Presented at Workshop on Gravitational Radiation
Ecole d'Ete de Physique Theorique, Les Houches, France
June 1982

OAP-648

INTERFEROMETRIC DETECTORS FOR GRAVITATIONAL RADIATION*

R. W. P. DREVER

W. K. Kellogg Radiation Laboratory

California Institute of Technology, Pasadena, California 91125

and

University of Glasgow, Glasgow, Scotland

ABSTRACT

A review of some of the principles of laser interferometer gravitational radiation detectors, with discussion of factors which may set limits to sensitivity. Possibilities for enhancing sensitivity in searches for various kinds of signals are suggested.

*Research supported in part by the USA National Science Foundation [PHY82-04056] and in the UK by the Science and Engineering Research Council.

*ONE OF THE ORANGE AID PREPRINT SERIES
IN NUCLEAR, ATOMIC & THEORETICAL ASTROPHYSICS*

October 1982

LIGO-T820001-00-R

TABLE OF CONTENTS

INTERFEROMETRIC DETECTORS FOR GRAVITATIONAL RADIATION

R. W. P. DREVER

California Institute of Technology, Pasadena, California
and
University of Glasgow, Glasgow, Scotland

1. INTRODUCTION

Most of the experiments aimed at the detection of gravitational radiation carried out to date have employed resonant bar gravity wave detectors, in which changes in longitudinal vibration of a suspended metal bar, due to the apparent differential action of the gravity wave on the material towards the ends of the bar, are sought. An alternative approach, in which changes in the relative motions of two or more widely separated and nearly free test masses are monitored using laser interferometry, is now being developed in several laboratories. We shall outline here some of the principles and ideas behind these laser interferometer gravitational wave detectors, and also some possibilities for further development of these techniques which seem interesting for future experiments.

An obvious way one might consider detecting gravity waves is through the changes in separation of free test particles, and the idea of using optical interferometers for observing this has certainly occurred to many physicists: indeed one might wonder why so few searches for gravity waves have been made this way. The smallness of the expected effects provides the main answer: for even the relatively strong signal from a supernova in our galaxy would give a relative motion in a pair of test masses 10 meters apart on only 10^{-16} m, and the idea of measuring this in a time of order of a millisecond using light of wavelength nearly 10^{10} times larger than this is not initially attractive. With the resonant bar technique, however, the test masses are linked together by the elasticity of a metal bar chosen to resonate near the frequency of interest, extending the time available for the measurement up to the damping time of the bar, and enabling piezo-electric or capacitative transducers to be used which approach this order of sensitivity. These resonant bar detectors, pioneered by Joseph Weber, have been, and are being, successfully developed in many laboratories.

If one looks for much higher sensitivity, however, as may be required for detection of supernova signals from the distance of the Virgo cluster, the very small energy changes to be sensed in a resonant bar detector do impose serious practical difficulties. Thermal noise in the bar, and transducer sensitivity, are both severe problems, even in a low temperature system. It used to be thought that quantum limits would set a fundamental barrier, but there now appear to be ways of avoiding these in principle and the thermal noise seems to be the dominant problem. In this region of gravity wave sensitivity, there are of course severe problems with free mass detectors too; but with these, there is the important advantage that the displacements to be observed may be increased considerably by increasing the distance between the masses – in principle till the distance becomes comparable to half the wavelength of the gravity wave, typically many tens of kilometers. Thermal moise is made even less important by the fact that there is no need for any material connection between the test masses to resonate near the frequencies of interest. A free mass detector also looks likely to operate over a wider range of frequencies than resonant bar instruments. These considerations have made it seem worthwhile to investigate and develop possibilities for free-mass gravity wave detectors with optical displacement sensing.

2. SENSITIVITY DESIRABLE

The wide spectrum of gravitational radiation signals expected from astronomical phenomena of various types presents a considerable range of possible targets for experimental searches, if adequate sensitivity can be achieved. Much effort has gone into estimating radiation fluxes, and recent work in this area is reviewed elsewhere in this volume. Several summaries of spectra of gravitational radiation anticipated at the earth have also been published.[1] A part of the spectrum relatively accessible to earth-bound experiments is that in the region between a few tens of hertz and a few kilohertz and here signals from stellar collapse in our galaxy may give amplitudes of order 10^{-17}, but probably occurring at a rate less than one per year. For a pulse rate of order one per month a sensitivity of order 10^{-21} or better in gravity wave amplitude may be required. Indeed at sensitivities around this several types of sources may become detectable and this might be an interesting target to consider for future pulse experiments-at least in the long term. Other types of signals are also possible targets, such as the continuous gravitational radiation from pulsars, or a stochastic background from the big bang or from stellar collapse processes occurring at an early epoch. In these cases the gravity wave amplitudes expected are even smaller than from impulsive events, but the continuous nature of the signal may in principle enable higher sensitivity to be achieved with an appropriate detector and suitable mode of operation, as we will consider later.

3. BASIC ARRANGEMENT

To attempt to measure by optical means a change in distance between a pair of masses of order one part in 10^{21} would require an exceptionally stable wavelength standard; and there are obvious advantages in making a differential measurement of two almost equal baselines perpendicular to one another, which may be opposite ly affected by a gravitational wave of suitable polarisation and direction of propagation. In principle this might be done using a Michelson interferometer tc compare distances between mirrors attached to three test masses suspended like pendulums, as schematically indicated in Figure 1. Monochromatic light is not

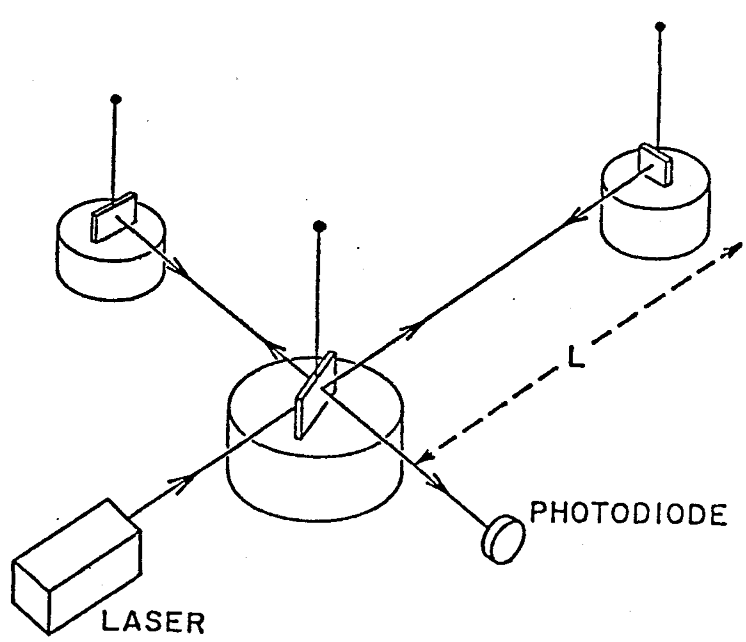

Figure 1

essential for such a measurement, but a laser is a convenient source because of the intensity and directional properties of its output. Let us assume that the gravitational waves of interest have a period short compared with the period of the pendulum suspensions, so that the test masses may be regarded as effectively free for small horizontal motions, and consider some of the more basic noise sources expected in a measurement of a short gravitational wave pulse.

3.1 Quantum Limit.

One limit to the sensitivity of a pulse measurement would be set by the quantum uncertainty in the position of each of the free masses. For detection of change in position over a time τ, the duration of the gravity wave pulse, the smallest displacement detectable is approximately $(2\hbar\tau/m)^{\frac{1}{2}}$, where m is the mass and $2\pi\hbar$ is Planck's Constant. If the baseline L between the masses is 40 m, the pulse duration τ is one millisecond, and test mass m = 100 kg, this quantum uncertainty would set a limit to gravity wave amplitude, h, detectable at unity signal to noise ratio, of order $h = 10^{-21}$. Thus for a 40 m detector, the quantum limit is of the same order as our target sensitivity for short pulses, and it could be reduced further by increasing the baseline. In fact the quantum limit is not likely to be a serious difficulty in searches for short pulses with this type of detector, although it may become important in measurements of long pulses or continuous signals. In practice, photon counting error is more likely to be a problem.

3.2 Photon Counting Error.

As the motions expected are small compared with the wavelength of the light, only a small change in output light intensity can be anticipated, and in a simple system this must be detected in the presence of intensity fluctuations due to photon counting statistics, at the least.[2] In the arrangement in Figure 1, a single photodetector is indicated receiving light from one side of the beamsplitter. In this situation, it may be shown that the displacement sensitivity set by photon counting error depends on the initial phase difference between the two components making up the output light, and optimum photon-shot-noise-limited sensitivity is obtained when the phase difference tends to π, that is near a dark fringe in the output light. If it is assumed that the photodiode has unity quantum efficiency, then the corresponding limit to the amplitude of gravitational wave detectable is $h = (\lambda\hbar c/ 8\pi L^2 I \tau)^{\frac{1}{2}}$, where I is the laser power, λ is the wavelength of the light, and c is the velocity of light. An alternative mode of operation would be to use two photodiodes, one detecting light from each side of the beamsplitter; and in this case the same overall sensitivity may be obtained anywhere in the fringe pattern. In either case, if we take a laser power of 1 watt at a wavelength of 500 nm, a baseline L = 40 m and measuring time τ of one millisecond as before, the gravity wave amplitude giving unity signal to noise ratio against the photon counting error is $h = 2 \times 10^{-17}$. This is far from our target sensitivity; and if we were to attempt to approach the quantum limit by merely increasing the laser power in this simple configuration we would require many megawatts of light.

It may be noted that some pioneering experiments with this type of gravity wave detector have been carried out using a configuration essentially similar to this by Moss and Forward[3], who showed that performance near the photon noise limit for a low power laser could be achieved.

An ingenious proposal for reducing photon counting error was recently made by C. M. Caves[4], who suggested use of squeezed photon states. By altering the distribution of vacuum fluctuations between two orthogonal phases, the photon counting fluctuations may be decreased at the expense of increased but less significant fluctuations in differential radiation pressure on the test masses. Practical application looks difficult at present, due partly to losses in the non-linear optical elements required; but the idea is in principle an extremely interesting one.

An important practical method for improving photon-noise limited sensitivity was suggested by R. Weiss[5]: the use of optical delay lines to reflect the light beam many times between the test masses, and thus increase the optical phase shift resulting from relative motion. Experimental work on this type of multiple-reflection Michelson interferometer has been, or is being, carried out at several laboratories including M.I.T., the Max Planck Institute at Munich[6], and the University of Glasgow.[7]

4. MULTIREFLECTION MICHELSON INTERFEROMETERS

A simplified schematic arrangement for a multireflection Michelson interferometer gravity wave detector is shown in Figure 2. Here the light is made to traverse the distance between the test masses many times by a suitable optical system, such as a Herriott delay line, before it recombines at the beamsplitter. This increases the total phase shift experienced by the light for a given movement of the masses by the number of round trips in each arm: and by using a suitable concave mirror configuration to minimize diffraction losses this number can be made large. In practice the useful number of reflections may be limited by one of two factors: the reflection losses at the mirror, or the total light travel time within each arm of the interferometer. In the first case, with mirror losses important, it may be shown that optimum photon-noise-limited sensitivity is obtained with a number of reflections in each arm equal to $2/(1-R)$, where R is the mirror reflectivity. The sensitivity achieved is then better than that of a simple Michelson interferometer by a factor of $e(1-R)$, where $e = 2.72\ldots$ In a system with baseline $L = 40$m, mirror reflectivity $R = 0.997$, and other parameters as before, this would give a gravity wave sensitivity of order $h = 10^{-19}$.

If, however, the baseline were large enough, and the mirror reflectivity high enough to cause light making $2/(1-R)$ reflections to spend a time within the system longer than the time scale in which the gravity wave reverses its sign, then

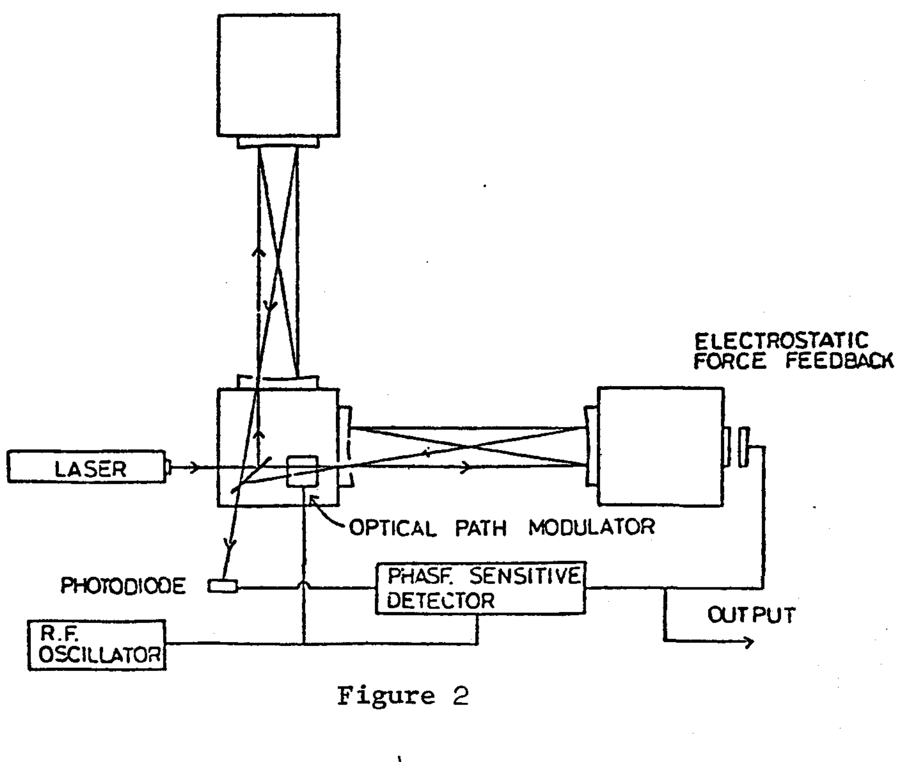

Figure 2

some cancellation of signal could occur. In this case it would be nearer optimum to choose the number of reflections to make the light spend a time in each arm equal to the time scale of the gravity wave. The sensitivity then becomes independent of arm length; and for a storage time of one millisecond and a laser power of 1 W, this could correspond to $h = 2 \times 10^{-21}$ for either a 40 m armlength system with 8000 reflections or a 4 km armlength system with 80 reflections.

These examples are idealised, of course, but they do suggest that interesting sensitivities might be achieved with this type of gravity wave detector if the many practical problems could be overcome. Also, there are some new ideas for improving the photon-noise-limited sensitivity even further, as we shall discuss later.

One practical difficulty in the optical sensing system just described became apparent in early experiments at Munich and at Glasgow - the potentially serious effect of incoherent scattering of light at the multireflection mirrors or elsewhere in the system. If scattered light reaches the photodetector having traversed a path different from that of the main beam, it will differ in phase from it by an amount dependent both on the path difference and the instantaneous wavelength of the light. The path difference involved can be very long - comparable to the total travel distance through the system - so small fluctuations in wavelength may give relatively large phase fluctuations in the output, particularly as the phase fluctuation in the resultant beam is proportional to the relative amplitude of the scattered light and not its relative intensity. The effect may be reduced by precise stabilisation of the wavelength of the laser, and also by arranging that the spots on the multireflection mirrors where successively reflections take place do not overlap, but it may still be important in a large system. The Munich group suggested[8] that the effect might be reduced further by modulating the wavelength of the laser light through an amount chosen to make the phase difference of the major components of the scattered light average to zero over the integration time of the measurement. Another approach would be to make the path traveled by scattered light equal to that of the main beam, and this may in fact be achieved if another type of optical system, a Fabry-Perot cavity, is used instead of a Michelson interferometer with many discrete reflections in each arm.

5. OPTICAL CAVITY INTERFEROMETERS

5.1 Principle.

The idea of using changes in the resonant frequency of an optical (or microwave) cavity to detect small motions is an old one, but one practical method of using optical cavities in gravity wave detectors was outlined only relatively recently.[9] The principle is indicated in Figure 3. Light from a laser passes through a beamsplitter to a pair of Fabry-Perot cavities formed between mirrors attached to the three test masses. If the lengths of the two cavities are adjusted to give resonance with the light from the laser, then differential changes in length may be sensed by changes in the resonance conditions and small changes near resonance may be detected by measuring phase changes between light within each cavity and the input beam, or directly between one cavity and another. The phase difference might be detected by interference between light emerging from each of the cavities back through its input mirror, possibly by using the high frequency phase modulation technique shown in Fig. 2 in connection with the multi reflection Michelson interferometer. One way of carrying this out is indicated schematically in Figure 4. Here light from the cavities is phase modulated by two Pockels cells, P1 and P2, driven in antiphase at a suitable radiofrequency, and is detected by photodiode D1. The output from this photodiode, when synchronously demodulated, can give a measure of the phase difference between the light in the cavities. An optical isolator I is used to prevent reflected light affecting the operation of the laser. The additional photodetectors D2 and D3

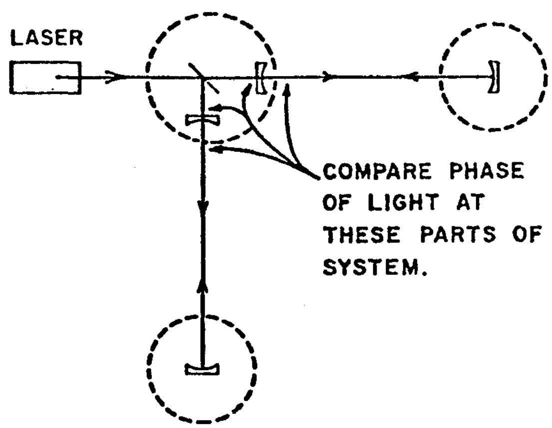

Figure 3

are for auxiliary functions which will be described later.

The maximum sensitivity in this arrangement is obtained when the second mirror in each cavity has the highest reflectivity available, R, say, and the reflectivity of the input mirror for each cavity is chosen either to give optimum photon-noise-limited displacement measurement or to give a light storage time equal to the time scale of the gravity wave, whichever is appropriate. In the former case it may be shown that the gravity wave sensitivity is given approximately by $h = (1-R)\ (\lambda \hbar c/8\pi L^2 I \tau)^{1/2}$, where it is assumed that absorption and scattering losses in the transmission of light by the input mirrors of the cavities are negligible (that is, transmission coefficient = 1-R). This expected

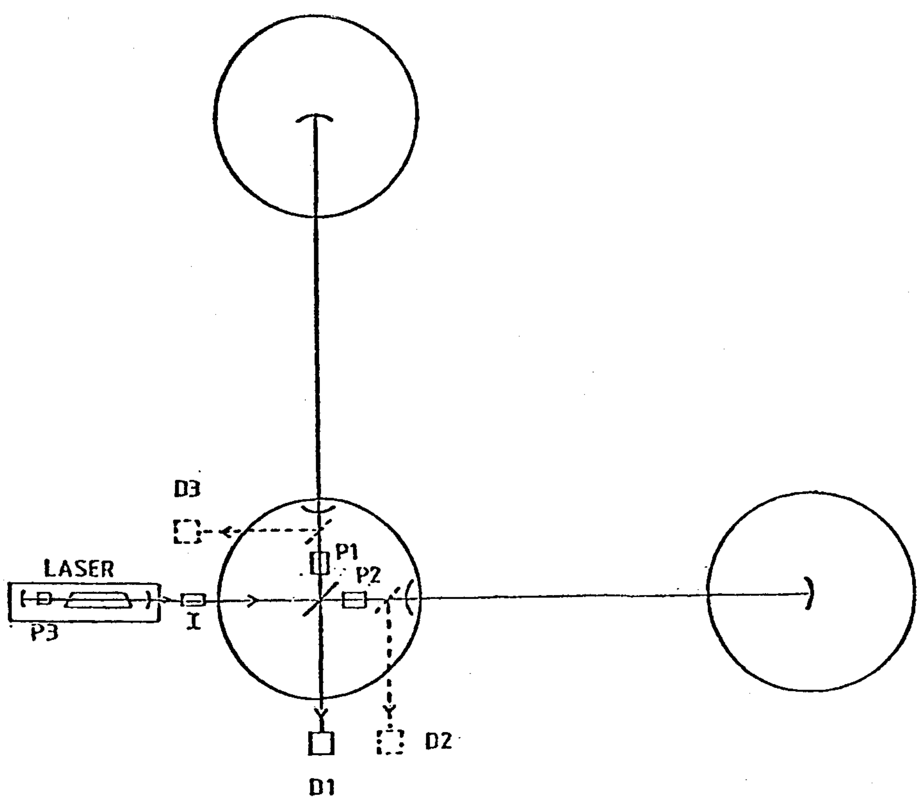

Figure 4

sensitivity is better by a factor of about 2 than the sensitivity obtainable by a multireflection Michelson interferometer using mirrors of the same reflectivity, but transmission losses may degrade this so that in practice the photon noise limit to sensitivity of the two types of optical system is likely to be roughly equal.

There are several advantages of this type of cavity interferometer over the delay-line Michelson system, apart from the possibility of reduced phase noise from scattered light. The diameter of the cavity mirrors can be considerably smaller than that of delay-line mirrors; and for example, even with cavities 10 km long, a mirror diameter of 18 cm is sufficient to make diffraction losses less than 1 part in 10^5 for light of wavelength 500 nm. This reduces the diameter of vacuum pipe required, and also may make it easier to keep mechanical resonances in the mirrors and their mountings high compared with the frequency of the gravity waves, thus minimizing thermal noise. The Fabry-Perot system has, however, some obvious disadvantages too – particularly the requirement for very precise control of the wavelength of the laser and of the lengths of the cavities. Indeed with long cavities of the high finesse desirable here exceptional short-term wavelength stability is required from the laser. A special laser stabilisation technique has been developed to provide this.

5.2 Laser Wavelength Stabilisation

The principle of the laser wavelength control system being used is shown in Figure 5. Plane polarised light from the laser is phase modulated by passage through a Pockels cell, at a frequency in the range of 10 to 40 MHz, and then enters one of the Fabry-Perot cavities through a polarising beamsplitter and a quarter-wave plate. The axes of the quarter-wave plate are oriented at $\pm 45^o$ to the polarisation of the input light, so that circularly polarised light enters the cavity. Light coming back from the input mirror of the cavity is circularly polarised in the opposite sense, is transformed into plane polarised light with polarisation orthogonal to that of the input beam, and is reflected by the polarising beamsplitter to the photodetector. The light arriving at the photodiode can be considered to have two components: the

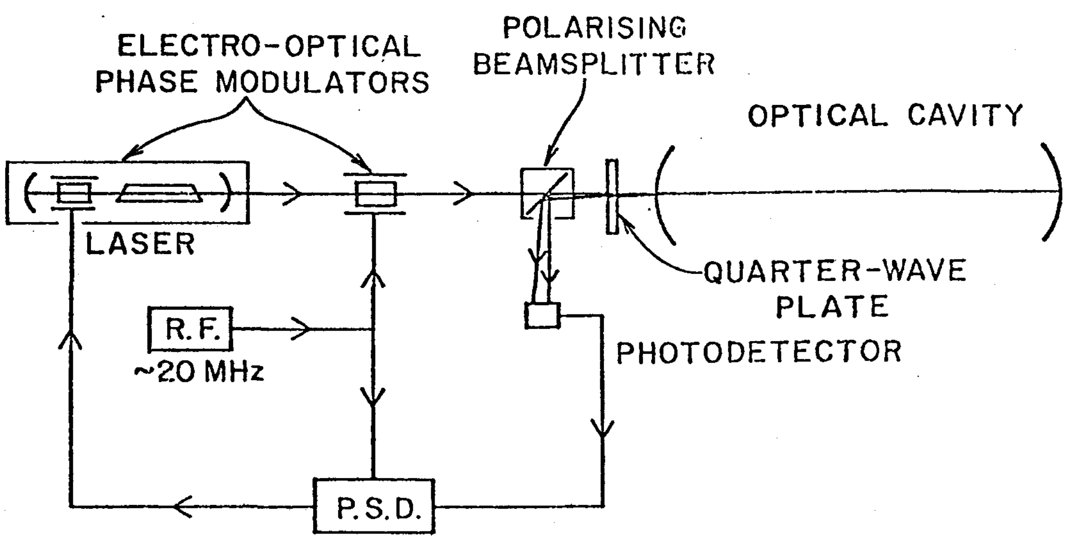

Figure 5

phase-modulated laser light directly reflected by the input cavity mirror, and light emerging from within the cavity - which has built up over the cavity storage time and thus has had its modulation sidebands removed. In the figure, these components are drawn as diverging rays to make the operation clearer, although they are of course coincident in reality. If the laser light is precisely in resonance with the cavity these two components have opposite average phase, and the photodiode output has no component at the modulation frequency. If the laser is slightly off resonance, the photodiode gives a signal at the modulation frequency whose amplitude and phase indicates the magnitude and sign of the error. Demodulation of the photodiode signal by a phase sensitive detector (P.S.D.) gives a voltage signal which may be applied to a second Pockels cell within the laser cavity itself, so that the wavelength of the light from the laser is driven closer to the cavity resonance, and the laser becomes locked in wavelength to the cavity. To achieve a high degree of stabilisation at the gravity-wave frequency it is important that the control system has a wide bandwidth, and a useful feature of the arrangement is that the rise time of the phase error signal is not affected by the fact that the cavity may have a very long storage time.

Early experimental work on this laser-cavity stabilisation technique has been done at the Joint Institute for Laboratory Astrophysics, Boulder, using dye and helium-neon lasers* and at Glasgow, and subsequently Caltech, with argon ion lasers[10,11], and has shown that adequate stabilisation for at least the current stage of development of the Fabry-Perot interferometers can be achieved.

A considerable amount of experimental work relating to gravity wave detectors using Fabry-Perot interferometers has been carried out at Glasgow and at Caltech, much of the earlier work being done with a slightly different arrangement, shown in simplified form in Figure 6. Here triangular cavities are used instead of 2-mirror cavities so that optical feedback to the laser is avoided without use of

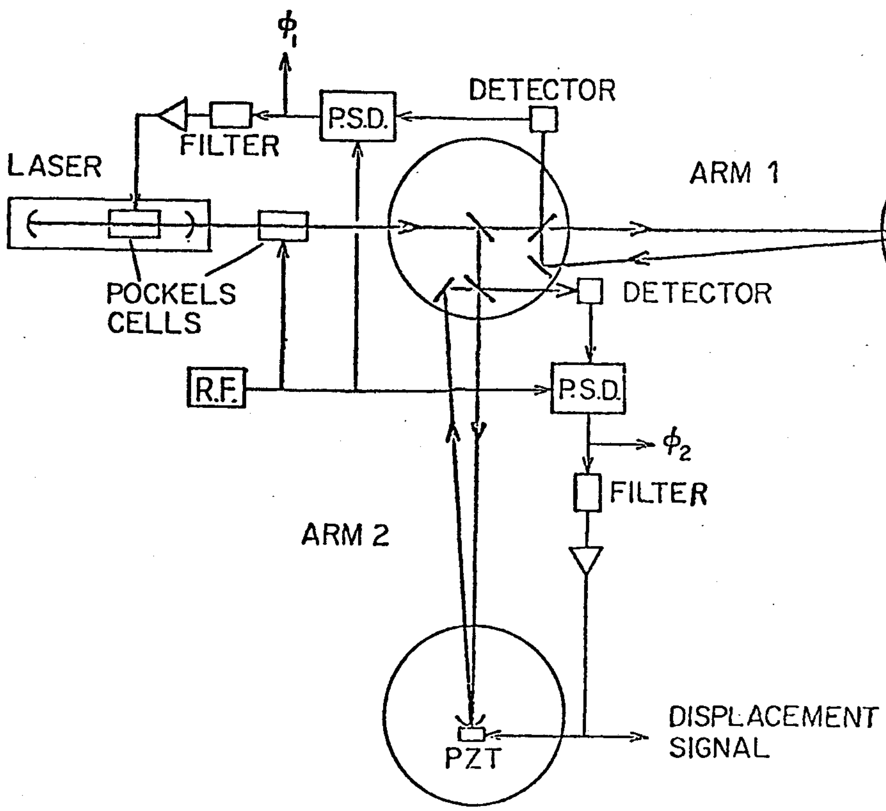

Figure 6

isolators, and separate detection of signals from the two cavities is used to simplify the optical system. The laser is shown arranged to be locked in wavelength to the right-hand cavity (arm 1) in the figure by the method described above;and a similar phase measuring system is then used to give a fine adjustment to the length of the lower cavity (arm 2) by a piezoelectric transducer (PZT) on which one of the cavity mirrors is mounted, so that this cavity becomes locked into resonance with the wavelength of the light. With this arrangement, a signal corresponding to a gravity wave disturbance may be obtained, approximately, from the feedback voltage applied to the piezoelectric transducer, or, more precisely, from a suitable combination of this signal with the phase error signals ϕ_1 and ϕ_2 from the two feedback loops.

It may be noted that separate detection of resonance in the two cavities, as indicated here, does in principle degrade the photon-noise-limited sensitivity by a factor of 2, but it is convenient for initial experiments since it avoids need for Pockels cells on any of the test masses, or matching of cavity finesse. Optical systems more like that shown in Figure 4 are now being developed. Here the auxiliary photodiodes D2 and D3 shown dotted are intended for laser stabilisation and to facilitate monitoring of the two cavities, and would be arranged to use only a small sample of the total available light.

The experimental development of laser interferometer gravity wave detectors based on either the multireflection Michelson or the optical cavity system outlined has led to overall arrangements which are in practice considerably more complex than suggested by the diagrams here, for additional feedback systems have to be incorporated to control orientation and position of the test masses in the presence of seismic disturbances, and fluctuations in direction and position of the laser beam have to be reduced by passive or active optical systems. Although many problems remain to be overcome, the experimental work has gone far enough to make it seem likely that optical sensing performance close to that indicated by the simple theoretical estimates given above may indeed be achievable by either of the techniques we have outlined. It may be useful to consider some other basic noise sources at this point, and in particular thermal noise - for this is a limiting factor in current resonant bar gravity wave detectors, and is not negligible here.

6. THERMAL NOISE IN LASER INTERFEROMETERS

The real or apparent fluctuations in motion of test masses have to be carefully considered in any gravity wave experiment, for the displacements to be observed are usually small compared with the mean amplitudes of thermal motion. In the type of nearly free mass detector discussed here the mechanical thermal noise may be conveniently divided into two parts - that associated with the low frequency pendulum mode of oscillation of the test masses, and that associated with internal degrees of freedom of the test mass and mirror structure itself. Relevant analyses of thermal noise fluctuations have been given by Weiss[5], Braginsky and Manukin[12], and others; we will just summarise some results here.

6.1 Thermal Noise - Pendulum Mode.

With a simple pendulum suspension of convenient length, the resonant frequency for the pendulum mode of a test mass is of order 1 Hz or lower, well below the frequency of interest for initial gravity wave searches. The power spectral density of displacement is given approximately by $(\delta x)^2/\delta f = 4\ kT\ \omega_0/m\ Q\ \omega^4$, where ω_0 is the angular frequency of the pendulum resonance, Q the quality factor of the resonance, m the test mass, ω the angular frequency of interest, k = Boltzman's Constant, and T the temperature. Some early tests at Glasgow suggest that construction of a simple pendulum with Q near 10^6 is quite practicable;and if we take this value for Q, a mass m=10 kg, $\omega_0=2\pi$, $\omega=2\pi.1000$,and T=300 we find that in a system with a 40 m baseline, thermal noise would set a limit to sensitivity of the order of $h = 3 \times 10^{-22}$ in a bandwidth of 1 kHz. This component of thermal noise is therefore not expected to be very serious at these frequencies, if an effective high Q can be maintained in a practical suspension system; and a longer baseline will reduce the noise further. However thermal noise may well become important at lower frequencies.

6.2 Thermal Noise - Internal Modes

Internal vibrations of the test mass structure can be very complex and there may be many modes near the frequency of interest when the test mass incorporates several mirrors and other components. To minimize the thermal noise in the frequency region of interest, it is desirable to keep the resonant frequency of all modes as high as possible, and certainly high compared with the gravity wave frequency - which may not be easy. In this case, for a single mode of angular resonant frequency ω_0, the power spectrum of displacement is given approximately by $(\delta x)^2/\delta f = 4\,kT/m\,Q\,\omega_0{}^3$. If we take as example $m = 10$ kg, $T = 300$, $\omega_0 = 2\pi.5000$ and $Q = 10^6$, we find that this sets a limit of about $h = 6 \times 10^{-21}$ in a bandwidth of 1 kHz with a system of baseline 40 m. These values for Q and ω_0 are however not easy to achieve in a complex structure. Increase of baseline makes this component of thermal noise less significant, but it is evident that careful design of the test mass structure is required.

It may be noted that the Fabry-Perot cavity type of interferometer may have a disadvantage here in that it is likely to require more precise mirror adjustment than a Michelson system, and thus lead to a more complex structure for at least one of the test masses. One arrangement which we suggest may ameliorate this problem involves use of two separate and very simple test masses at the junction of the two baselines, each containing merely a single cavity mirror, with a separate and more complex suspended structure incorporating the rest of the optical components. In this way, the thermal noise may be minimized in the parts where it is most significant, although the system as a whole does become more complex. At the present stage these problems have not been fully investigated, although considerable advances in reducing thermal noise in a Michelson interferometer system have been made by the Munich group. At present, it appears that to keep internal thermal noise sufficiently small does require careful design of the test masses, but we feel that the problems involved are by no means insoluble ones.

Some notes on the question of seismic isolation of an interferometer gravity wave detector may be appropriate at this point.

7. SEISMIC ISOLATION

Isolation from seismic disturbance is an important practical problem for any type of gravitational wave detector. In the region of the spectrum around 1 kHz, however, it has been tackled very successfully in work with resonant bar gravity wave detectors. At these frequencies good vibration attenuation can be obtained by simple stacks of lead or steel masses alternating with layers of rubber, of the general type developed and widely used since the initial experiments of Joseph Weber. These same methods are applicable for interferometer detectors, and indeed in some ways the problems are simpler than for resonant bar detectors of the same sensitivity, for the displacements to be observed are larger with the laser detectors due to the much longer baselines involved. The seismic motions at the ends of a long baseline are of course less correlated than the motions at the two ends of a resonant bar, but the isolation of the simple pendulum suspension of a single test mass is sufficient on its own to give good attentuation at 1 kHz. Overall, it seems that seismic isolation is unlikely to be a very serious problem for gravity wave frequencies near 1 kHz, although it becomes rapidly more difficult at lower frequencies. It may be noted that low frequency motions of the suspended test masses can give dynamic range problems in optical interferometer systems, and active feedback systems are necessary to damp and restrain the low frequency movements of the masses. The masses may be controlled by applying magnetic or electrostatic forces, or by mechanical motion of the points from which the suspension wires are supported, and all of these methods have proved satisfactory to some degree. The problems involved are technically quite challenging ones, and the solutions are interesting, but it is not appropriate to discuss these in detail here in this article which relates more to basic limitations to the interferometer techniques.

We have now discussed many aspects of laser interferometer gravity wave detectors and have indicated how there may be real possibilities for achieving gravity wave amplitude sensitivities of the order of 10^{-21} for 1 millisecond pulses, with large scale instruments of this type. The most serious limitation to sensitivity in this part of the spectrum looks likely to come from photon counting noise, and although this may possibly be reduced by increases in laser power, or use of multiple lasers, there would seem to be practical limits to these solutions. It may be useful to briefly discuss here some relatively new ideas which suggest alternative ways of improving sensitivity, although it should be emphasized that these suggestions relate more to future possibilities than to the current stage in the experimental development of the techniques.

8. POSSIBILITIES FOR FUTURE ENHANCEMENT IN SENSITIVITY

8.1 Possibility for More Efficient Use of the Light.

It has been mentioned in Section 3.2 that in a Michelson interferometer using a single photodetector maximum sensitivity is obtained when the detector is near a dark fringe; and if the system is efficient and adjusted so that one fringe extends over the whole width of the output beam this implies that most of the light leaves the interferometer through the other side of the beamsplitter. It has occurred to us that this light may be fed back into the interferometer by making it add coherently to the initial laser beam by means of an additional mirror of suitably chosen reflectivity, as indicated in Figure 7. Accurate adjustment of path lengths or of laser wavelength would, of course, be necessary to insure that maximum enhancement of light is achieved, and one way of doing this might be with the phase modulation laser-cavity locking system described in Section 5, using a phase modulating Pockels cell P3 and additional photodetector D2, with the system arranged to minimise the light intensity at D2. The whole optical system then

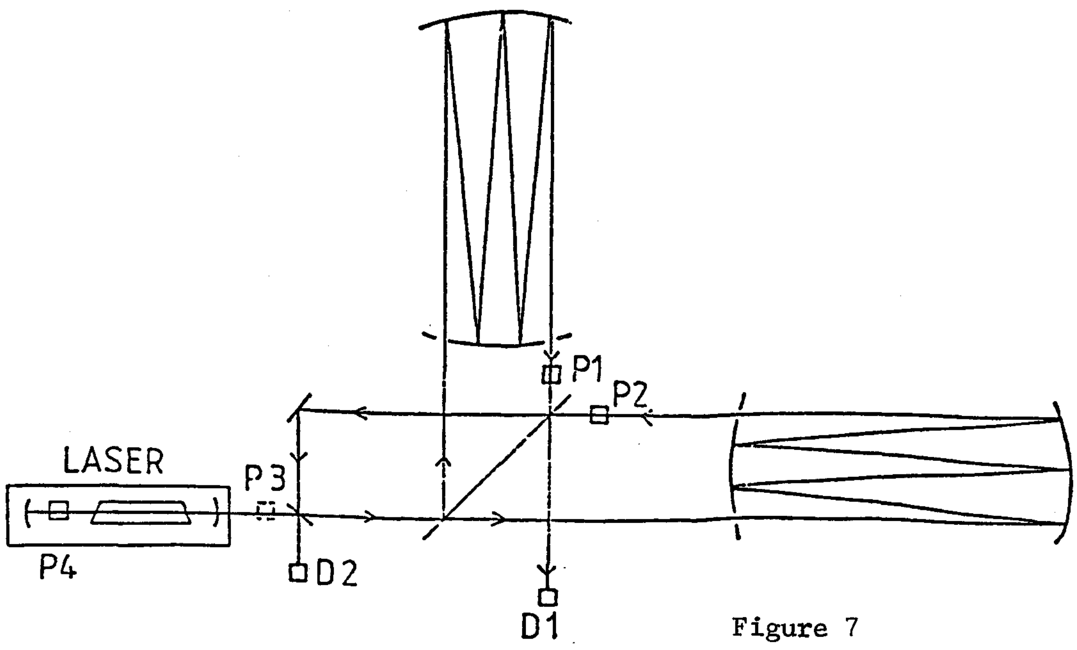

Figure 7

functions like a large Fabry-Perot cavity , and if losses are small and the input mirror reflectivity is suitably chosen there can be considerable enhancement of internal light flux. This arrangement is only useful if the combination of arm length and reflectivity of the delay line mirrors is such that the maximum achievable storage time of the light within each delay line is longer than the time-scale of the gravity waves of interest. The number of reflections in each arm would then be chosen to give a storage time which matches the gravity wave time-scale, and the light intensity within the whole system can then build up over a time approaching the maximum storage time permitted by the losses in the mirrors and other components. If the system is such that the dominant losses are those associated with delay line mirrors of reflectivity R, and the reflectivity of the feedback mirror is chosen for maximum light buildup, then the sensitivity is given approximately by $h = \{ \lambda \hbar (1-R)/2 \pi L \; I \tau^2 \}^{\frac{1}{2}}$, where I= output power of laser. If one considers a large system, with baseline L= 10 km, and $(1-R) = 10^{-4}$, then the sensitivity would be of order 10^{-22} for 1 millisecond gravity wave pulses, with a laser power of 10 watts. These parameters are not impossible ones for future experiments.

The same method may be applied to optical cavity interferometers also, as shown, for example in Figure 8. Again, the system is only useful if achievable storage times exceed the time-scale of the gravity waves of interest. The reflectivity of the input mirror of each cavity is chosen to give a storage time within the cavity which matches the time-scale of the gravity wave, which under these conditions would lead to reflection of a large fraction of the light incident on each cavity input mirror back towards the laser. An additional mirror is added in front of the laser to return most of this light back to the interferometer, with phase adjusted to enhance the input light from the laser. If the reflectivity of the input mirror is suitably chosen for maximum light buildup, then the

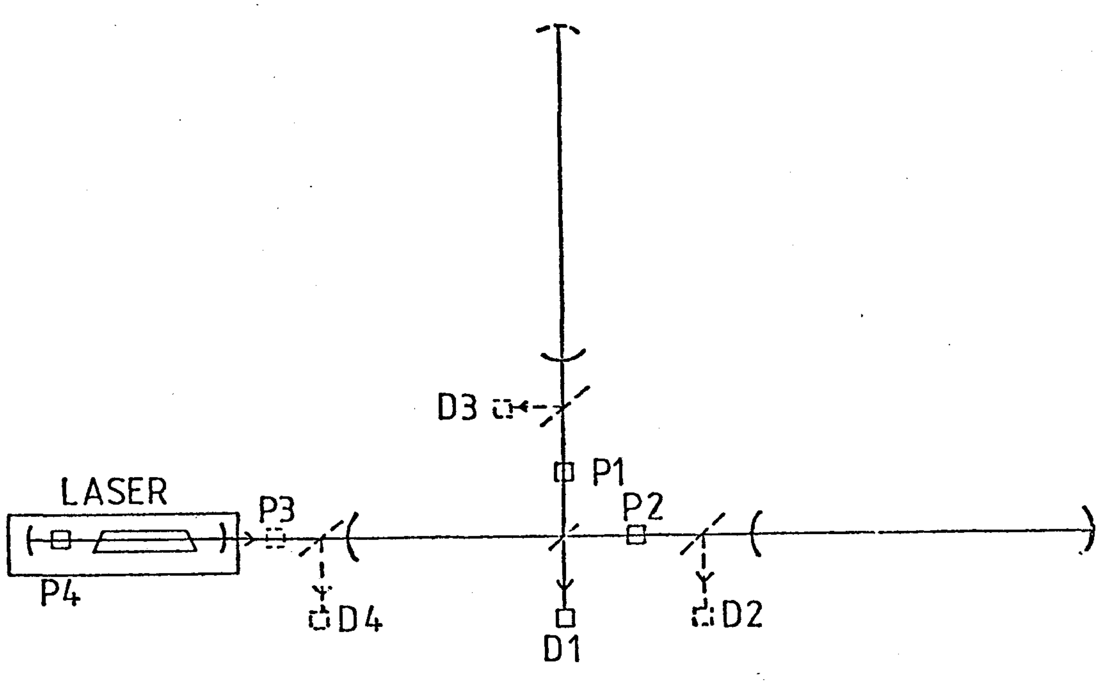

Figure 8

photon-noise-limited sensitivity of this system becomes essentially equal to that of the Michelson interferometer system just described. Precise adjustment of optical paths as well as laser wavelength is required to achieve correct phasing within this system, and auxiliary photodiodes D2, D3 and D4 along with phase modulators P1, P2 and P3 are indicated as means of achieving this. As the internal phase adjustment requires only a narrow bandwidth the photodiodes D2 and D3 need only remove a very small fraction of the light circulating within the system.

With these proposed techniques for re-use of light within an interferometer,[13] the optical system as a whole may be regarded as a large cavity which stores up light to an extent limited in principle only by the losses in the components. When a gravity wave pulse arrives, the resultant phase changes allow a part of this stored energy to pass out quickly to the output photodiode. The system may thus be quite energy-efficient, and it looks a promising one for future experiments.

8.2 A Possibility for Enhancing Sensitivity for Periodic Signals.

Our discussion so far has concerned principally the detection of short gravity wave pulses, but it is evident that the same kind of apparatus could be used for searching for periodic gravity wave signals, such as those expected from pulsars, from rapidly rotating neutron star binaries, or possibly from vibrations of neutron stars or other objects. By use of appropriate data processing and integration over many periods of the gravity wave it is clear that better amplitude sensitivity may be obtained with periodic signals than with single pulses. Consideration of expected signal strengths from known sources, such as the Crab or Vela pulsar, does however suggest that it would be useful to have a sensitivity higher than obtainable in this way. We propose now a possible method for further enhancing the sensitivity of a laser interferometer detector for periodic signals. This technique, like the ones described in the previous section, depends on use of an optical system capable of giving very long light storage times - the condition in this case being that the combination of baseline length and mirror losses should enable light to be kept in the system for times long compared with the period of the expected signal.

The idea is most easily explained for a multireflection Michelson interferometer which in this application might have its optical system re-arranged as shown in Figure 9. Light from the laser enters the system through a beamsplitter, M1,

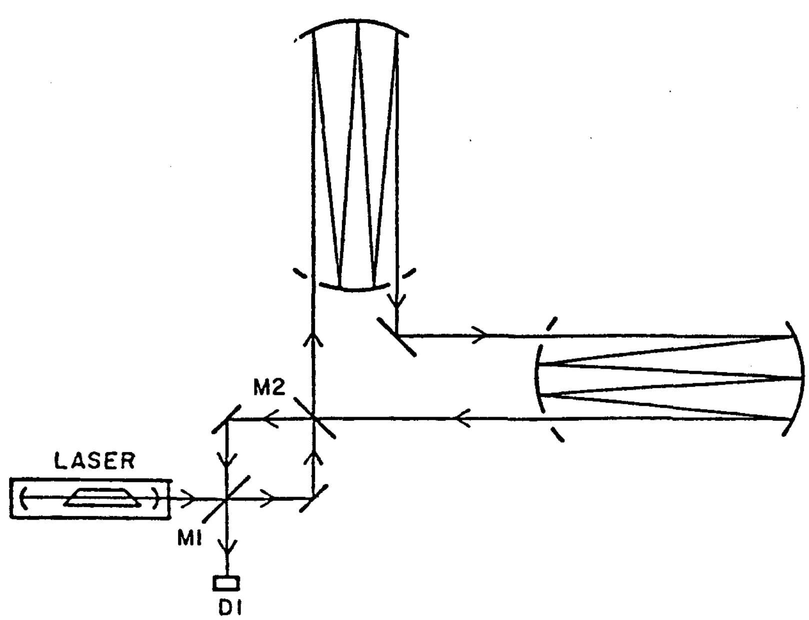

Figure 9

which divides it into two equal parts which pass through a mirror, M2, of suitably chosen high reflectivity and then traverse the delay lines in opposite directions. It is arranged that each delay line introduces a delay equal to half of the gravity wave period. Light travelling in the direction of the arrows which enters the upper delay line at a time when the gravity-wave-induced displacement of the test masses is changing its sign will have its phase shifted in one direction while it is within this delay line. It then leaves this delay line and enters the right-hand one just as the gravity-wave displacement is reversing, so that this light experiences a further shift of phase in the same direction in the second delay line. Most of the light then retraverses the first delay line where further phase shift takes place. Light passing through the delay lines in the opposite direction experiences a buildup of the opposite phase shift, and the phase differences generated over the total storage time of the system may eventually be detected at photodiode D1, possibly using a radio-frequency phase modulation system (omitted from the diagram for simplicity).

An optical cavity gravity wave detector can also be arranged in a similar way to have enhanced sensitivity for periodic signals, as indicated in Figure 10. Here the storage time of each cavity is made to equal half of the period of the expected signal by suitably choosing the reflectivity of mirrors M3 and M3'; and by use of polarising beamsplitters (labelled POL. in the figure) and quarter-wave plates (labelled $\lambda/4$) the light is made to circulate from one cavity to the other, building up phase shift from a gravity wave signal over the total storage time of the system.

The buildup of phase differences over a long storage time can give a considerable improvement in the photon counting limit to the sensitivity of both these types of interferometers. In essence the sensitivity is improved over that obtainable in one period of the signal with a conventional multireflection system by a factor approximately equal to the ratio of the storage time to the period of the signal, with a further improvement by the square root of the number of periods integrated over. The photon counting limit to sensitivity becomes approximately

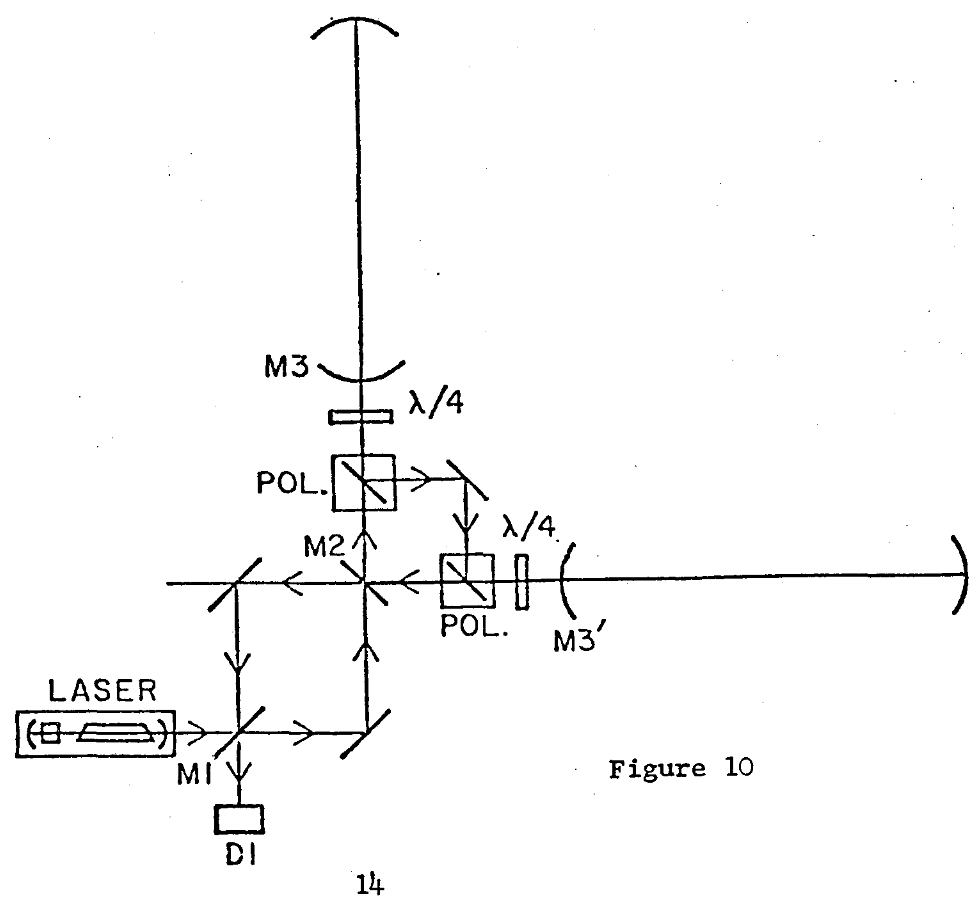

Figure 10

$h = \{ \lambda \hbar c (1-R)^2 / 2\pi I \tau' L^2 \}^{\frac{1}{2}}$, where R is the maximum mirror reflectivity available, and τ' is the total duration of the measurement. This arrangement can in principle give such a good photon counting limit to sensitivity that substitution of parameters for a large low-loss interferometer might make it seem straightforward to detect the expected gravity wave flux from the Crab or Vela pulsars. This is misleading, however, since other noise sources have to be considered also, and in this case thermal noise from the suspension and even the quantum limit for the test masses are likely to be serious problems. This type of interferometer will probably be more useful at slightly higher frequencies, perhaps for the more intense periodic signals which may follow some collapse processes.

Having now discussed techniques for detection of pulses and of periodic signals using laser interferometer gravity wave detectors, it might be worth mentioning briefly how these same instruments might be used to detect a stochastic background of gravitational radiation.

9. DETECTION OF A STOCHASTIC BACKGROUND

Laser interferometer detectors seem quite promising instruments for searches for a stochastic background of gravitational radiation, as might arise for example, from collapse of black holes at an early epoch. In a search of this type, the signal has the form of noise itself, and a considerable improvement in effective sensitivity can be obtained by use of a pair of detectors in a correlation mode to provide discrimination against internal noise from either instrument. Early experiments of this type have been carried out using resonant bar gravity wave detectors at Glasgow[14] and similar experiments have also been performed at Tokyo[15]. There is, however, a real possibility of achieving a much more interesting sensitivity with laser interferometers due to their higher expected intrinsic sensitivity together with wide bandwidth.

The principle of such an experiment is indicated in Figure 11 where the outputs

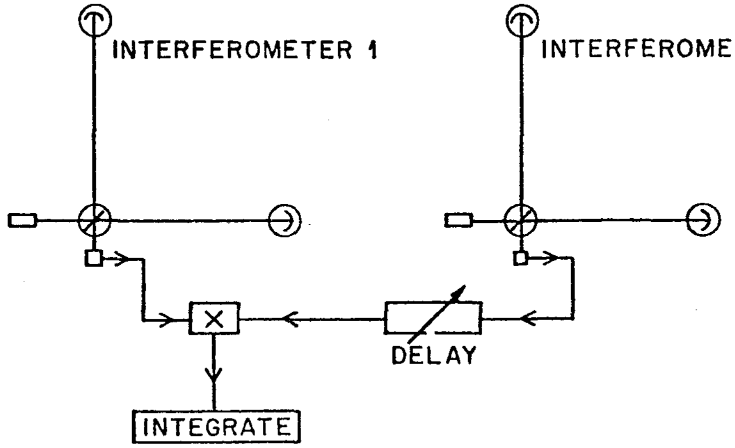

Figure 11

from two laser interferometric gravity wave detectors are multiplied together and integrated over a suitable observing time τ'. If the distance between the detectors is small compared with the wavelength of the gravitational radiation of interest, any common signal will give a correlated output and the power sensitivity obtained in the measurement becomes better than that achievable with a single detector alone by a factor of $(\pi B \tau')^{-\frac{1}{2}}$, where B is the bandwidth of each instrument by itself. If we take as example, a pair of optical cavity detectors with armlengths of 40 m, mirrors having reflectivity corresponding to $(1-R)=10^{-3}$ operating at a frequency centered on 100 Hz with a bandwidth of 100 Hz, and with other parameters as before, we might expect a gravity wave amplitude sensitivity for the individual detectors of the order of $2 \times 10^{-21}/\sqrt{Hz}$. An experiment involving correlation over 10^5 seconds could then set a limit of about $3 \times 10^{-23}/\sqrt{Hz}$ for radiation with the most favorable polarisation and flux direction. If it were assumed that gravitational radiation flux is concentrated in a frequency region near the frequency investigated, then an experiment of this type might set a limit to this gravity wave energy corresponding to a few percent of the closure density for the universe. With larger and more sensitive detectors such as those discussed earlier, correlation searches become feasible at a quite interesting level, and such experiments could form a very useful part of a general search for gravitational radiation of all types. They might, for example, provide the best sensitivity achievable for a wide range of unpredicted kinds of signals, such as large numbers of very small pulses, or nearly periodic signals of various types.

10. GENERAL REMARKS

It is hoped that the account given here of some current developments and ideas relating to laser interferometer gravity wave detectors gives a fair picture of the present state of this type of research. These instruments are complex and difficult ones, and their development presents a real challenge to the experimental physicist. It is too early yet to know which experimental approaches will prove most successful for the eventual unambiguous detection and investigation of gravitational wave signals, but the detectors discussed here seem at least as promising as other instruments of comparable cost and difficulty and the possibility of tailoring a single detector for several different types of experiment, suggested by some of the ideas outlined here, seems an interesting one. A considerable amount of difficult experimental work will still be necessary before experiments near the limits of sensitivity discussed here are likely to be made, but the prospects look good and the possibilities for real development of gravitational wave astronomy look interesting and exciting.

ACKNOWLEDGMENTS

The author would like to acknowledge the essential contributions of his colleagues at the California Institute of Technology and the University of Glasgow both in relation to discussions of principles and ideas and to underlying experimental work. The research in the USA is supported by the National Science Foundation (Grant NSF PHY82 04056) and in the UK by the Science and Engineering Research Council.

FOOTNOTE

*Some of the initial development and testing of this stabilisation technique was done in collaborative work by J.L. Hall and F.W. Kowalski of the Joint Institute for Laboratory Astrophysics, University of Colorado, and the University of Glasgow gravity wave group.[9]

REFERENCES

(1) Thorne, K.S., Rev. Mod. Phys. 52 (1980) 285.
Smarr, L. Sources of Gravitational Radiation (Cambridge University Press, 1979).
Epstein, R. and Clark, J.P.A. in: Smarr, L. (ed.) Sources of Gravitational Radiation (Cambridge University Press. 1979).
Thorne, K.S. in: Lebovitz, N.R., Reid, W.H. and Vandervoort, P.O. (eds.) Theoretical Principles in Astrophysics and Relativity (University of Chicago Press, 1978) 149.
Douglass, D.H. and Braginsky,V.B., in:Hawking,S.W. and Israel, W.(eds.), General Relativity: An Einstein Centenary Survey (Cambridge University Press, 1979).
Tyson, J.A. and Giffard, R.P., Ann Rev. of Astro. Astrophys. 16 (1978) 521.
Press, W.H. and Thorne, K.S., Ann. Rev. of Astro. Astrophys. 10 (1972) 335.

(2) Edelstein, W.A., Hough, J., Pugh, J.R., and Martin, W. J. Phys. E. Sci. Instrum., 11 (1978) 710.
Caves, C.M., Phys. Rev. Letters 45 (1980) 75.

(3) Moss, G.E., Miller, L.R. and Forward, R.L., Appl.Opt. 10 (1971) 2495.
Forward, R.L., Phys. Rev. D17 (1978) 379.

(4) Caves, C.M., Phys. Rev. D23 (1981) 1693.

(5) Weiss,R., Progress Report 105, Res. Lab Electronics, MIT (1972) 54.

(6) Billing, H., Maischberger, K., Rudiger, A., Schilling, S., Schnupp, L. and Winkler, W., J. Phys. E12 (1979) 1043.

(7) Drever, R.W.P., Hough, J., Edelstein, W.A., Pugh, J.R., Martin, W., Proc. of the Intern. Sympos. on Experimental Gravitation, Pavia 1976, B. Bertotti (ed.) (Accad. Nazionale dei Lincei, 1977).

(8) Schilling, R., Schnupp, L., Winkler, W., Billing, H., Maischberger, K. and Rudiger, A., J. Phys. E. Sci. Instrum., 14 (1981) 65.

(9) Drever, R.W.P., Ford, G.M., Hough, J., Kerr, I., Munley, A.J., Pugh, J.R., Robertson, N.A. and Ward, H., 9th International Conference on General Relativity and Gravitation, GR9, Jena (1980), (in press).

(10) Drever, R.W.P., Hough, J., Munley, A.J., Lee, S-A., Spero, R., Whitcomb, S.E., Ward, H., Ford, G.M., Hereld, M., Robertson, N.A., Kerr , I., Pugh, J.R., Newton, G.P., Meers, B., Brooks III, E.D. and Gursel, Y., Proc. of the 5th International Conference on Laser Spectroscopy (Springer-Verlag, 1981) 33.

(11) Hough, J., Drever, R.W.P., Munley, A.J., Lee, S-A., Spero, R., Whitcomb, S.E., Ward, H., Ford, G.M., Hereld, M., Robertson, N.A., Kerr, I., Pugh, J.R., Newton, G.P., Meers, B., Brooks III, E.D. and Gursel, Y. Proc. of the NATO Advanced Study Institute, Bad Windsheim, West Germany 1981 (in press).

(12) Braginsky, V.B. and Manukin, A.B., Measurement of Small Forces in Physical Experiments (Nauka, Moscow, 1974; University of Chicago Press, 1977).

(13) Drever, R.W.P., Hough, J., Munley, A.J., Lee, S-A., Spero, R., Whitcomb, S.E., Ward, H., Ford, G.M., Hereld, M., Robertson, N.A., Kerr, I., Pugh, J.R., Newton, G.P., Meers, B., Brooks, III, E.D. and Gursel, Y. Proc. of the NATO Advanced Study Institute, Bad Windsheim, West Germany 1981 (in press).

(14) Hough, J., Pugh, J.R., Bland, R. and Drever, R.W.P. Nature 254 (1975) 498.

(15) Hirakawa, H. and Narihara, K., Phys. Rev. Lett. 35 (1975) 330.