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Renewal Proposal to the National Science Foundation for a five-year grant:

INVESTIGATIONS IN EXPERIMENTAL GRAVITY AND GRAVITATIONAL RADIATION

submitted by the California Institute of Technology

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PROJECT SUMMARY

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RECTORATE/DIVISION	PROGRAM OR SECTION	PROPOSAL NO.	F.Y.

AME OF INSTITUTION (INCLUDE BRANCH/CAMPUS AND SCHOOL OR DIVISION)

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INVESTIGATIONS IN EXPERIMENTAL GRAVITY AND GRAVITATIONAL RADIATION

CHNICAL ABSTRACT (LIMIT TO 22 PICA OR 18 ELITE TYPEWRITTEN LINES)

The continuing Caltech program for development and use of gravitational wave detection techniques using laser interferometers, aimed at the observation and study of gravitational radiation from astronomical sources, forms the main part of this research. Detection of the radiation will both give a test of predictions of general relativity, and provide a new tool in physics and astronomy. Performance already achieved with the Caltech 40-meter interferometric gravitational wave detector together with new ideas from this research indicate that instruments with arm lengths of order 5 km should have the sensitivity required for detection of expected signals from various sources. Detection facilities capable of accommodating interferometers on this scale are being designed as a related joint project of Caltech and MIT, for use in future joint and independent experiments.

Further development and testing of relevant techniques will be carried out partly with the existing 40 m apparatus at Caltech and with enhancements of it to permit use of higher light powers and larger optics and test masses. Searches for gravitational radiation will be performed at increasing levels of sensitivity, initially with interferometers in the 40 m system and later in the 5 km scale facilities.

1. INTRODUCTION

The research program which forms the subject of this Renewal Proposal is the next phase in an ongoing research effort which began at Caltech with the formation in 1979 of a group to carry out experimental work in Gravitational Physics, and with the first Proposal in January of that year for an NSF grant for this work. Our main effort has been directed towards the development of practical techniques for detection and study of gravitational radiation, with the objective of observing gravitational radiation from astrophysical sources and opening a new field in physics and astronomy. We have concentrated on laser interferometer detection techniques based on use of optical cavities, techniques devised in earlier work[1] with the aim of achieving maximum possible sensitivity at relatively low cost. This has led to the successful construction and operation at Caltech of an interferometric gravitational wave detector with arms 40 meters long - currently the world's largest - with a sensitivity better than that of the best of the room-temperature resonant bar detectors along with a bandwidth three orders of magnitude greater. Extension of these techniques alone to an instrument with arms 5 kilometers long is expected to yield an energy sensitivity for gravity wave pulses at least two orders of magnitude better than any experiment to date.

Our research program has also led in the last few years to a number of quite new ideas which give possibilities for further major improvements in the sensitivity and versatility of these instruments, making it practicable now to design a large scale detector system which may have a reasonable chance of detecting expected gravitational wave fluxes from a variety of different types of sources.

The present Proposal requests a grant for continuation and extension of this research program over a period in which we plan to advance from our laboratory prototypes to multi-kilometer-scale instruments of sensitivity designed to overlap expected signal strengths, and capable of a range of parallel investigations of gravitational radiation of various types.

Along with this Renewal Proposal, we are submitting with a group from the Massachusetts Institute of Technology a Joint Proposal for a grant to support a design study for the major facilities to house 5-kilometer-scale laser interferometer gravitational radiation detection systems, to be followed subsequently by a Joint Proposal for construction of facilities of this type and for their use in various investigations.

Research on laser interferometer techniques for gravitational wave detection has been going on for many years at the Massachusetts Institute of Technology. Although based on the same fundamental principles as our own work, the research there has concentrated on slightly different experimental techniques, using optical delay lines instead of low-loss cavities, with laboratory experiments on an interferometer with arms 1.5 meters long. There are economic and scientific advantages in designing large scale facilities compatible with the experimental techniques being developed by both groups, and we plan to design and construct the facilities with the MIT group. We plan also to jointly construct with them a detection system in the facilities, to carry out a joint search for gravitational wave bursts as indicated in the accompanying Joint Proposal, and to use the facilities in most of our future investigations on gravitational radiation and possibly in other experiments.

The current Caltech gravitational wave detector has now demonstrated successful operation at the 40 meter scale of many of the basic experimental techniques which we expect to use in the larger instruments, but achieving still further improvements in sensitivity, range of frequency covered, and other parameters will be a major objective of our research program. Our overall plan has four main components:- continuing development and testing of detection techniques with the 40 m interferometer; performance of gravitational wave searches with this instrument whenever significant improvements in sensitivity have been achieved; development of techniques, construction of detection equipment, and design of facilities for the large-scale experiments; and performance of gravitational wave searches and experiments with the large scale facilities, both jointly with the MIT group and separately. Our experiments will cover the widest possible range of signal types and frequencies as rapidly and sensitively as practicable. Our plans are outlined in more detail later in this Proposal.

In addition to our own work we plan a close collaboration with the group at MIT as indicated in our Joint Proposal. We also plan a continuing and extending collaboration with other experimental groups in this field, and in particular with the group working at the University of Glasgow where many of the techniques we are developing originated and are being actively developed, and also with the group at the Max Planck Institute, Garching and the new group at the CNRS, Orsay. We also plan to exchange data and collaborate with groups operating resonant-bar gravitational wave detectors.

If our research proceeds according to plan, there may be a real possibility of detection of gravitational waves during the period of this Proposal. This might appear in some sense as a culmination of our earlier work over many years, but we would regard it rather as an opening of a much wider research field. At that stage we would plan more extensive investigations both to further study the radiation itself, and to use it as a new tool for application in physics and astronomy.

2. THE SCIENTIFIC CASE

The scientific justification for the research described in this proposal is, of course, the gravity-wave experiments and observations that will be possible when the detectors become sensitive enough to detect waves from astrophysical sources. It is reasonable to expect that those experiments and observations will:

(1). open up a new window onto the universe through which will come information qualitatively different from that carried by electromagnetic waves;

(2). produce totally unexpected discoveries about the universe, in much the same way as radio astronomy did; and

(3). test fundamental laws of physics that have never been tested before.

For a detailed discussion of these possibilities see Section 2.4 of the joint Caltech-MIT proposal.

A crucial aspect of the scientific justification is the expectation that the proposed research program will produce, on a reasonable timescale, detector sensitivities in the range where theory suggests that real astrophysical sources lie. Indeed, variants of the detector we are developing -- variants now on the drawing boards but not yet ready for construction -- have projected sensitivities well within the range of anticipated sources. For details see Section 2 of the accompanying Joint Caltech-MIT proposal.

Another aspect of the discussion of sources in the joint proposal which should be emphasized is the diversity of possible sources. Many types of sources and waveforms are potentially detectable, and no single type stands out as <u>the</u> source to look for. In such a situation, the experimental program should retain the maximum flexibility and should cover as wide a range of possibilities as available resources allow.

3. CURRENT STATE OF DEVELOPMENT OF LASER INTERFEROMETER TECHNIQUES FOR GRAVITATIONAL WAVE DETECTION

3.1. Preface: Introduction and Work of Other Groups

As a background to this proposal, we will briefly review the status of the four main research groups, other than our own, actively working on interferometric gravitational wave detectors.(A fifth group is reported to have formed in the Soviet Union, but we know few details of their work - see section 3.6 of the joint proposal).

It may be helpful, however, to first briefly introduce the ideas behind the two main types of laser interferometer currently being used in this work. In all of these instruments, the intention is to observe the gravitational radiation by sensing the differential changes in the separations of pairs of free test masses forming two baselines at right angles to one another, using an optical interferometer. Simple Michelson interferometers are not sensitive enough for this purpose due to the photon shot noise at practical light levels, but significant improvements can be obtained by causing the light in each arm to traverse the distance between the masses many times, until the light travel time approaches the gravity-wave period. This may be done by use of an optical delay line, in which a light beam undergoes many reflections between a pair of near-confocal mirrors, giving a circular pattern of discrete reflection spots on each mirror; or by use of a Fabry-Perot cavity in which the light beam repeatedly traverses the same path between a pair of mirrors, with the round trip distance arranged to be an integral number of wavelengths, giving resonant buildup of light intensity. In either case, optical phase shifts in the output light may be observed by recombining the beams; or with the Fabry-Perot system phase shifts between output light from each cavity and its input may be measured separately and subtracted from one another.

These two optical systems have in principle comparable sensitivity and performance, and their relative advantages are practical rather than fundamental. Neither system is new, but in its current application and configuration the delay line Michelson interferometer technique was conceived at MIT and has been developed there and at the Max Planck Institute, Garching; and the Fabry-Perot interferometer technique was conceived at Glasgow University and has been developed there and at Caltech. The main effort in developing either system has gone into overcoming the many experimental difficulties of achieving the extreme sensitivities required, but good, and essentially equal, performance has currently been reached with a multireflection Michelson interferometer at Garching and a Fabry-Perot interferometer at Caltech. Differences between the two techniques which may be important will be discussed later in this proposal.

In beginning our review of groups working in the field we may note that in general each has emphasized different aspects of the research, depending on interest, expertise, resources, and differing conceptions about how the experiments might be carried out. (Further details of the various prototype antennas may be found in the accompanying joint proposal.)

The MIT group, with whom we are submitting the companion proposal, has built a prototype detector with 1.5 meter arms using a Michelson interferometer with Herriott delay lines[2]. The delay line has 56 bounces. Light is injected into the interferometer via a single mode optical fiber to reduce the fluctuations in the laser beam size and direction. The interferometer employs a random phase modulation technique for reducing the effects of scattered light--an extension of a periodic phase modulation technique used earlier by the Max Planck group. The laser light is passed through a Pockels cell which is driven by wide band noise to reduce the temporal coherence of the light. Since scattered light travels a different distance before striking the photodetector, it will be incoherent with the main beam and will not produce excess noise. The MIT interferometer has achieved shot noise limited performance ($\sim 3 \times 10^{-17}$ m Hz$^{-1/2}$ for their present configuration) above ~ 3 kHz.

The prototype antenna at Glasgow[3-6] is the one which bears the greatest similarity to the Caltech antenna. It uses two pairs of suspended test masses carrying high reflectivity mirrors which define the ends of two perpendicular 10 meter long optical cavities. The major differences between the Glasgow and Caltech antenna are that the Glasgow detector at present, has lower finesse cavities (200 vs. 15,000) and that the Glasgow detector has provisions to use a "mode cleaner" (similar to that first used by the Munich group) and to recombine the reflected light from the two cavities. This detector has reached a sensitivity[7] of 1.5×10^{-16}m Hz$^{-1/2}$ above 500 Hz. This is the shot-noise limit for the low power (<1mW) and low finesse cavities currently used.

The group at the Max Planck Institute (Garching) was the first to achieve a displacement sensitivity in the 10^{-17}m Hz$^{-1/2}$ region. Their laboratory work began with a 3 meter instrument, shifting more recently to a 30 meter instrument[8]. The MPI detector uses a Michelson interferometer with optical delay lines giving from 50 to 150 transits in each arm. Instead of the reduced coherence scheme adopted by MIT, the current MPI detector uses a highly stabilized laser to reduce the effects of scattered light. In earlier work a periodic phase modulation method was used in addition. Beam size and direction are stabilized by passing the laser light through an in-line optical cavity ("mode cleaner") or through a single-mode optical fiber. The MPI detector was the first to use four separate test masses to define the ends of the two arms and a fifth suspended mass to hold the beamsplitter and associated optics--an arrangement suggested from Caltech[9]; in fact the masses which define the arms are nothing more than the delay line mirrors themselves. This has the effect of raising the internal vibrational mode frequencies and consequently lowering the thermal noise due to these modes. With 50 mW of laser power and 50 transits in each arm of the 30 meter detector, this instrument has given[10] shot noise limited performance ($\approx 2 \times 10^{-17}$m $Hz^{-1/2}$) from 500-2500 Hz.

The group at CNRS, Orsay is the newest, having started work on gravitational wave detection approximately one year ago. They are planning a prototype with arm lengths in region of 10 meters. Their laboratory work to date has concentrated on producing higher power from frequency stabilized lasers. They have already produced over 1 watt from a stabilized argon laser[11].

3.2 Recent Experimental Work at Caltech

(a) HISTORY AND DESCRIPTION OF THE PRESENT DETECTOR

The gravitational physics group has been engaged in the development of laser gravity wave detectors since laboratory work started early in 1980. The first 2½ years were devoted to preparatory research and construction. During that period, fast laser stabilization techniques[3] were developed, a 10-meter long Fabry-Perot test bed was built and used to compare optical schemes for measuring small displacements,[4] and mass suspension systems were designed and built. Concurrently, a building to house the present 40-meter detector was erected, and the vacuum system was designed, constructed, and assembled. These efforts converged in June of 1982 with the first operation of the Caltech gravity wave detector.[5,12,13]

Performance improved steadily over the next two years. Figure 3.1 shows the rapid improvement in detector noise level. The four noise spectra plotted are from May 1983, January 1984, May 1984, and September 1984. Performance gains have come from continuing refinements in the mechanical, optical, and

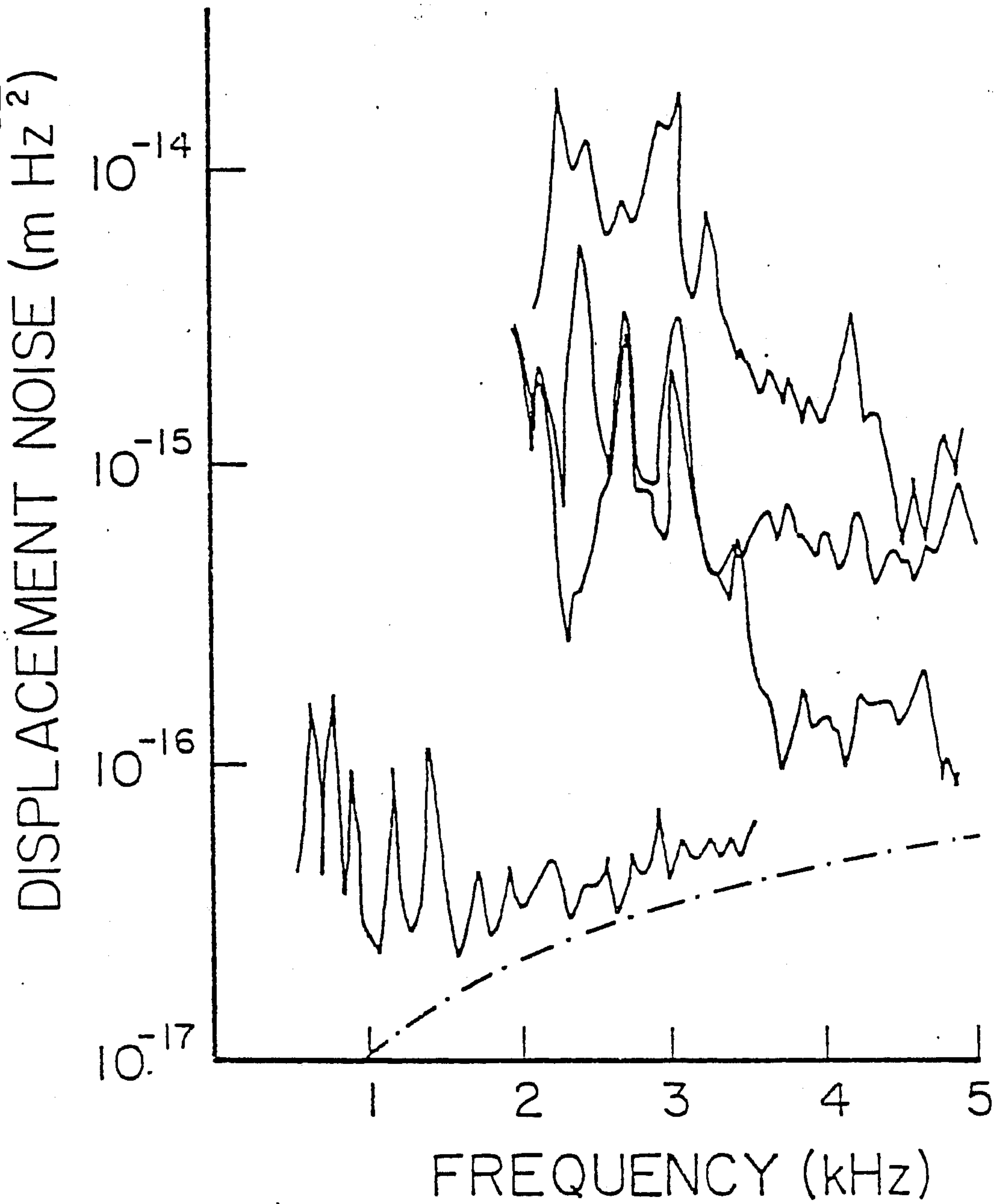


Figure 3.1 Sequence of noise spectra showing improvement with time. The top spectrum was taken in May 1983. The second spectrum (January 1984) was taken after improvements to the laser stabilization servoloop. The next spectrum (May 1984) shows the improvements due to replacing the initial cavity mirrors with extremely low loss mirrors. The final spectrum (September 1984) is the result of the new low-noise test masses. The dashed line represents the shot noise for the most recent configuration. Some of the spectra were only calibrated over a limited range of frequencies and are truncated accordingly. At the frequency resolution shown the lowest spectrum (September 1984) is contaminated by unresolved peaks at harmonics of the line frequency which raise the baseline. A higher resolution version of this spectrum reveals that, when the peaks are resolved, the baseline is close to the shot noise level (see Figure 3.6).

electronic systems. Sensitivity continues to improve at a rate faster than one order of magnitude of displacement sensitivity per year; at least two more orders of magnitude of improvement are possible before the 40-meter detector approaches its maximum sensitivity. To go much beyond this level would require very high laser power, heavy high-Q masses to reduce the quantum limit and thermal noise, and high-Q suspensions as well as ultra-high vacuum to minimize the noise due to Brownian motion of the suspended masses.

The present Caltech antenna (Figure 3.2) consists of two similar 40-meter long Fabry-Perot cavities arranged in an L. The cavity mirrors are affixed to 10 kg masses suspended by wires; the masses are free to respond to impulses fast compared to the pendulum period of one-second. Light from an argon ion laser of wavelength 514 nm enters the antenna at the corner of the L, where it is split between the two cavities. An incident gravity wave changes the length of the two arms differently, and alters the optical phase difference between the two cavities. The phase difference as monitored by photodetectors is proportional to the gravity wave signal.

The corner vacuum chamber houses three separately suspended masses—a large aluminum disc and two identical compact brass cylinders, horizontally suspended and capped with planar high-reflectivity mirrors. The disc is centered in the vacuum chamber and supports a beam splitter and assorted steering optics, including beam-splitting polarizers and quarter-wave plates to deflect the cavity light into photodetectors. Vacuum chambers at the ends of the L each house one mirror-bearing mass similar to the corner masses. The end mirror surfaces are ground to a curvature radius of 62-meters and coated for the highest reflectivity that available technology can produce. Piezoelectric transducers between the mirrors and masses are used to fine tune the cavity length and to calibrate the gravity wave detector.

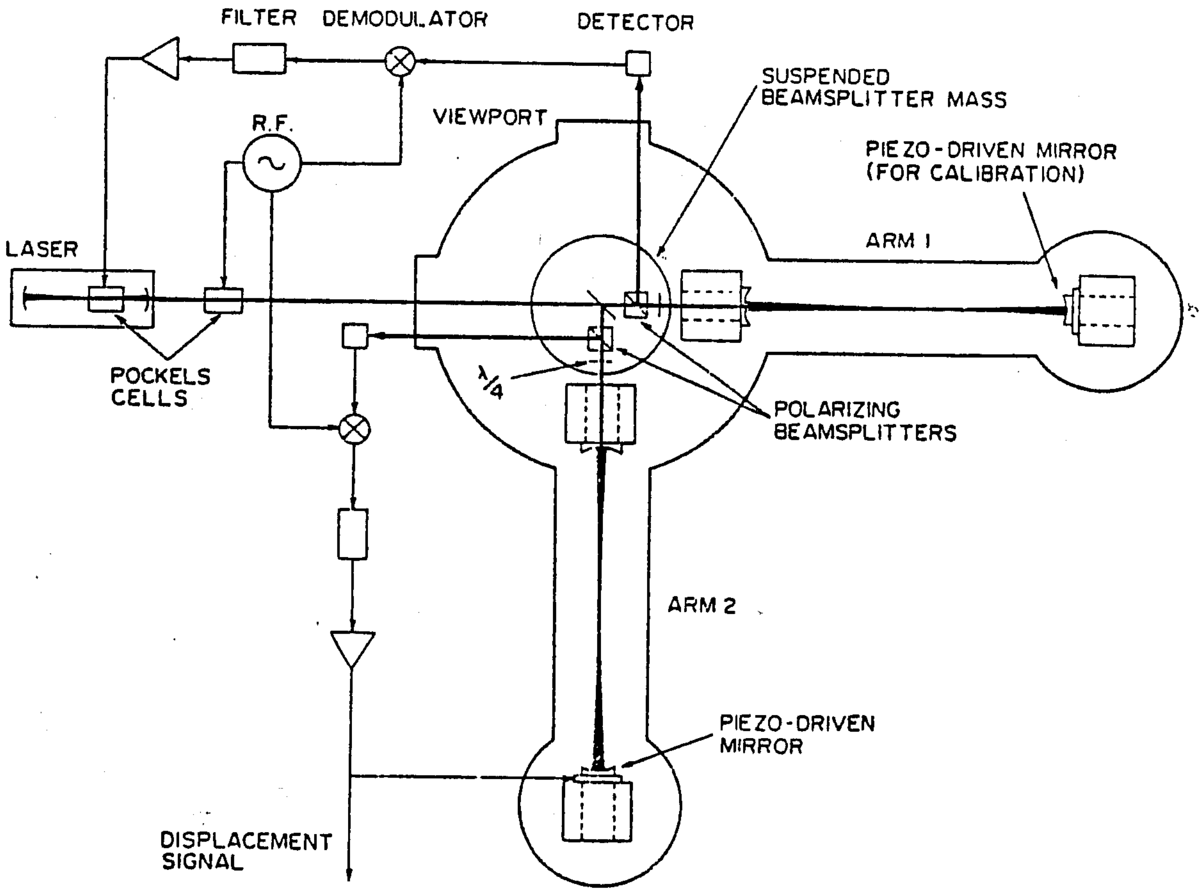


Figure 3.2 Schematic diagram of the Caltech 40-meter prototype as of September 1984. The interferometer uses five suspended masses inside the vacuum chamber -- four to carry the mirrors which define the ends of the two arms and one which carries the beamsplitter and associated optics. An rf phase modulation technique is used to lock the laser frequency to the first arm, while the second arm is locked to the laser frequency using a piezoelectrically driven mirror. The gravity wave signal appears as a voltage applied to the piezo-mirror to compensate for the difference in arm lengths caused by the wave.

The optical paths between the cavity mirrors are spanned by stainless steel pipes of 20 cm diameter evacuated to 2×10^{-3} torr (see Figure 3.3). Pipe flanges are joined with metal seals; by adding high vacuum pumps the detector can be evacuated to the 10^{-6} torr range when performance becomes limited by effects of residual gas.

In operation, phase sensitive servos keep the two cavities in resonance. An electro-optic (Pockels) cell applies phase modulation at radio frequency to the light before it enters the cavities. The light reflected directly from the input cavity mirrors has sidebands due to the modulation, but the sidebands are stripped off the light which is stored in the narrow bandwidth (200 Hz) cavities. The phases of the stored and reflected pieces of light incident on the photodetector are compared, and the difference signal controls the frequency of the laser and lengths of the cavities to maintain resonance.

Low-frequency control of the orientation and longitudinal position of the masses is provided by multi-wire suspensions. Mass orientation is monitored by 40-meter long optical levers which use the cavity mirrors to reflect beams from low-power He-Ne lasers onto position-sensitive photodiodes. The signals from these photodiodes are attenuated at frequencies above 30 Hz and fed back to coil-and-magnet transducers which exert forces near the points of suspension, fixing the angular degrees of freedom of the masses to within a microradian. Low-frequency longitudinal motion is monitored by the phase of the resonant cavity light and by separate LED-photodiode shadowmeters mounted below each test mass; feedback signals to keep the cavities in resonance are applied to piezoelectric stacks which push and pull on the cluster of suspension wires, controlling the longitudinal position of the test masses.

Several stages of seismic and acoustic isolation are used, beginning with isolated concrete pads anchored to piles extending approximately five meters below floor level before contacting the ground. The vacuum chambers containing the masses rest on vibration-damped optical tables, and are isolated from the 40-meter pipes by flexible bellows. A four-layer stack of alternating lead and rubber inside the vacuum isolates against seismic and acoustic disturbances above the stack's resonance frequency of approximately 5 Hz. We estimate that this passive isolation, in conjunction with the wire suspension, provides adequate attenuation to prevent seismic or acoustic noise from limiting performance at frequencies above 100 Hz.

The first sensitivity goal of the prototype development is to achieve shot-noise limited performance in the region of 1 kHz with high-reflectivity mirrors and high laser power. The mirrors now installed (loss per reflection = 4×10^{-5}) give a cavity storage time which is long enough to exhibit maximum sensitivity at all frequencies above 200 Hz, using a simple Fabry-Perot system. Mirrors with higher reflectivity will not be needed until advanced optical schemes (such as light recycling) are employed. The laser in use (Lexel Model 95) has produced a maximum power of 300 mW in the present configuration.

At the heart of the detector is a technique for wide-bandwidth stabilization of lasers with respect to long storage-time cavities. First demonstrated[8] in 1979, the new stabilization technique compares the phase of the laser light reflected off the input mirror of a cavity to the phase of the light stored in the cavity. The laser frequency is servo-controlled to cancel any phase difference, locking the laser frequency to the cavity length. Figure 3.2 indicates how, once the laser is stabilized to one cavity, reflected light from a second, orthogonal, cavity can be used to monitor the type of length changes induced by gravity waves. One spin-off from the early work at Caltech is the growing use, in laser spectroscopy and elsewhere, of this method to stabilize the frequency of lasers.

At every stage of development of the detector, the guiding principle has been to improve performance as rapidly as possible. We have attempted to design the apparatus to facilitate quick tests and reasonably easy modifications. The vacuum system has gate valves located so that individual end tanks can be opened and evacuated in just a couple of hours. This fast cycle time has permitted a number of quick tests which would not have been possible otherwise. This approach is also evident in the evolution of the test mass design. The initial test masses were three identical double-layer aluminum disks, with large surfaces for mounting optics. This design allowed different optical configurations to be easily implemented and tested. These tests included different piezo drivers for the second arm cavity mirror (moderately successful), addition of optics for wide range mass orientation control (very successful), tests of an auxiliary Michelson interferometer to damp large-scale motions (only partly successful), and installation of extremely low loss mirrors (very successful). As noise sources associated with the optics were reduced noise due to the masses became more important, and the original test masses were replaced in phases with inherently quieter masses (Figures 3.4 and 3.5). Eventually, all four cavity mirrors were mounted on similar low-noise masses, and the central mass was retained with minor modifications to split and redirect laser beams. Photographs of one of the end masses, removed with its suspension from its vacuum tank, are shown in Fig. 3.4 and 3.5.

The 40 m antenna has been used for one search for gravitational radiation; a very speculative search for radiation from the millisecond pulsar in March 1983. The detector was run continuously for two weeks, integrating the signal in frequency bands centered on the pulsar rotation frequency and its first harmonic. Although no signal was detected (and none expected at the sensitivity level attained at that time), the experiment demonstrated the versatility of interferometric antennae to respond to new types of sources, and provided us with valuable experience.

(b) CURRENT SITUATION

The most recent noise spectrum from the Caltech 40 m prototype interferometer is shown in Figure 3.6. This preliminary measurement was taken about one month before the submission of this proposal, and was the first measurement taken after the installation of the new test masses. Due to its preliminary nature, this spectrum has a calibration uncertainty of ~ 30%. The measurement was made with ~ 1mW of light incident on each photodiode and a fringe visibility of ~ 0.65. The energy storage time of the cavities was measured to be 0.7ms (see Figure 3.7), corresponding to a finesse of 15000 and a Q of 3×10^{12}. This spectrum shows a noise level near the shot noise calculated for these parameters, also shown in Figure 3.6.

The sensitivity shown in Figure 3.6 is comparable to that achieved by the group at the Max Planck Institute, previously the best interferometric gravity wave antenna in the world. However, the antennae are significantly different, requiring the development of substantially different techniques. One major difference is that the Caltech detector uses a long storage time and low laser power while the MPI detector has a short storage time and moderate power. This difference shows up, for example, in the frequency dependence of the shot noise limits for the two antennae. The MPI shot noise (in m $Hz^{-1/2}$) is constant below 10 kHz, while the Caltech shot noise is proportional to f for $f \gtrsim 200$ Hz.

The 40 m prototype is intended to be a functioning gravity wave antenna, because we felt that this would provide the most realistic test of the techniques needed for larger antennae. As a gravity wave detector it would now have a 1 kHz burst sensitivity of $\sim 10^{-17}$. The same displacement sensitivity in a 5 km antenna would yield a burst sensitivity of 10^{-19}, already an interesting level. In

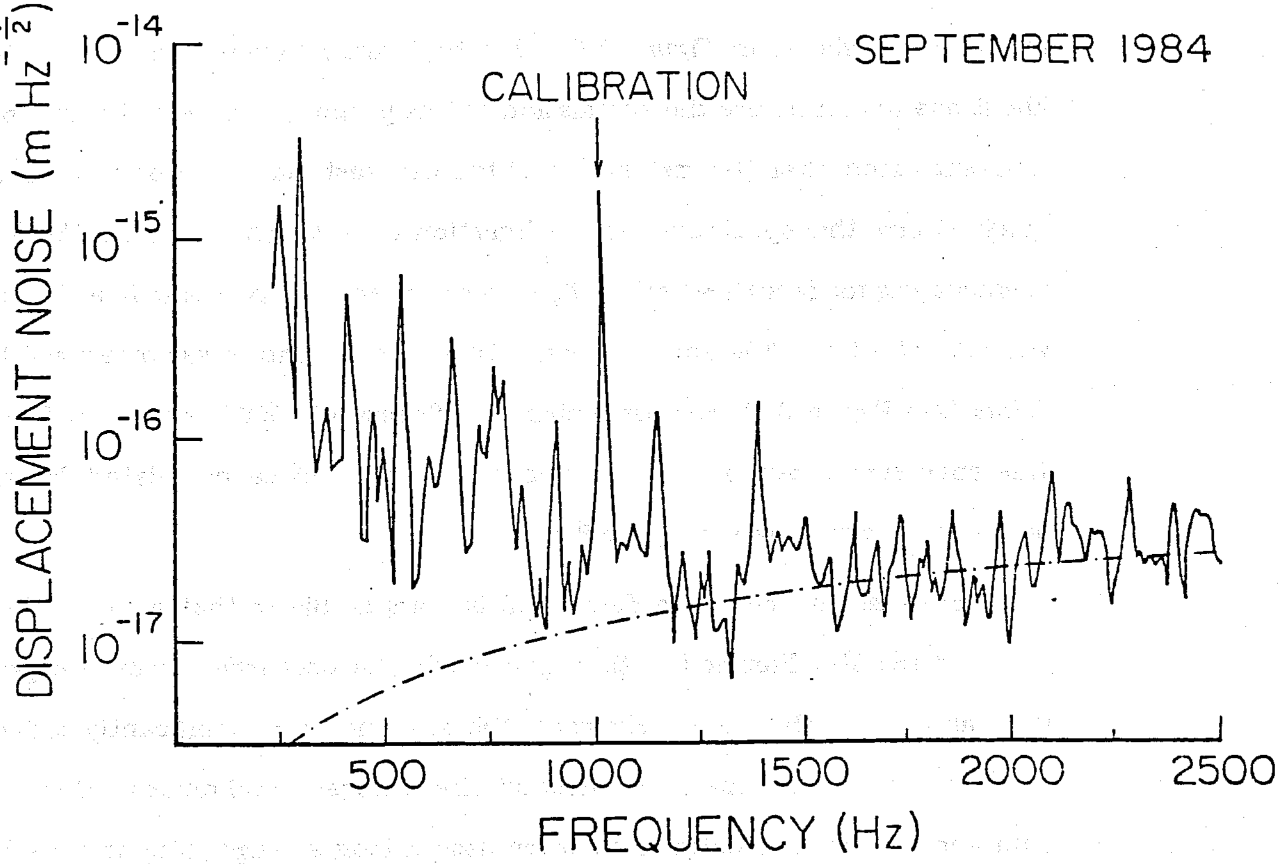


Figure 3.6 Noise spectrum of the Caltech prototype. This noise spectrum, taken in September 1984, is expressed as an equivalent difference in arm lengths for the two arms. To convert this to a gravity wave sensitivity (strain per square root Hz), divide by the arm length of 40 m. The dashed curve shows the calculated shot noise for the light power (1 mW) and fringe visibility (0.65) of the interferometer at this measurement. The portion of the spectrum below 250 Hz was not well calibrated in this measurement and is not shown. Many of the peaks below 1 kHz are multiples of the line frequency and may be due to pickup in the electronics.

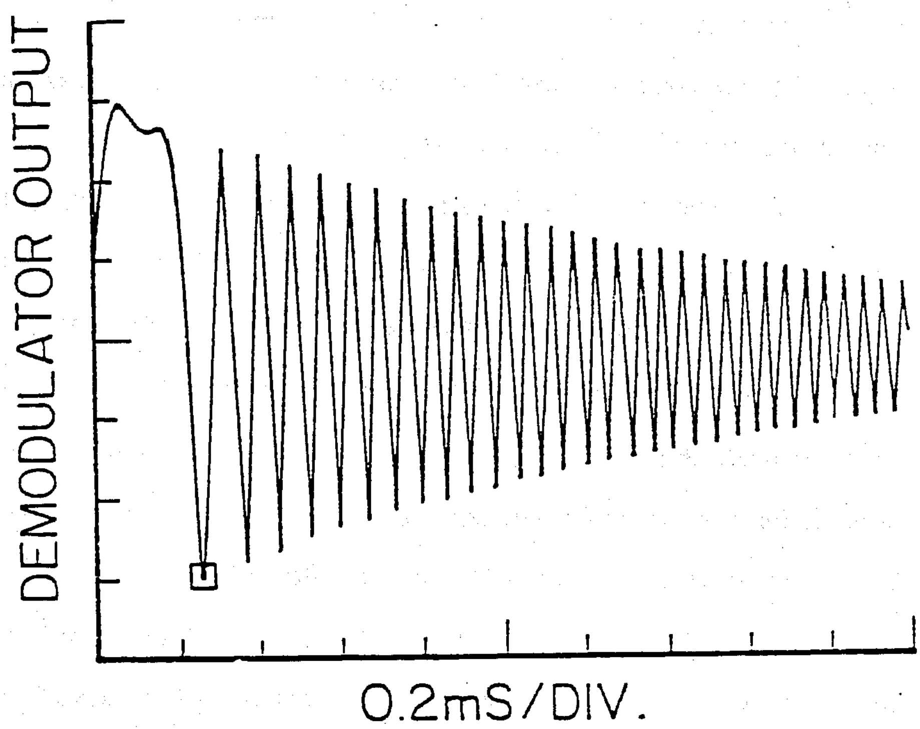


Figure 3.7 "Wiggles" showing the cavity storage time. This oscilloscope trace shows the demodulator output for the second arm. For this measurement the laser was locked to the first arm while the second arm was allowed to swing freely, moving in and out of resonance. When the second cavity moves into resonance, light is injected into the cavity. As the cavity moves out of resonance, the cavity light continues to interfere with the laser light for the cavity storage time. The demodulator output shows the interference between the cavity and laser light. The slowly increasing beat frequency is the instantaneous frequency difference while the decay of the envelope gives the storage time. The decay time shown, ~ 1.4 ms, is the e- folding time for the field inside cavity, or twice the cavity storage time.

addition we can draw the following conclusions about specific techniques to be used on larger antennae:

1). *Low loss mirrors*- The cavity mirrors have a total loss[14] (scattering and absorption) of $\leq 5 \times 10^{-5}$ over areas of $\sim 1 cm^2$. Such losses are low enough to make the sensitivity enhancement techniques discussed in Section 4 below quite feasible, provided the losses do not increase significantly as the size of the mirror increases. We have no indication that any problems will arise. Earlier concerns about the practicality of such low loss mirrors have not proven important. The mirrors can be cleaned if necessary, and do not degrade in a vacuum. Errors in mirror figure do not significantly degrade the mode-matching to the input laser beam, and the alignment requirements for the high finesse cavities seem attainable. We have found no evidence that the high finesse cavities behave in any way except as expected.

2). *Laser Stabilization*- The degree of laser stabilization is already nearly good enough for use on the 5 km antenna. The servoloop now gives shot-noise limited performance locking to a cavity with a 200 Hz bandwidth. A 5 km antenna optimized for the 1 kHz region would have a comparable bandwidth so that no changes whatsoever would be needed in the servoloop. The only difference between our laboratory prototype and our planned detector would be an increase in laser power. Even if difficulties are encountered in achieving shot-noise limited frequency stability at higher powers, we can use an electronic subtraction technique to remove the effects of residual laser frequency noise. This has been tested and gives about two orders of magnitude additional safety margin.

3). *Suspension Systems*- The current sensitivity demonstrates that our relatively simple suspension systems would be adequate in a 5 km antenna for a burst sensitivity at or below the mid-10^{-20} level at 1 kHz without any modification. Since the microseismic noise is likely to be lower at any plausible large antenna site than it is in Pasadena (if only because of the absence of man-made noise), the isolation from ground noise is probably already adequate at 1 kHz even for the advanced antennae discussed in Section 4.

The prospects for rapid improvements to the sensitivity shown in Figure 3.6 are good. If the limiting noise is due only to shot noise, improved fringe visibility and increased laser power could lead to as much as a factor of 10 improvement in the next six months. During the measurements shown in Figure 3.6, the power from the laser was only 30 mW, approximately a factor of ten less than the maximum ever obtained from this laser and Pockels cell. (The reduced power could be due to either laser tube or Pockels cell degradation.) In addition, the efficiency of the optical train leading from the laser to the interferometer is low (~10%). Simple improvements such as antireflection coatings for currently uncoated elements could realistically give an efficiency of ~30%. Higher fringe visibility, to be achieved through improved mode-matching and alignment, should give an additional factor of two improvement in sensitivity. Overall, these relatively modest changes should result in an order of magnitude improvement. Of course, other noise sources could be discovered in the process, but this is one aim of the prototype work, to uncover and solve noise sources.

4. NEW EXPERIMENTAL TECHNIQUES FOR LARGE-BASELINE INTERFEROMETERS

The experimental work just described had the main aim of developing the basic Fabry-Perot interferometer system conceived earlier into a practical gravitational wave detector, and we are encouraged by the results. No serious or worrying problems have emerged, and our experience with these systems has made us confident that large scale interferometers of this type will be entirely practical instruments, and likely to give very good performance. In one respect we have been much more fortunate than we expected when we began this project in 1979: at that time we did not know of any mirrors having reflectivity of more than 99.9%, and it has been a remarkable piece of luck that the requirements of laser gyroscopes have led to the development of mirrors having losses better by at least a factor of 20, and moreover very conveniently applicable in the Fabry-Perot technique we have developed. The realization that such mirrors could give us achievable light storage times of more than a tenth of a second in a 5 km cavity stimulated us to consider ways of exploiting storage times much longer than the periods of the signals of interest, and has led us to new concepts for enhancing the performance of long-baseline interferometers. We have not tested these ideas yet, for they will only be practically useful on a large system, but they give promise of very significant improvements in gravitational wave sensitivity, to a level unrivaled by any other technique of which we are aware. We think these will be important techniques for the large scale interferometers we are planning, so we might outline them briefly here.

These concepts are summarized in Section 4 of the accompanying Joint Proposal, and if the reader has already covered that Section of the Joint Proposal we could suggest that he or she might like to skip directly to the next Section (5) of this present Proposal. However in case this Proposal is being read on its own we reproduce here material we have written for Section 4 of the Joint

Proposal with only relatively minor changes.

4.1. Enhancement of Interferometer Sensitivity by "Light Recycling"

The limits to the sensitivity of laser interferometer gravitational wave detectors set by photon shot noise are summarized in the first chapter of the accompanying Joint Proposal. For simple delay line or Fabry-Perot interferometers the sensitivity is proportional to (light power)$^{-1/2}$. We plan to use laser powers of some tens of watts, being limited at present by availability of suitable continuous wave lasers capable of giving the required highly stable output. To increase sensitivity further and make possible detection of signals over a larger region of the range of expected amplitudes some new methods for improving interferometer efficiency have been devised in the course of the Caltech work[9]. These depend on the fact that when the interferometers are operated close to a dark fringe in the output - with minimum light intensity on the final photodiode - very little light is actually consumed in the measurement. In fact most of the input light is either wasted in optical losses of various kinds or is rejected by the system. For example, in a simple Michelson interferometer with path differences adjusted for minimum light on the photodiode most of the light emerges from the interferometer from the other side of the beamsplitter, and is wasted. It is proposed that this light be re-used, by feeding it back to add coherently to the input light from the laser. One way of doing this is illustrated, in principle, in Figure 4.1. Here the laser beam enters the system through a mirror of carefully chosen transmission, with the fed back light added at this mirror. In effect, the extra mirror turns the whole system into a large Fabry-Perot cavity, and with correct adjustment of wavelength or optical path differences a large buildup of light flux may be achieved within the interferometer, giving a corresponding improvement in sensitivity. Adjustment of the phase of the

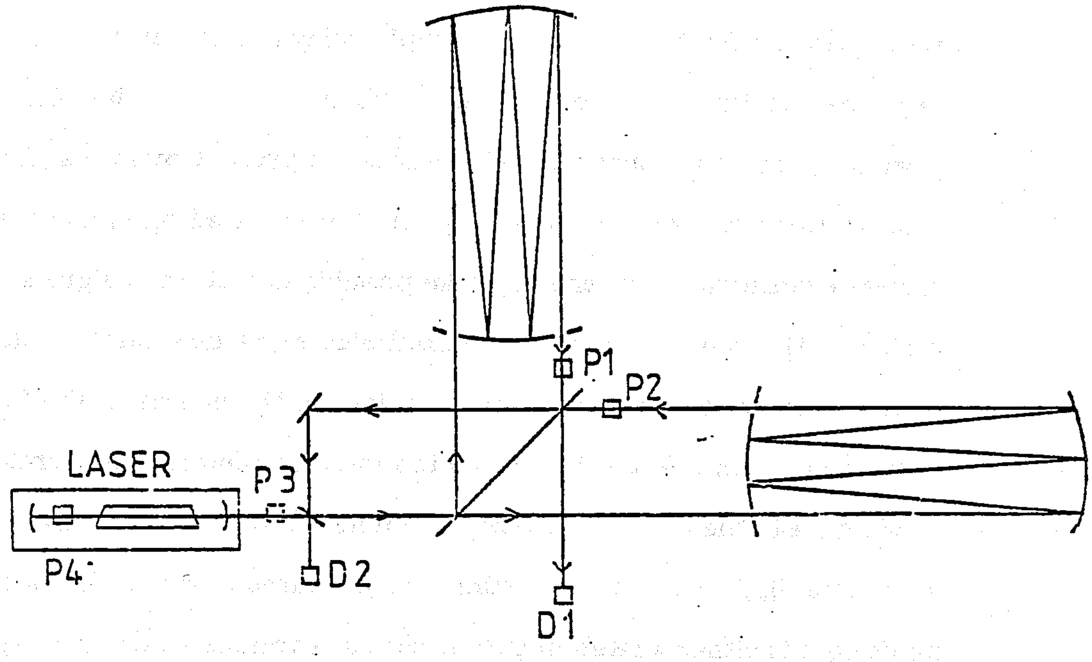


Figure 4.1 Possible method for enhancing the sensitivity of a delay line antenna using recycling.

recycled light may readily be made automatic by monitoring the phase of light reflected back from the recycling mirror, using the high frequency phase modulation techniques already developed in this work for locking the frequency of a laser to an optical cavity resonance.

The same basic idea may be applied also to Fabry-Perot interferometers. In a gravity wave detector based on optical cavities, the reflectivity of the back mirror in each cavity would normally be made as high as possible and the input mirror in each arm would have lower reflectivity, chosen to give a storage time for the light within the cavity appropriate for the period of the gravitational waves of interest. Under these conditions, with low-loss mirrors, most of the light incident on each cavity will be reflected back and will contribute to the rejected light emerging from the unused side of the main beamsplitter. It is proposed that this light be returned to the system by an extra mirror of suitably chosen reflectivity in the initial laser beam, as indicated in Figure 4.2. As in the case above, this forms a larger Fabry-Perot cavity around the whole interferometer system, giving in principle a useful buildup in light intensity if phases and reflectivities are correctly arranged.

The improvements in sensitivity achievable with these recycling schemes depend on the optical losses in the main parts of the interferometer. Multilayer dielectric mirrors with losses less than 1 part in 10,000 have been developed for applications in laser gyroscopes, and special mirrors of this type have been tested and used in the Caltech 40 meter interferometer. However other optical elements, such as Pockels cell modulators, have at present much larger losses. Designs for practical recycling systems have therefore been devised at Caltech in which electro-optical modulators are kept out of the sensitive part of the interferometer, and the radio- frequency modulation useful for low noise phase measurement is achieved by mixing a separately modulated external beam with

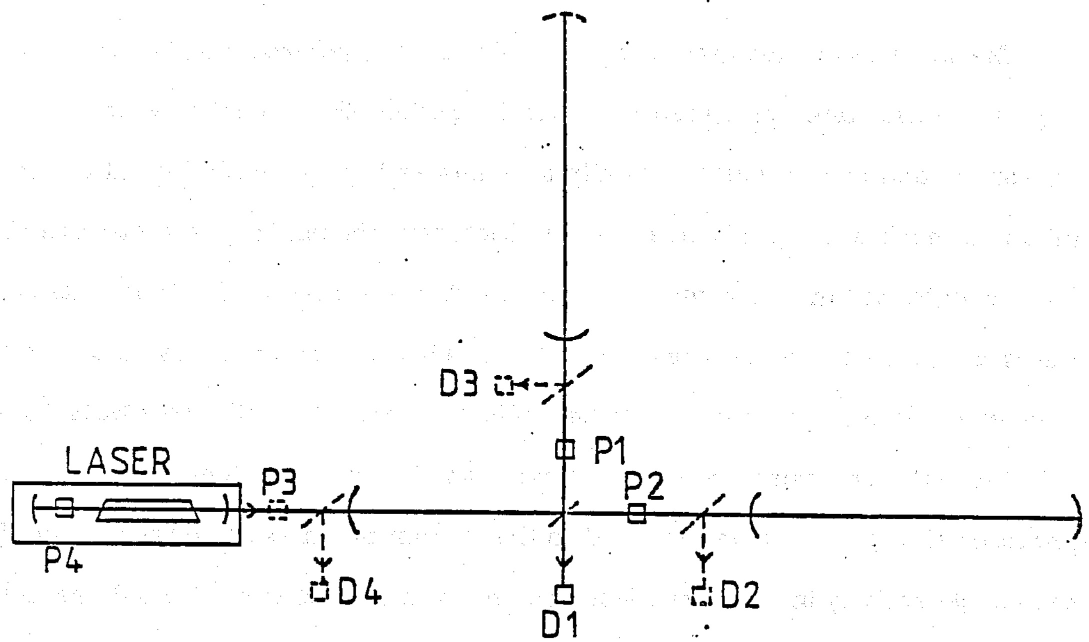


Figure 4.2 Possible method for enhancing the sensitivity of a Fabry-Perot antenna using recycling.

the interferometer output, as indicated schematically in Figure 4.3.

The increase in effective light power obtainable by these recycling systems is given approximately by the ratio of the total storage time achieved to the storage time in each arm. In a search for millisecond pulses with a large interferometer, this factor could be more than 1000, giving significant improvements in potential sensitivity. (See Sec. 2.2.2. of the Joint Proposal.)

It may be noted that the minimum gravity wave pulse energy detectable in a recycling interferometer system at the photon shot noise limit is proportional to the ratio of mirror losses to arm length. This emphasizes the importance of using mirrors having very low losses, and indicates why the recent development of low-loss gyro mirrors is so promising for this research. Currently, the low-loss mirrors have only been made in diameters up to 4 cm (and these were specially made for the Caltech prototype), but it appears that available equipment could make mirrors up to the 20 cm diameter required for Fabry-Perot cavities or other compact optical systems of 5 km length. We do not know if comparable mirrors can be made in the much larger sizes required for delay line systems; and it does seem likely that it will be more difficult to achieve very low losses in large mirrors than in small ones. One might therefore expect an advantage in sensitivity for Fabry-Perot interferometers for any given length of baseline, particularly for long-duration pulses, but how large this advantage will be cannot be predicted yet. In any case it is clear that with our present uncertainties about gravitational wave fluxes it is important to have both very low mirror losses and very large interferometer baselines.

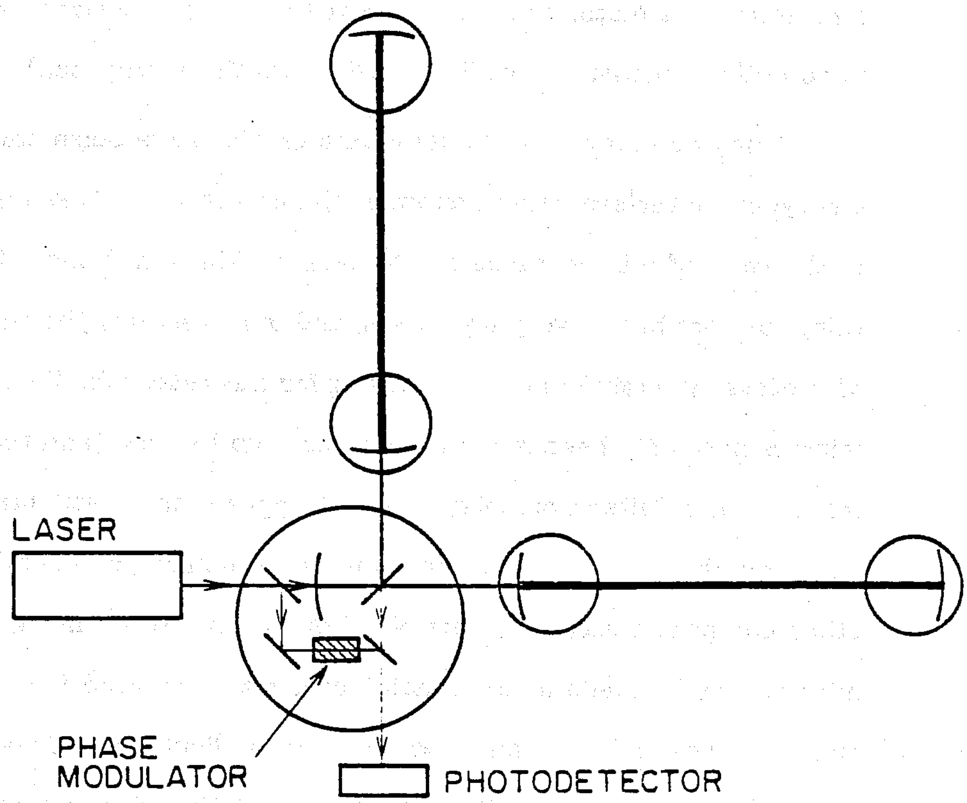


Figure 4.3 More practical version of the recycling scheme from Figure 4.2 in which the Pockels cell modulator is placed outside the cavities to reduce losses.

4.2. Enhancement of Interferometer Sensitivity for Periodic Signals

A technique for achieving even higher sensitivity in searches for periodic signals has also been devised in the Caltech work[9]. If the light is stored in each arm of the interferometer for a time equal to half of the period of the gravitational wave, and if it is arranged that the light passes from one arm to the other in a suitable way, then the optical phase shifts induced by the gravitational wave may be made to accumulate over many periods, giving a corresponding enhancement in sensitivity. In a delay line Michelson interferometer this might be done as indicated, in principle only, in Figure 4.4. Here light is arranged to circulate round both arms of the interferometer in opposite directions, and a relative phase shift builds up which may be detected as shown. In a Fabry-Perot system, the cavities in the two arms may be coupled together, as indicated in Figure 4.5, so that again a resonant condition is achieved. The operation of this latter system is perhaps more easily understood by considering the whole system as a pair of coupled oscillators, having one resonance which matches the laser frequency, and a second resonance which is made to correspond to the sum or difference of the frequency of the laser and the frequency of the gravitational wave, so that both resonances play a part in enhancing the output signal.

The improvement in sensitivity achievable for a periodic signal by these optically resonant systems is given approximately by the ratio of the total storage time achieved to the period of the gravitational wave, and can be very large in a long baseline detector. For example, the amplitude sensitivity for the signal from a millisecond pulsar might be enhanced by three orders of magnitude, corresponding to a flux sensitivity improvement by six orders. (See Sec. 2.2.2 of the accompanying Joint Proposal.)

The photon shot noise limit to sensitivity for gravitational wave flux in a resonant interferometer of this type varies as the square of the ratio of mirror

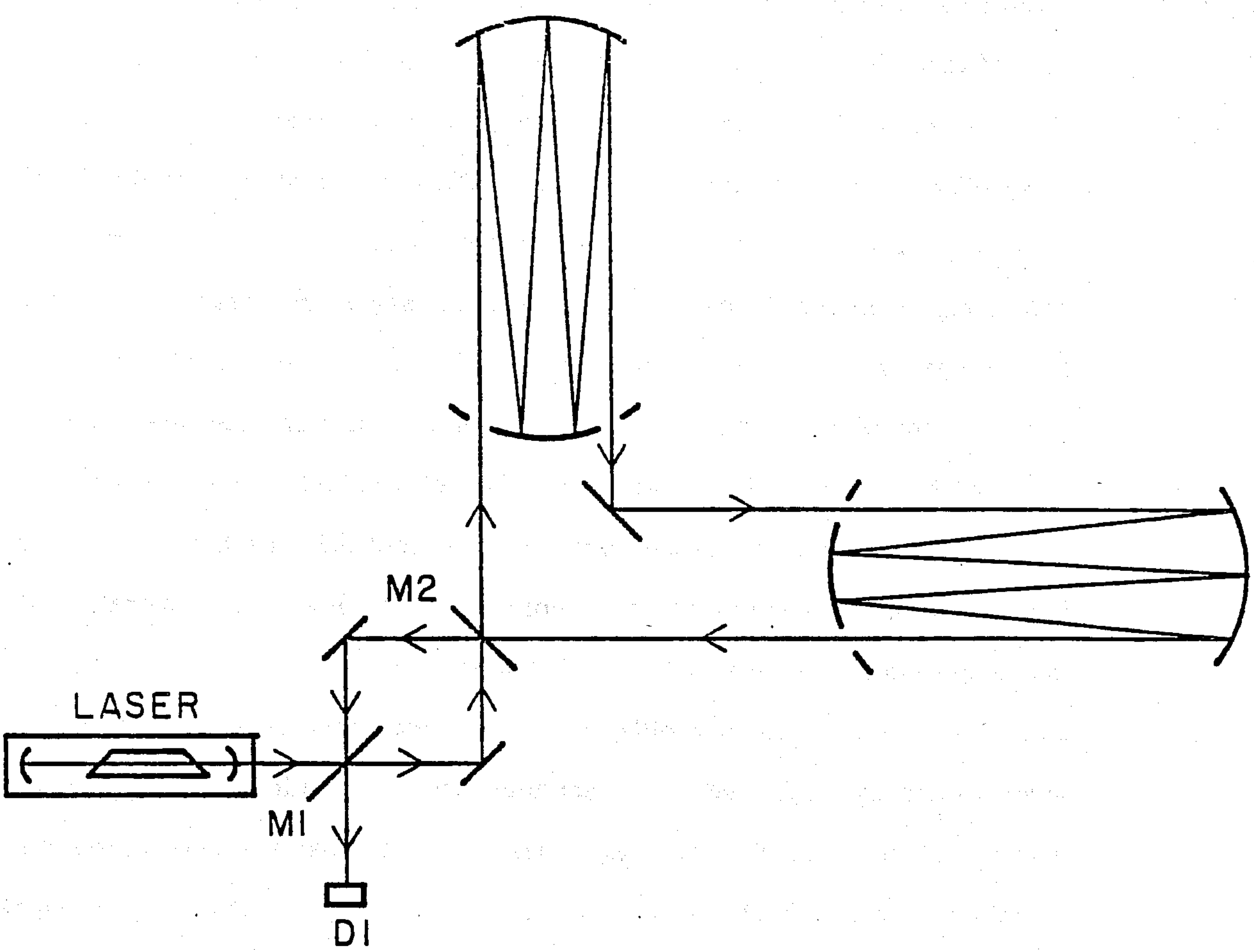


Figure 4.4 Method for enhancing the sensitivity of a delay line antenna for periodic signals.

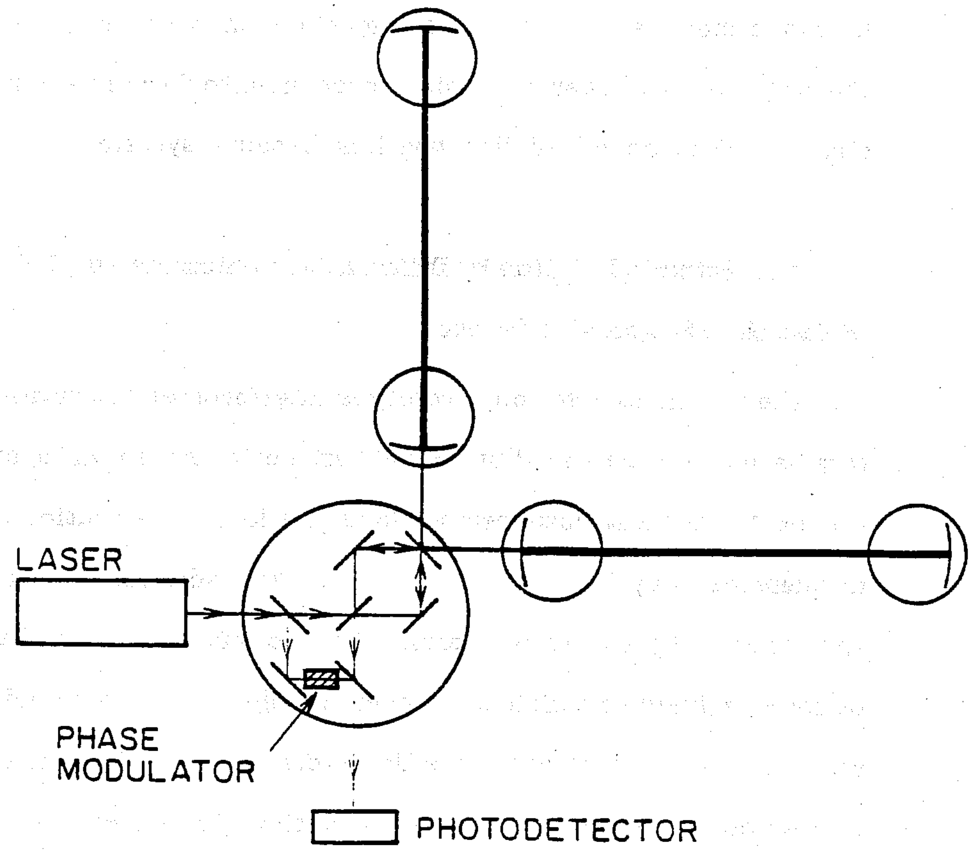


Figure 4.5 Method for enhancing the sensitivity of a Fabry-Perot antenna for periodic signals.

losses to arm length, so low loss mirrors are even more important here than for pulse searches, and Fabry-Perot interferometers may be particularly appropriate. This type of search also benefits most rapidly from increase in interferometer baseline, and indeed if stochastic noise forces acting on the test masses can be made small enough to be unimportant then the requirements of periodic gravitational wave searches using resonant interferometers may be among the strongest reasons for building very long baseline systems.

4.3. Seismic Isolation by Differential Monitoring and Coherent Driving of Test Mass Suspension Points

The test masses for our prototype interferometric gravitational wave detectors have been suspended by sets of three or four thin wires, and for frequencies around 1 kHz these suspensions alone give large attenuation of seismic noise at frequencies away from wire resonances. The addition of relatively simple passive isolation by stacks of alternate layer of rubber and lead within the vacuum tanks - techniques which have been widely used and found satisfactory with resonant bar gravitational wave detectors -can give isolation at these frequencies which is adequate for current experiments at least. At lower frequencies, however, the increasing amplitude of seismic noise together with the decreasing attenuation given by a mass-spring isolator makes simple passive isolation systems of this type inadequate, and transmission of seismic noise is likely to limit the interferometer performance below a few hundred Hertz. A relatively simple method for improving rejection of seismic noise by the system was proposed at Glasgow in 1976. Here an auxiliary interferometer is set up between the upper points of attachment of the suspension wires, and the output of this interferometer is fed back to a piezoelectric transducer which drives one of the suspension points, so that the difference in distance between the suspension points of the masses in each arm remains constant. Thus the suspension points are forced to move in a highly correlated way, and if the wire lengths and test masses are suitably matched the seismic disturbances should cancel out, at least to first order. Indeed, it can be shown that if the sensitivity of this seismic monitor interferometer is as good as that of the main interferometer, then seismic noise can in principle be made unimportant at all frequencies above a few times the frequency of the pendulum mode resonance of the test masses, typically of order 1 Hz. In practice it would be difficult to achieve isolation as good as this, because of limitations of servo loop gain in a system with many mechanical resonances and also because of high-order couplings of seismic noise from other degrees of freedom. However a useful improvement in low frequency isolation seems relatively easily obtained by this method, and in addition the residual error signal from the monitoring interferometer could be used for some further seismic noise compensation during subsequent data analysis, as well as providing a check for unusually large disturbances penetrating the passive isolation.

For modest improvements in isolation the monitoring interferometer can be a relatively simple one, possibly just a single-pass Michelson using low laser power, and the small beam diameter required could be accommodated fairly easily in vacuum pipes of the diameter we propose.

4.4. Techniques for Active Seismic Isolation of Individual Test Masses

The differential suspension point monitoring and driving technique just described is probably the simplest active method for improving on the performance of a passive suspension. However it only operates in one dimension, and is likely only to be practicable and economical with large-diameter vacuum pipes - such as we are proposing to use in the kilometer-scale facilities. A considerable effort has gone into more general types of active seismic isolation in various laboratories. A promising approach for gravitational wave detectors involves causing the suspension point of each test mass to track the motion of the mass below it, using a high-gain servo loop. This method has been extensively experimentally developed at Glasgow, primarily for the horizontal degrees of freedom most relevant for gravitational wave detectors.[15] An equivalent system for vertical motions has been very successfully developed at JILA for isolation of gravimeters,[16] and has also been tested and analyzed at MIT. The existence of tilt components in the seismic noise makes horizontal isolation more complicated in these schemes than vertical isolation, because of the difficulty of defining a steady vertical reference against which to monitor the relative positions of test mass and suspension point. A technique using a "reference arm" - a vertical arm of large moment of inertia freely suspended at its center of gravity - was introduced at Glasgow to avoid this problem; and use of the moment of inertia of the test mass itself in an equivalent way has recently been suggested at MIT also.

The improvement in isolation achieved by these techniques is usually limited in practice by the existence of mechanical resonances in the various structures involved; and for this reason multistage isolation systems have been considered at Glasgow, Caltech and MIT for achieving greater isolation.

Coupling between successive isolation stages may cause difficulties in such systems, and methods of compensating reaction effects have been devised at Glasgow and Caltech, and coupling effects in uncompensated systems have been analyzed at MIT. Overall, it looks likely that extremely good seismic isolation can be achieved by active isolation methods, although the systems may become relatively complicated for large degrees of low frequency isolation.

It should be noted that passive isolation seems entirely adequate for gravitational wave experiments at frequencies down to a few hundred Hertz, and we may use this alone for the first experiments in the large installations. The development of complex active seismic isolation techniques is likely to be more important for subsequent extension of the experiments to much lower frequencies, and the vacuum tanks we propose will be designed with such extension in mind.

4.5. Discrimination Against Local Disturbances By Use of Half- and Full-length Interferometers.

Experience with resonant bar gravitational wave detectors as well as with prototype laser interferometer detectors has shown that such instruments usually give significant numbers of spurious output pulses which form a serious background for gravity wave pulse searches. These may come from many sources, including release of strain in the test masses, mode hops in the laser, outbursts of gas from the walls of the vacuum pipes, seismic disturbances, and rapidly changing gravitational gradients due to moving local objects. Monitors for some of these phenomena may be used to reject many of the spurious pulses; but the most powerful single method of discrimination against such effects will come from the cross correlation of data from the two widely separated sites. This cross correlation may well involve a real-time, wide-bandwidth data link. This method alone, however, can only be effective in the search for rare signals if the rate of individual spurious pulses from each site is low; and it may be difficult to achieve this with single interferometers. The situation may be improved significantly by use of a pair of interferometers at each site, arranged to give signals related to one another in a known way. An economical solution is possible if the interferometers use optics sufficiently compact to allow two or more separate interferometer beams to be accommodated alongside one another within the same vacuum system. If one interferometer is made to span half the length of each arm of the vacuum system, then a comparison of signals from this half-length interferometer and from the full-length one can discriminate against many types of spurious phenomena. In particular, bursts of gas from the vacuum pipe walls would give strain signals of quite different sizes in the two interferometers, as would changes in gravitational gradients from local moving objects; and pulses due to mode hops or other transient optical effects would be unlikely to be coincident if separate lasers were used. Thus, these types of phenomena could be rejected efficiently, at least for signals large compared with system noise. Important additional data would be available on candidate gravitational wave events, for the signature of a gravitational wave burst would have to include matching waveforms from the full- and half-length interferometers at each site, with their displacement amplitudes in the ratio of 2:1, and in general it would be unlikely for disturbances to mimic this.

Half-length interferometers together with full-length ones, could be useful in other ways. In particular, they would speed up investigations of noise sources and facilitate the general debugging of the apparatus by providing some discrimination between various spurious phenomena, and they would permit development to proceed efficiently even in the absence of a real-time data link between the sites, or at times when one site might be out of action due to equipment failure or rebuilding.

4.6. Operation of Multiple Interferometers Within a Single Vacuum System

The half- and full-length interferometer system just described is a special case of a more general concept of multiple use of the beam pipes of a single vacuum system, which has gradually developed at Caltech and Glasgow. The cost of vacuum pipes in the size ranges we are considering does not vary very rapidly with pipe diameter, and pipes of the diameter required for experiments with delay line Michelson interferometers would in principle be able to contain up to 20 separate interferometers using Fabry-Perot or other compact optical systems. This opens interesting new possibilities. It could obviously provide useful redundancy in simple experiments; but, more importantly, it can make practical highly efficient simultaneous searches for several different types of gravitational wave signal. The optimum design of test mass for an interferometric detector depends on the time scale of the signals being sought, for at low frequencies thermal noise comes mostly from the pendulum mode of the suspension and is reduced by use of a large mass; while at higher frequencies thermal noise from internal modes tends to be dominant, and may be reduced by use of small masses, giving high frequencies for internal resonances and possibilities of fabrication from low-loss material such as monocrystal sapphire. Thus higher effective sensitivity may be obtained by operating simultaneously with a number of relatively specialized test masses instead of with a single one whose design is more of a compromise. Further, the new interferometer techniques outlined above in (4.1) and (4.2) give possibilities of large improvements in sensitivity for both wideband and periodic signals, with the maximum improvements achieved by matching the optical system to the signal being sought. Again, greatly improved overall performance may be obtained by use of a number of different types of receiver elements instead of any single one. The simultaneous use of a number of different interferometer beams and test masses within a single vacuum system makes this enhanced performance achievable at much lower cost and with higher efficiency than if separate vacuum systems were employed. A schematic diagram of a possible arrangement is shown in Figure 4.6.

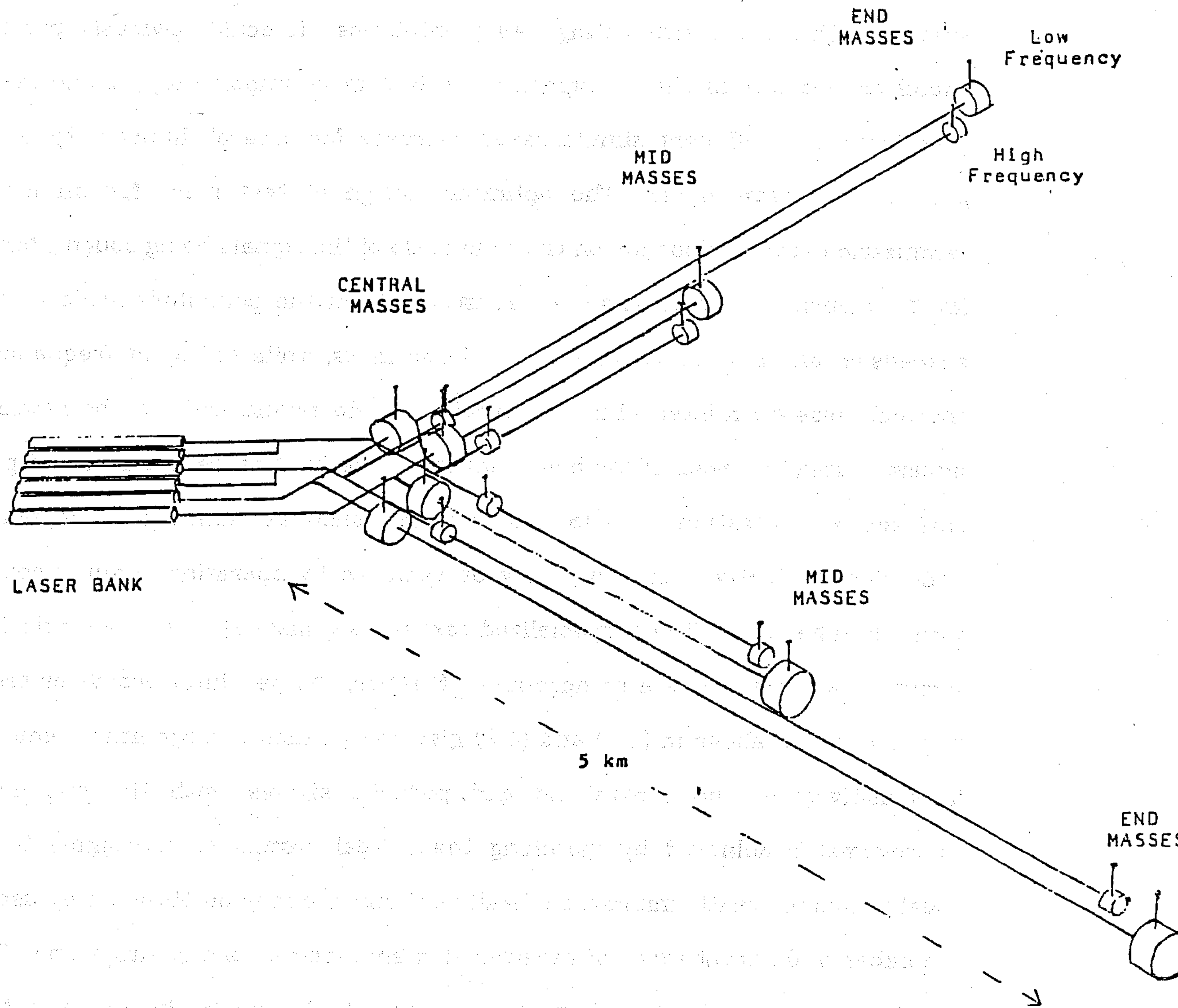


Figure 4.6 Example of a possible type of multiple interferometer system. Initially only some of the masses might be installed. Further masses--and possibly more than those shown here, to facilitate periodic searches--might be added later. (Note diagram is highly schematic and not to scale: light beams would be closely packed to fit within the single vacuum pipe for each arm.)

A multiple interferometer system has other useful benefits. As a number of parallel experiments become economically practicable there are more opportunities for interesting individual experiments by scientists and graduate students, and this is likely to lead to much more stimulating and effective research.

4.7. An Alternative Interferometer System

The basic multireflection interferometer systems tested to date have been of two types - the delay line Michelson interferometer and the Fabry-Perot cavity interferometer. Other types are possible, however, and it is interesting to note that a third type of multireflection interferometer, the frequency-tagged interferometer, was recently devised independently and at about the same time at both Caltech and MIT. In this system, the light in each arm of a basic Michelson interferometer bounces back and forth in each arm of the gravitational wave detector between a distant mirror which is similar to that used for a Fabry-Perot cavity, and an inboard reflecting system on one of the central masses which is itself made up from a frequency-selective system such as a smaller Fabry-Perot cavity. The light within the arm is made to shift in frequency on each pass through the system, so that after entering at a frequency corresponding to one mode of the input Fabry-Perot it becomes trapped until it has made enough passes for its frequency to match another mode of the input cavity, at which time it escapes. Thus a system giving a discrete number of reflections is achieved with mirrors of small diameter. The frequency shifting could be obtained in several different ways: Doppler shifting by moving one of the mirrors has been suggested at Caltech, and use of electro-optic or acousto-optic devices within the arms has been suggested at MIT.

At present it is not clear if this type of interferometer has significant advantages over systems already being developed, but we mention it partly to indicate that new ideas continue to arise in this field; and we feel it is important that the large-scale vacuum facilities discussed in the accompanying Joint Proposal are made sufficiently flexible to accommodate a wide range of optical systems.

4.8. Note on Overall System Outlined Here

Putting together the various experimental techniques and ideas outlined above along with the encouraging results with ultra-low-loss mirrors described in Section 3.2 (b) leads to a concept for a complete interferometric gravitational wave detection system with very attractive features: high sensitivity, great flexibility, good discrimination against spurious phenomena, and potential for high scientific productivity. This concept for a complete gravitational wave detection system is an attractive goal for a large scale installation. Experimental work to verify some of the ideas not yet tested is planned for the near future.

5. EXPERIMENTAL PROGRAM

5.1 Introduction

Our proposed experimental program for the next five years is a natural continuation and extension of our current program, and from the accounts of our current research and of the new concepts for large interferometers developed in the course of this work given in the previous two sections of this Proposal the general direction of our future plans will be clear. We feel, however, that we should preface a more detailed discussion of our proposed program by noting that in this rapidly developing subject we cannot be certain that there may not be significant changes in our program several years ahead. Of course this is generally true in any active research field, but it is more apparent than usual in our present situation when we are making a joint proposal for the main facilities for our future work with a group at MIT who have been developing experimental techniques somewhat different from our own ones. For example, the delay-line interferometer techniques developed at MIT require considerably more space within the vacuum pipes spanning the distance between the test masses than the optical cavity methods developed at Caltech, and this could affect our program. We plan to choose two years from now the optical design for our first joint Caltech-MIT gravity wave antennas in the large facilities, and if at that time the delay line techniques seem to have advantages which outweigh their greater space requirements it may not be possible to accommodate as many parallel experiments as we might have wished. Experimental problems or financial limitations which we cannot foresee might also impose compromises. However all our experience so far suggests that the techniques and ideas we have outlined above are promising, practical, and economical ones, and we base our currently proposed program on this experience.

The overall objective of our proposed investigations is to detect and study gravitational radiation, and in planning a program to achieve this in a way likely to give maximum probability of success along with minimum cost in both finances and scientific effort we regard it as very important to aim at detection of the radiation as early as possible. Maximizing the probability for early detection is likely to minimize total cost, even though initial cost per year may be higher than for a slower approach; and, very importantly, this will make the whole project much more attractive and stimulating to the researchers, providing them with a real possibility of making major scientific advances in a reasonable time scale.

This aim of earliest possible detection influences our program in many ways. For example, it leads us to plan an advance over a fairly wide front, covering a wide range of types of gravitational wave signals, and planning simultaneous experiments right from the beginning, where appropriate and when resources permit.*

Our program is, of course, mainly related to experiments with the large detection facilities being proposed jointly with the MIT group, for it is only with facilities on this scale that we can expect a reasonably high probability of detection of signals. However the possibility of much larger gravitational wave signals cannot be ruled out, and we regard it as important to carry out searches with our present 40 meter instrument at any stage where a sensitivity significantly better than that of prior experiments is achievable for any type of signal or in any region of the frequency spectrum, provided that this does not significantly slow down the work on the larger instruments. Indeed, reasonably quick experiments of this type carried out on the way to the large detectors will also give

*This program would be arranged to complement and be compatible with the joint Caltech-MIT receiver system and first joint experiment, and would be done in such a way as not to compromise it but rather enhance it.

practical experience which is likely to be very valuable for the larger-scale experiments, as well as giving possibilities of early construction of equipment which may subsequently be operated inside or in conjunction with the large facilities.

These considerations lead us to a program which is made up of a number of related parts, which we shall now outline.

5.2. Continuing Development of Detection Techniques Using the 40 meter Interferometer System.

This part of our program will include:

(a) Work aimed at overall understanding and control of all observed sources of noise to give general improvement in sensitivity. This will include increasing the laser power available by development of improved stabilization techniques giving higher power output, and use of coherent addition of the outputs from two or more phase-locked lasers.

(b) Experimental investigation and development of the new optical techniques we have devised for improving photon-shot-noise limits to sensitivity. In general, these techniques are only effective when the ratio of achievable storage time in the interferometer to the period of the gravitational wave signals is large. The 40 m interferometer has already demonstrated storage times a factor of five greater than necessary for optimal detection of 1 kHz signals, and larger storage times are achievable, so this will probably be done with this instrument.

5.3. Performance of Short Gravitational Wave Searches with the 40 m System

We plan to carry out gravitational wave searches at each major improvement in sensitivity. Although our best estimates make the detection of gravitational waves with the 40 m antenna seem somewhat unlikely, sources stronger than expected and detectable with this instrument are certainly possible. Just the fact that this antenna has a much wider bandwidth and frequency coverage than detectors of comparable sensitivity used in earlier gravitational wave experiments makes it practicable to extend searches for particular kinds of signals further than carried out previously. The search made with the 40 m detector for radiation from the millisecond pulsar at both the pulsar rotation frequency and its first harmonic, already mentioned, was an example of this, and it was carried out only a few months after the discovery of the pulsar.

These searches take only a small part of the overall effort and time, but they are stimulating, and particularly important in providing the types of thesis topic expected for graduate students associated with the project. Future searches will also facilitate development of data analysis techniques required for larger-scale experiments, and provide valuable experience with the performance and reliability of the complete interferometer and data recording systems.

5.4. Development of Test Masses and Optics for the Large Scale Interferometers

A major part of our experimental program will be the design, development, and experimental testing of the test masses, optical systems, and complete receiver elements for use in the large facilities. In line with our aim of earliest possible detection of gravitational radiation we would plan to fully develop and operate the test masses and optics for the large facilities in our 40 m interferometer while the large vacuum facilities are in their construction phase, so that as soon as the large facilities become available we could expect to have complete and tested receiver systems ready for rapid installation and operation.

In order to make operation of the full size test masses and optics in the 40 meter system simulate as closely as possible the final operation in the 5 km system we may plan to fit them temporarily with mirrors and mode matching lenses having slightly different radii of curvature than the final ones, so that the diameter of the beam over the 40 meters matches approximately the final diameter in the full size system. The vacuum pipes in our present system are already large enough to accommodate the beam diameter required by a Fabry-Perot cavity in a 5 km system. We would plan to fit larger central and end tanks to our present system, however, to leave more space for optics and for the larger test masses we would plan to use in interferometers optimized for low frequency experiments. With these modifications, and additional lasers to give higher light power, we expect to be able to fully develop in our existing facilities at Caltech a range of receiver elements covering a wide spectrum of experiments.

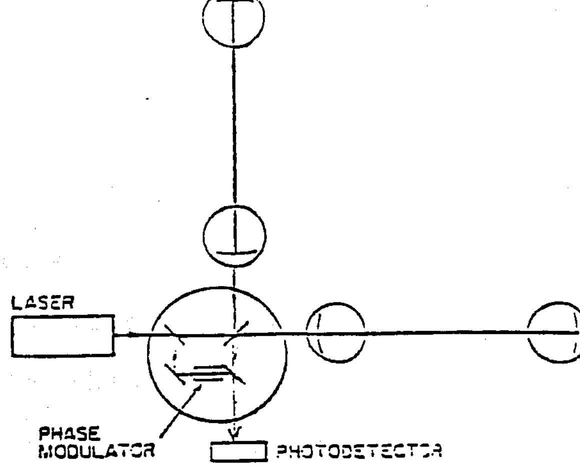
We have already indicated how significant improvements in sensitivity of gravitational wave searches may be made by use of interferometer designs matched to the particular signal being sought, particularly when light recycling and optically resonant techniques are used, and we have shown how several different interferometers may be operated simultaneously in a suitably designed vacuum system. With these possibilities in mind, we plan to minimize cost and development effort by designing the test masses and associated optics in a modular fashion, making as many of the components as possible common to all the interferometer variants. This modular type of design is considerably simplified by the technique of breaking up the central mass of the detector into two separate test masses and an optics block, which has proved so successful in the interferometers at Glasgow, Caltech and Garching, and which we suggested originally mainly as a means of reducing thermal noise. Fig. 5.1 shows schematically how the principal differences between the three different types of interferometer design we might wish to use can be accommodated by relatively small changes in the optics block (indicated by the large circle), with no change in test mass design, apart from a change of mirrors on the inboard masses to give reflectivity appropriate for the period of the expected signals.

For gravitational wave experiments at higher frequencies, above about 500 Hz, the minimum thermal noise is obtained with fairly small test masses, of mass around 10 kg, and high mechanical Q-factor, which can be designed to have no mechanical resonances at low frequencies. For low frequency experiments larger masses are more appropriate, of order 1 ton, for these reduce thermal noise in the pendulum mode of the suspension, which may dominate here. Overall, we feel that most experimental requirements could be covered with interferometers assembled from two sizes of test mass and two or three patterns of the suspended optical block.

In our program for receiver development for the large facilities, we would begin with the simplest systems, for operation at medium and high frequencies. We would gradually extend the systems to include recycling and optically resonant interferometers, and at a later stage extend the operating frequency downwards. In about 2 years from now the basic decision about the general type of interferometer optics to be used in the first joint experiments with the large facilities will be made. If we assume that Fabry-Perot optics be chosen at that point, we would expect that these would probably give minimum risk in their simplest form, which is important for first experiments with a new system. In this case we would initiate production of a number of the simple systems to our tested design, but we would continue studies of the recycling and optically resonant systems, so that we would be in a position to install one or both of

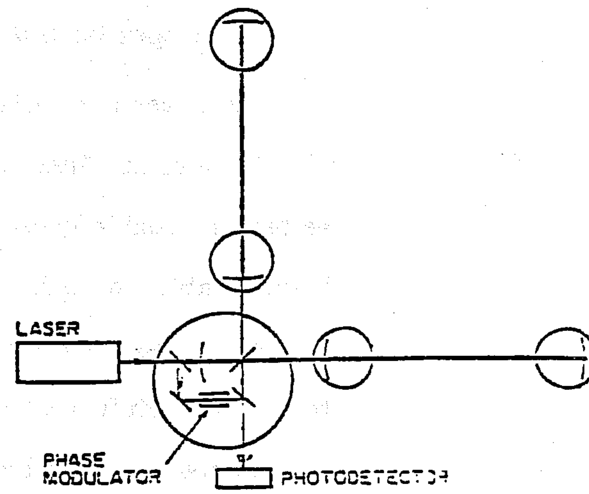
(a)

A proposed configuration for an optical cavity gravitational wave detector with differential optical output.



(b)

A proposed configuration for a high sensitivity wideband gravity wave detector using light recycling.



(c)

A proposed configuration for an optically resonant gravitational wave detector for very high sensitivity in a narrow bandwidth.

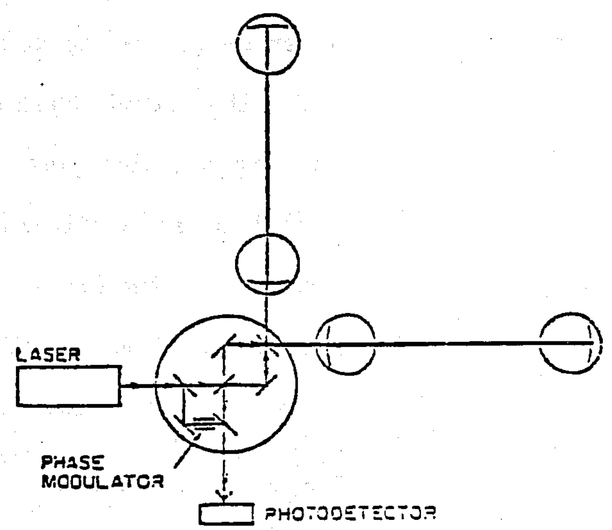


Figure 5.1 Gravitational wave detectors designed for different types of experiments, but arranged to have many components in common. (Diagrams are schematic and show principal features only.)

these in auxiliary vacuum tanks whenever they were ready. It may be noted here that we don't expect the development of these different variants of a basic receiver to involve much more effort or cost than development of a single design, for most features are common, and the designs are in no way independent of one another. Indeed we think that this approach will enable us to cover a wide range of gravitational wave searches rapidly and in an interesting way.*

5.5. Development and Test of Laser Stabilization Techniques and Other Optics

The present interferometer system provides a very effective test bed for almost all of the final optical system, and we plan to develop the optical system as far as possible using it. A crucial element of our interferometer system is a highly stabilized, high power laser source. In our current work we have already achieved a laser frequency stability which would be adequate for the 5 km system - although further improvements are possible and would allow other experimental conditions to be relaxed. However we have only been operating at relatively low laser power so far, and our main efforts will now be in the direction of increasing output power from the laser system. We plan to achieve the required power by increasing the output from an individual laser and by coherently adding the outputs from a number of lasers. There are several possible ways of carrying out this plan, among them a technique using injection-locking of several slave lasers to a highly stabilized master laser, which is currently being developed by the French gravitational wave group under A. Brillet. We propose to investigate this and other techniques, and to test their performance in regard not only to fluctuations in frequency, but also to fluctuations in beam direction,

*We have assumed here that the choice of optics for the first joint receiver system will be of Fabry-Perot type, but if some unexpected problem with Fabry-Perot detectors emerges and it looks preferable to use a delay line system initially then we might wish to modify this program slightly.

beam convergence, and beam width. These latter types of fluctuation may be of particular importance in our interferometer systems, and we also plan to continue investigation of techniques for reducing these fluctuations, and to extension of these techniques to the relevant high power levels.

5.6. Development of Suspension and Isolation Techniques

The test mass suspension and control systems in our 40 m interferometer have gone through several successive development stages, and the current version operates very satisfactorily. We feel that this basic design will be quite suitable for high frequency experiments in the large scale facilities, with only minor modifications to remove or seal off some materials which are unsuitable for use in vacua of order 10^{-8} torr. A slightly scaled-up version of the same design could be used for much larger test masses. For experiments at low frequencies we would plan to supplement the passive seismic isolation of our current design with active isolation. Here we may employ both the differential suspension point monitoring and coherent driving method described in section 4.3 of this Proposal and the feedback mass tracking system of section 4.4. Both these methods of improving seismic isolation can be applied to our basic suspension system in a relatively simple and compact way. We feel that compactness has important advantages in these systems, partly because it facilitates the packing of several test masses in a confined space if the size and number of the vacuum tanks is severely limited by financial constraints, but more importantly because it makes it easier to avoid low frequency structural resonances which can complicate the operation of the high-gain servo loops used to control mass orientation and position.*

*This general area may be a useful one for collaboration with the MIT group, for our experience of seismic isolation and low-loss suspensions in several previous gravitational-wave detectors of both resonant-bar and interferometric types might well complement a different range of experience at MIT in servo systems or other areas.

We have been investigating[17] methods for deriving orientation control signals from the main interferometer, and may use these to automate alignment adjustments. We plan to test all aspects of the operation of the mass suspension and control systems in our existing interferometer system. Even over a baseline of 40 m, we expect much of the seismic noise to be sufficiently uncorrelated at the frequencies of interest to make these tests useful for exploring the performance to be expected in the large scale facilities.

5.7. Development of Data Analysis Techniques for Future Experiments

Data analysis forms an important part of gravitational wave experiments of all types. The fundamental problem is to find practical means to search large quantities of data for weak signals of different types. A single antenna can produce more than 10^{11} data samples per year which should be analyzed for bursts, continuous waves, and stochastic backgrounds. Some searches are straightforward and practical with existing equipment, while others will require more work.

We have already developed some relevant techniques in the test experiments to date. Future experimental searches for gravitational radiation of various types with the 40 m antenna will lead to continuing development. In this way, both the hardware and software for the data acquisition and analysis systems can be thoroughly tested under the most realistic conditions.

Two problems particularly seem difficult enough and important enough to justify a serious effort, which might lead to new analysis methods. The first is a search technique for unknown continuous sources, such as nonaxisymmetic rotating neutron stars. Simple Fourier analysis of the signal is insufficient, since for the integration times needed ($\gtrsim 10^6$ seconds), the doppler shift due to the earth's rotation will spread the signal over a wide frequency range. To correct for the doppler shift we must search not only over source frequency but also over source position. The other analysis problem is to devise an efficient means to search for the chirping type signal associated with a decaying compact binary (see section 2.3 of the joint Caltech-MIT proposal). The antenna output must be searched with a set of masks derived theoretically from a range of binary parameters. Since the integration time should be of order one hour, the range of the search will be limited unless a very efficient algorithm is devised.

5.8. Collaborative Aspects of our Experimental Program

We envisage a considerable amount of collaboration with other groups in our program, and particularly, of course, with the group at MIT with whom we are submitting the accompanying Joint Proposal for a design study for the planned large facilities. A close future collaboration with that group is planned on many aspects of the research. We also envisage a continuing and extending collaboration with the group working on gravitational radiation at the University of Glasgow. The Caltech project has benefited greatly from the exchange of people and ideas with the Glasgow group, and many features of the Caltech 40 m detector had their origin in Glasgow. This collaboration on detector techniques is beneficial all round, and will certainly continue; but just as valuable to all concerned could be gravitational wave searches with prototype antennas.

Coincidence searches for gravitational wave signals with the 40 m antenna and other interferometric gravitational wave detectors such as the 10 m Glasgow detector and the 30 m detector at the Max Planck Institute would be interesting scientifically and also most useful for facilitating the development of the special wideband data acquisition and analysis techniques required to make full use of these instruments. Coincidence experiments with groups operating resonant bar gravitational wave detectors will be interesting and useful also, and will be pursued. The interferometer experiments could well lead to joint long-baseline experiments using future larger antennas. Both the Glasgow and the Max Planck groups are planning kilometer-scale antennas, and the Orsay group has similar long-term plans. If these detectors are funded and built they would very much enhance the possibilities for long-baseline experiments. With three, and even more with four, widely spaced detectors the value of the experiments as tests of gravitational wave properties are much improved, and much more accurate and less ambiguous directional information for identifying astrophysical sources can be obtained.

In general there has been very good relations in the past between all the experimental groups in this field, and we expect and hope that this beneficial and friendly collaboration will continue in the future.

6. PERSONNEL

Since its inception five years ago, the experimental gravity group at Caltech has grown to a present size of about 10. It consists of 3 senior people (vitae in Section 7), two post-doctoral research fellows, four graduate students and one technician. This number has been just sufficient to maintain good progress on the 40m prototype, but not to attack some of the longer term problems (e.g. high power laser stabilization, active antiseismic systems) which must eventually be solved. For this reason, we expect the overall size of the group to grow somewhat during the five year grant period but to retain its present mix of personnel. This mix provides a continued flux of new ideas and talents, while retaining continuity in the ongoing research. The fact that students and post-doctoral research fellows can spend a few years on the project, make a valuable contribution, and then move to other projects and institutions has already been demonstrated. The gradual growth in the group should open a variety of new research areas, as well as providing for the increased activity connected with the large interferometers.

Another personnel development is the recent addition of Frank Schutz to serve as Project Manager for the joint Caltech/MIT project. Although his primary responsibility will be the design and construction of the large antenna facilities rather than with the laboratory work described in this proposal, his presence should have a positive effect on the prototype development. The anticipated growth of a small team of engineers associated with the joint project represents an additional resource which can be tapped, as appropriate, to help with key problems in the laboratory developments at both Caltech and MIT.

The budget includes each year a visiting associate for 3 months. It is expected that this visitor will be a relatively senior member from one of the other laser interferometer gravitational wave detector groups (Glasgow, MIT, Max Planck or CNRS/Orsay). The difficulty of gravitational wave detection and the need for coincidence experiments between widely separated detectors demands close cooperation between groups to coordinate joint experiments and to insure compatibility of exchanged data. The most effective means to bring about such cooperation is through visits and short-term exchanges of personnel. Although we foresee a clear need for such visits, the precise timing and duration of the visits, and even the personnel involved, are left flexible.

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