.

d. Suspension research:

The proposed vibration isolation system in the LIGO uses a bellows-encapsulated elastomer concept. A model of one element of such a system will be tested in the suspension test tank of the 5-meter prototype during the grant period.

3. Other Laboratory Work

Optics Test Program:

The project intends to develop facilities for the qualification of optical components used in the prototypes and the LIGO but not to duplicate the capabilities available in industry unless it is economically advantageous to do so. The areas of most concern for the LIGO project are absorption, total and small angle scattering, and scalar and vector wavefront distortion. Measurements will be divided between facilities at Caltech and MIT.

At MIT there is experience in measuring small angle scattering and in the visualization of absorption by infrared thermal mapping. A small angle scatterometer in vacuum is being designed and will be assembled to measure scattering from both plane and curved surfaces.

At Caltech, apparatus used for routine ringdown testing of mirrors and substrates already exists. We plan to upgrade the current power test apparatus in the 40-meter lab by the addition of additional vacuum tanks, which will allow expanded test capabilities, and the addition of new optics to allow the use of the backup large frame laser for power tests without interfering with the 40-meter laser system.

We plan to test our current stock of Litton mirrors and to evaluate mirrors from two alternate sources (PMS and Ojai). This will include measurements (such as outside scatterometry evaluations) to diagnose failures in coated mirrors. We plan to measure the power absorbed by mirrors in the thermal saturation regime by thermometry, and a similar evaluation of the bulk absorption of various substrate materials.

C. Nd:YAG 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.

III. RESIDUAL FUNDS STATEMENT

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

IV. PUBLICATION LIST

1. "Measuring High Mechanical Quality Factors of Bodies Made of Bare Insulating Materials," A. Čadež and A. Abramovici, *J. Phys. E: Scientific Instruments*, **21**, 453, 1988.
2. "Development of a Multi-dimensional Optimization Servo for Gravity Wave Detector Mirror Alignment," B. Lemoff, *Senior Thesis*, Caltech, May 1989.
3. "A Near Optimal Solution to the Inverse Problem for Gravitational Wave Bursts," Y. Gürsel and M. Tinto, LIGO Preprint 89-1, *submitted to Physical Review D*, June 1989.
4. "Frequency Fluctuations of a Diode-pumped Nd:YAG Ring Laser," P. Fritschel, A. Jeffries, T. Kane, *Optics Letters*, accepted for publication, 1989.
5. Conference Papers, 12th International Conference on General Relativity and Gravitation, Boulder, Colorado, 1989.
    - i. "Tests of Recombination Schemes in a Fixed Arm Fabry-Perot Laser Interferometer," N. Christensen, P. Fritschel, J. Giaime.
    - ii. "Developments in Interferometric Gravity Wave Detectors for Large Scale Operation," R.W.P. Drever.
    - iii. "The Performance of a Double Pendulum Vibration Isolation System," J. Kovalik, P. Saulson, M. Stephens.
    - iv. "Observation and Analysis of a Mirror Heating Threshold in Fabry-Perot Cavities," F. J. Raab.
    - v. "Thermal Noise in Suspensions for Interferometric Gravitational Wave Antennas," P. Saulson.
    - vi. "Status Report on the Caltech 40-meter Fabry-Perot Prototype Gravitational Wave Detector," R. Spero.
    - vii. "The LIGO Project—A Progress Report," R. Vogt.
    - viii. "Laser Interferometer Detectors," R. Weiss.