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DOCUMENT GIVEN TO NOVEMBER PANEL
SIMILAR TO 1985 ENGINEERING PROPOSAL EXCEPT
FOR CHANGES IN "ESSENTIAL FEATURES OF THE LIGO"
THE FIRST ITERATION ON IMPROVING THE ARGUMENTS FOR
LENGTH, VACUUM, ULTIMATE USE OF FACILITIES, INTERNATIONAL
ASPECTS OF THE PROGRAM, TWO SITES

Scientific Case for and Overview of the

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY (LIGO) PROJECT

~11/86

This document has been prepared for the Committee that will review the plans for the LIGO at a meeting in Cambridge, Massachusetts on 10–14 November 1986. The document has been adapted from a proposal for the Final Design Study for the LIGO, which was submitted to NSF in September 1985 and which will be resubmitted, with modifications, in December of this year if the Committee gives a favorable report. This document is accompanied by a companion entitled *Description of LIGO Design and Project Plans*.

LIGO-M860001-00-M

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1. INTRODUCTION

1.1 Brief description of what is being proposed

Laser interferometer gravity wave receivers have been under development in a number of laboratories since 1971.[1] Now, after 14 years of prototype development and experimentation, the time has come to proceed with the final design and construction of a Laser-Interferometer Gravity-Wave Observatory ("LIGO") to house full-scale receivers with sensitivities in the range of anticipated astrophysical gravity wave signals. The timeliness of such facility development is driven by the present sensitivity of the laboratory prototypes, their rapid rate of improvement, and the extensive past and present studies of the feasibility, design, and cost of a LIGO.

This document describes the scientific justification for the LIGO and gives overviews of its conceptual design and of the development of prototype gravity-wave receivers.

1.2 Brief Description of the Design and Intended Use of the LIGO

The LIGO will consist of two L-shaped vacuum systems, with arm lengths of order 4 kilometers, and associated buildings and supporting apparatus, at two widely separated sites (Fig. 1.1). Two sites are needed to discriminate local noise which may simulate gravity waves; arm lengths of order 4 kilometers are needed to achieve sensitivities adequate for a high probability of gravity wave detection.

The LIGO will be designed, constructed, and operated jointly by Caltech and MIT. Caltech and MIT will also jointly design and construct a first gravity wave detector to be installed in the LIGO. This detector will consist of a pair of gravity wave receiver systems, one at each site, with cross-correlated outputs; the receiver system at each site will consist of freely suspended, "inertial" test masses at the ends, intermediate points, and corner of the evacuated L, and a laser-interferometer system for monitoring the relative positions of these test masses. This two-site detector will be used jointly by Caltech and MIT in searches for gravity waves from astrophysical sources.

The design, construction, and operation of the LIGO, and of its first joint gravity-wave detector, will be carried out under the terms of a Memorandum of Understanding between Caltech and MIT, which is presented in Appendix J of this document.

The LIGO as initially constructed will permit simultaneous operation of one detector and development of another so that gravity-wave searches need not be halted in order to carry out detector improvements.

The LIGO will be designed so that additional instrumentation chambers

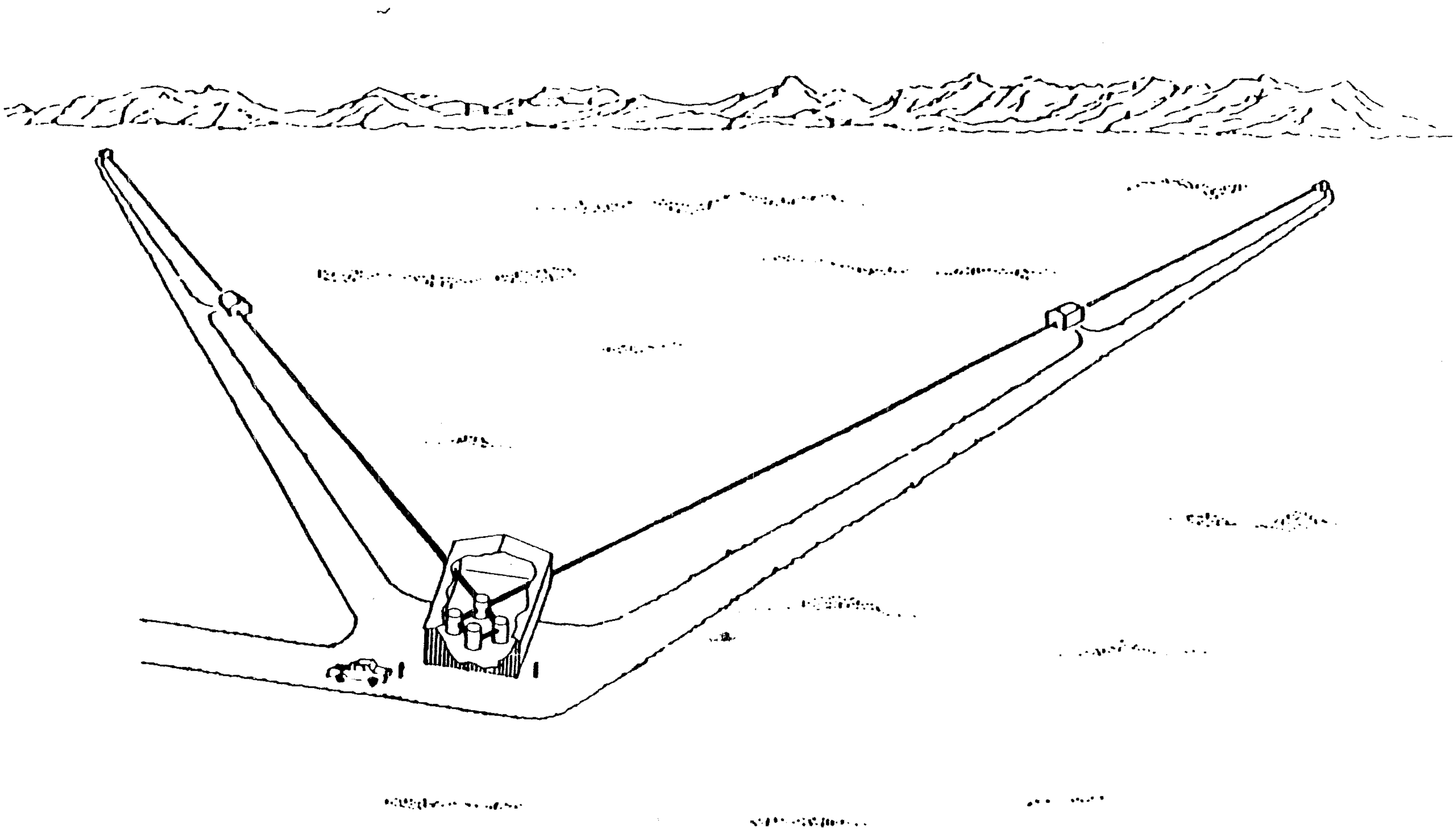


Figure 1.1 Artist's impression of one variant of the above-ground, west-coast site of the Laser Interferometer Gravitational Wave Observatory.

can be added at a later date to support several detectors operating simultaneously in the same L-shaped vacuum tubes. We anticipate that it will support a number of successive generations of detectors over a period of perhaps 20 years, detectors constructed and operated jointly or independently by scientists from Caltech and MIT, and also from other institutions. To some extent the LIGO will be like a high-energy particle accelerator, and the gravity wave detectors in it will be like high-energy experiments at an accelerator.

1.3 The Organization of this Document

The remainder of section 1, together with Appendix A, describes the scientific case for the LIGO and the prospects for its successful detection of gravitational waves. Section 2, together with Appendix E, describes our present conceptual design of the LIGO and the studies that have led up to that design. Especially important is the discussion, in Section 2.1, of the essential features of the LIGO design. Appendices C, D, and B describe prototype receiver research at Caltech, MIT, and in Europe and new concepts for advanced receiver technology that may be implemented in the LIGO. Appendix F is the Memorandum of Understanding between Caltech and MIT, under which the LIGO is being proposed.

1.4 The Expected Payoffs from Gravitational-Wave Detection

1.4.1 Payoffs for Astronomy

Until the 1930s, optical-frequency electromagnetic waves were man's only tool for studying the distant universe. The electromagnetic view of the universe was revolutionized by the advent of radio astronomy; and further but less spectacular revolutions were triggered by the opening of the infrared, X-ray, and gamma-ray windows.

The radio-wave revolution was so spectacular because the information carried by radio waves is so different from that carried by light. As different as radio and optical information may be, however, they do not differ as much as the information carried by gravitational waves and by electromagnetic waves.

Gravitational waves are emitted by, and carry detailed information about, coherent bulk motions of matter (e.g., collapsing stellar cores) or coherent vibrations of spacetime curvature (e.g., black holes). By contrast, astronomical electromagnetic waves are usually incoherent superpositions of emission from individual atoms, molecules, and charged particles. Gravitational waves are emitted most strongly in regions of spacetime where gravity is relativistic and where the velocities of bulk motion are near the speed of light. By contrast, electromagnetic waves come almost entirely from weak-gravity, low-velocity regions, since strong-gravity regions tend to be obscured by surrounding matter. Gravitational waves pass through surrounding matter with impunity, by contrast with electromagnetic waves which are easily absorbed and scattered, and even by contrast with neutrinos which, although they easily penetrate normal matter, presumably scatter many times while leaving the core of a supernova.

These differences make it likely that gravitational wave astronomy will bring a revolution in our view of the universe comparable to that which came from radio waves -- though it is conceivable that we are now so sophisticated and complete in our understanding of the universe, compared to astronomers of the 1930s and 1940s, that the revolution will be less spectacular.

It seems quite unlikely that we are really so sophisticated. One sees this clearly by noting the present, sorry state of estimates of the gravity waves bathing the earth (Appendix A): for each type of source that has been studied, with the single exception of binary neutron-star coalescences, either

(i) the strength of the source's waves for a given distance from earth is uncertain by several orders of magnitude; or

(ii) the rate of occurrence of that type of source, and thus the distance to the nearest one, is uncertain by several orders of magnitude; or

(iii) the very existence of the source is uncertain.

Moreover, of the nine specific sources discussed in Appendix A, only two (pulsars and supernovae) were considered likely sources 10 years ago. Of the other seven, two (neutron-star binaries and black-hole binaries) were thought unlikely until the discovery of the binary pulsar changed our prejudices; one (population III stars) was thought unlikely until strong observational evidence of massive galactic haloes and pre-population-II nucleosynthesis made it fashionable; and four (Friedman-Schutz instability in neutron-star spinup, inflation, cosmic strings, and phase transitions in the early universe) were not even conceived of 10 years ago. This enormous change in our outlook over the last 10 years suggests that today we probably are still overlooking a variety of important gravitational-wave sources.

Although this uncertainty makes us unhappy when we try to make plans for gravitational-wave searches, it will almost certainly reward us with great surprises when the searches succeed: the detected waves will give us revolutionary information about the universe that we are unlikely ever to obtain in any other way.

1.4.2. Payoffs for Fundamental Physics

Detailed studies of cosmic gravitational waves are likely to yield experimental tests of fundamental laws of physics which cannot be probed in any other way

The first discovery of gravitational waves would verify directly the predictions of general relativity, and other relativistic theories of gravity, that such waves should exist. (There has already been an indirect verification -- in the form of inspiral of the binary pulsar due to gravitational-radiation-reaction[2])

By comparing the arrival times of the first bursts of light and gravitational waves from a distant supernova, one could verify general relativity's prediction that electromagnetic and gravitational waves propagate with the same speed – i.e., that they couple to the static gravity (spacetime curvature) of our Galaxy and other galaxies in the same way For a supernova in the Virgo cluster (15 Mpc distant), first detected optically one day after the light curve starts to rise, the electromagnetic and gravitational speeds could be checked to be the same to within a fractional accuracy (1 light day)/(15 Mpc) = 5×10^{-11}

By measuring the polarization properties of the gravitational waves, one could verify general relativity's prediction that the waves are transverse and traceless – and thus are the classical consequences of spin-two gravitons.

By comparing the detailed wave forms of observed gravitational wave bursts with those predicted for the coalescence of black-hole binaries (which will be computed by numerical relativity in the next few years.[5]) one could verify that certain bursts are indeed produced by black-hole coalescences – and, as a consequence, verify unequivocally the existence of black holes and general relativity's predictions of their behavior in highly dynamical circumstances. Such verifications would constitute by far the strongest test ever of Einstein's laws of gravity.

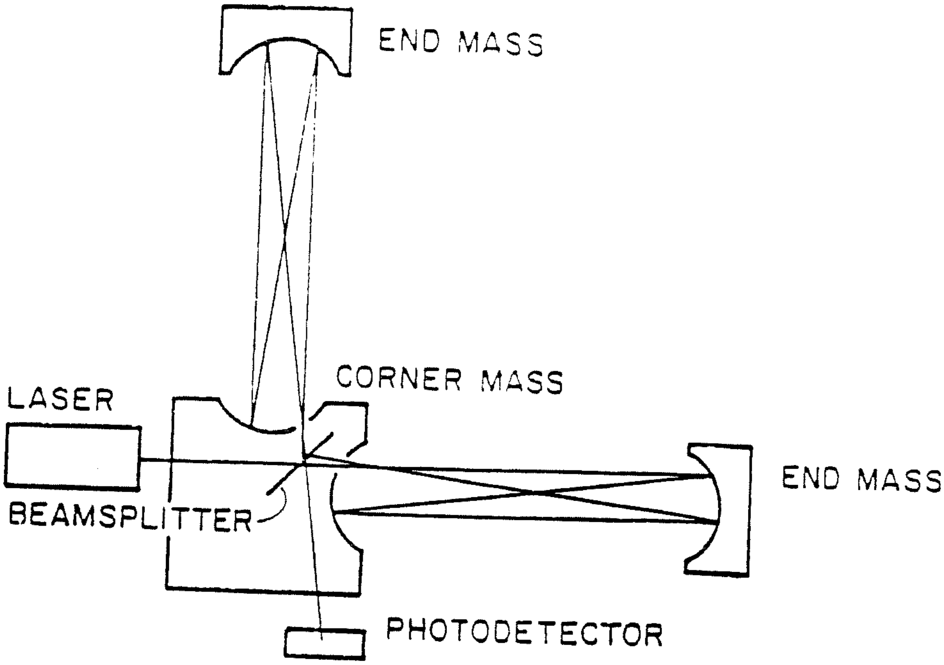
1.5 Gravity-Wave Detectors in the LIGO and their Prospects for Successful Detection

1.5.1 Simple First Detectors

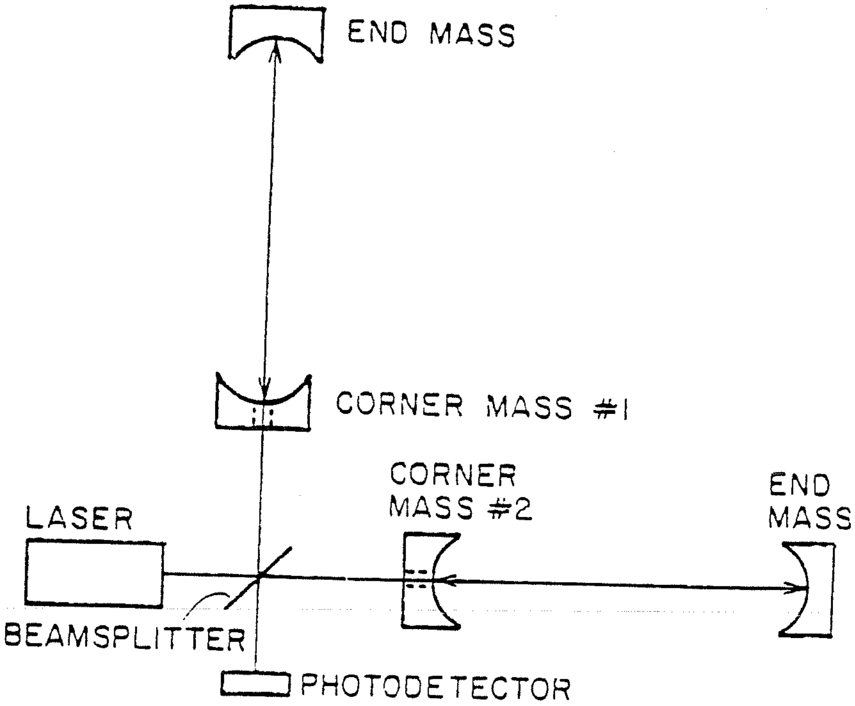
Description of Laser-Interferometer Gravity-Wave Detectors.

A gravitational wave is a propagating distortion in the metric of spacetime. If a beam of light makes a round-trip path between two free masses, the time it takes for the light to return to the first mass depends on the integral of the metric over its path, and thus contains a term which is proportional to the gravitational wave amplitude over its path. An interferometric gravitational wave receiver exploits this effect. Schematically (Figure 1.2a), such a receiver in its simplest form consists of three (nearly) free masses arranged in an L-shape. Light from a laser shines on a beamsplitting mirror on the central mass, which directs half of the light toward each of the two end masses. Mirrors on the end masses return the light to the central mass. The polarization properties of gravitational waves are such that for most propagation directions the changes in the round-trip travel time for light along the two orthogonal paths have opposite signs. One simple detection method is to superimpose the two returning beams, forming a Michelson interferometer (Figure 1.2a). Differences in the travel times in the two arms show up as shifts in the relative phase of the two beams, and thus as shifts in the fringe at the output of the interferometer. If the gravitational wave has dimensionless amplitude h (equal to the component of the metric perturbation along one arm), then the fractional difference in the round trip time between the two arms is approximately equal to h.

Because the travel time difference depends on an integral over the time which the light spends in the arms, the effect grows linearly as the round trip time increases, until the round trip time becomes comparable to the period of the gravitational wave. Thus, unless the arms are already so long that one round trip time is of order the wave period, there is a benefit to increasing the total storage time of the light by folding the path of the light, allowing many round trips before making the phase comparison between the light in the two arms. One method for doing this is to make each arm of the interferometer in the form of an optical delay line of the type developed by Herriott (Figure 1.2a). Light is injected through a hole in one mirror and makes a number of passes between



A) MICHELSON RECEIVER



B) FABRY-PEROT RECEIVER

Figure 1.2. Simplified diagrams of Michelson and Fabry-Perot gravitational wave receivers. (In the lower diagram the corner mass is divided into two parts — a method for avoiding the thermal noise associated with low frequency resonances of a complex mass.)

the two spherical mirrors before exiting from the same hole and interfering with light from the other arm. Receivers based on this scheme are sometimes called "Michelson" and sometimes "delay line". Another method is to make each arm of the interferometer a Fabry-Perot resonant optical cavity (Figure 1.2b). Light is injected through a partially transmitting mirror. If the length of the cavity is matched to the wavelength of the light, then the phase matching between the light which has made one round trip, two round trips, and more results in the storage of the light in the cavity for many round trips. Receivers based on this scheme are called "Fabry-Perot".

Even though the measurement is being made with light which has a wavelength of around 0.5 microns, it is possible (indeed vital) to compare the phase of the light in the two arms to a precision many orders of magnitude finer than one fringe. The fundamental limit to the precision of an interferometric measurement comes from the Poisson noise ("shot noise") in the intensity of the light at the output. Thus the precision can be made finer by increasing the illumination, until the power is so great that Poisson fluctuations in the light pressure on the end mirrors cause comparable noise. The resulting limiting precision is called the "quantum limit".

There are of course other sources of noise which experimenters must render negligible. Most of these have the form of stochastic forces which limit the extent to which the masses in the interferometer can be considered free. The most serious of these noises, seismic vibrations and thermal (Brownian) motion, are substantially weaker at high frequencies than at low frequencies. Thus an actual gravitational wave receiver can be expected to show the ideal shot noise limited performance above some frequency (~500 Hz in the LIGO's first simple receivers), with poorer performance at lower frequencies.

A laser interferometer gravity wave detector will typically consist of two or more receivers (like those of Figure 1.2) and associated electronics at widely separated sites, together with the data processing system which correlates their outputs and searches for gravity wave signals. In this ~~proposal~~ document we shall use the terms "receiver" and "antenna" interchangeably to mean one L-shaped interferometer system (Figure 1.2) at one site; and we shall use the terms "detector" and "detector system" to refer to the combination of receivers and data processors that are used in a gravity wave search or observation.

Sensitivities of Simple First Detectors in the LIGO. Receivers of the delay-line and Fabry-Perot types described above have been under development at MIT since 1971, at Caltech since the late 1970's, and at other laboratories throughout this period. Some technical details of that receiver development program are described in Appendices C and D. The Caltech and MIT gravity wave groups have furnished NSF with a list of "Milestones" which they expect to achieve between now and the target date for final approval of LIGO construction. The milestones are designed to guarantee that, even if no further progress were made on receiver technology between the time of approval of construction and the completion of construction, receivers could

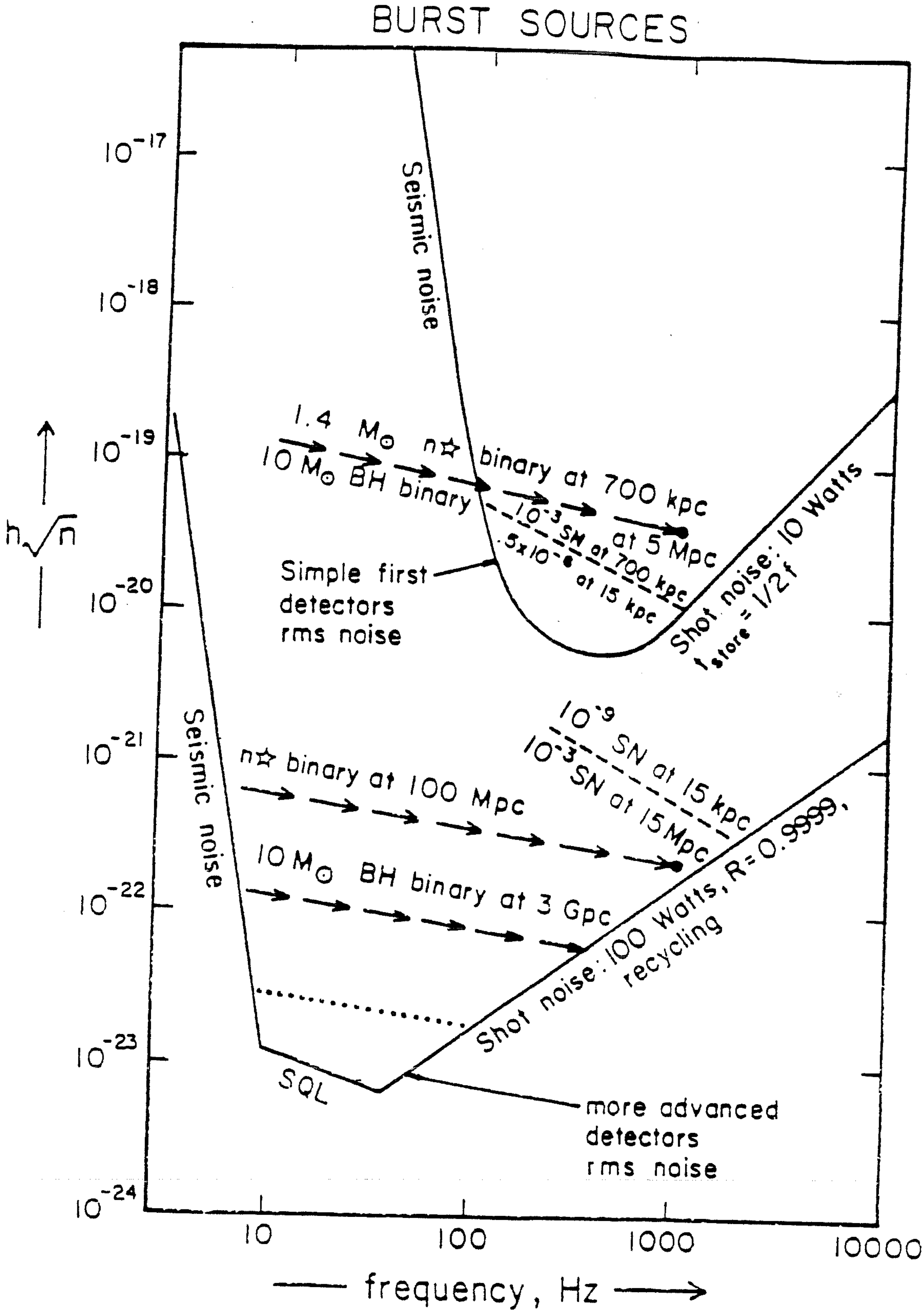


Figure 1.3. Comparison of predicted gravity wave strength for *burst* sources (Appendix A) with possible detector sensitivities in the LIGO (text and Appendix A).

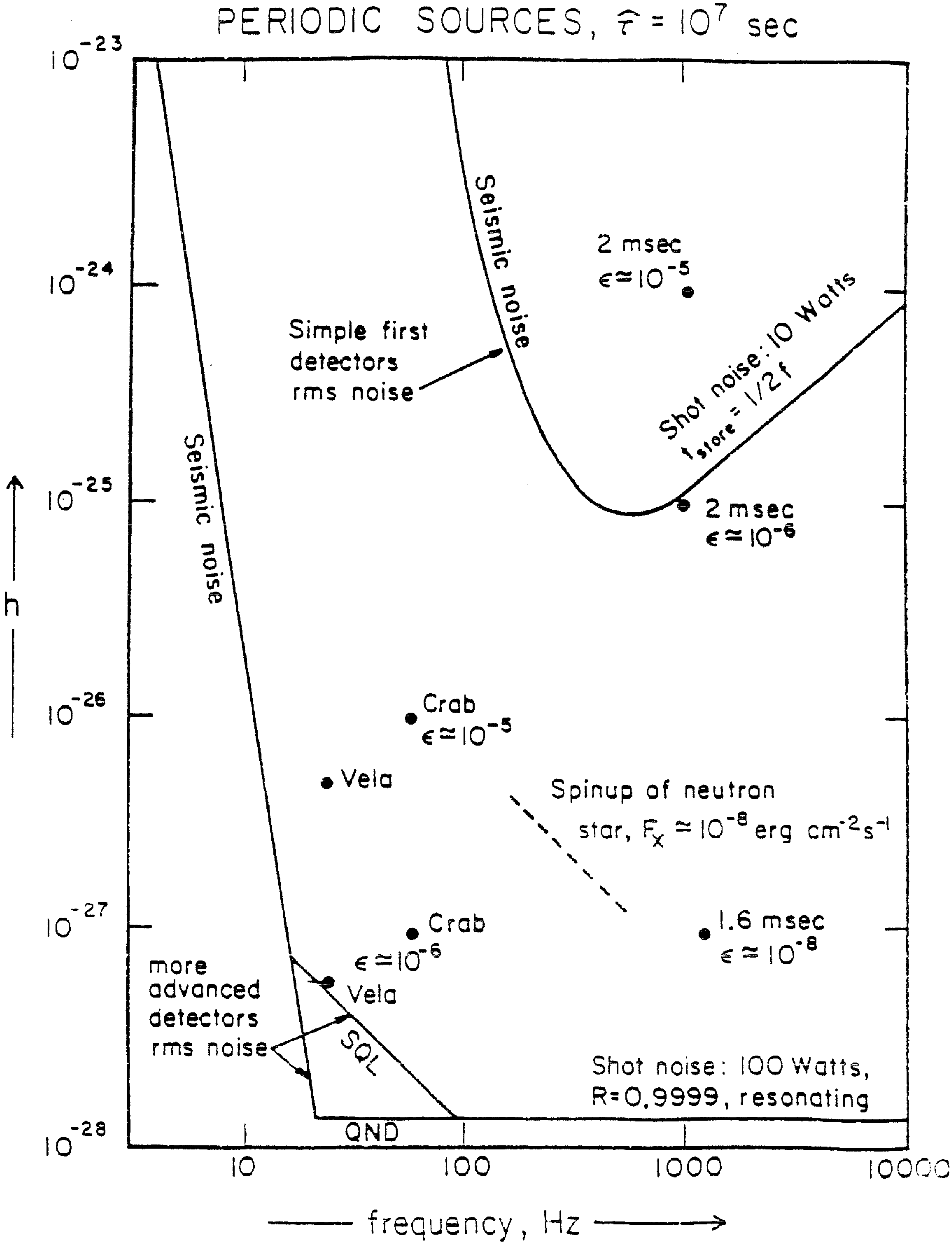


Figure 1.4. Same as Fig. 1-3, but for *periodic* sources of gravitational waves.

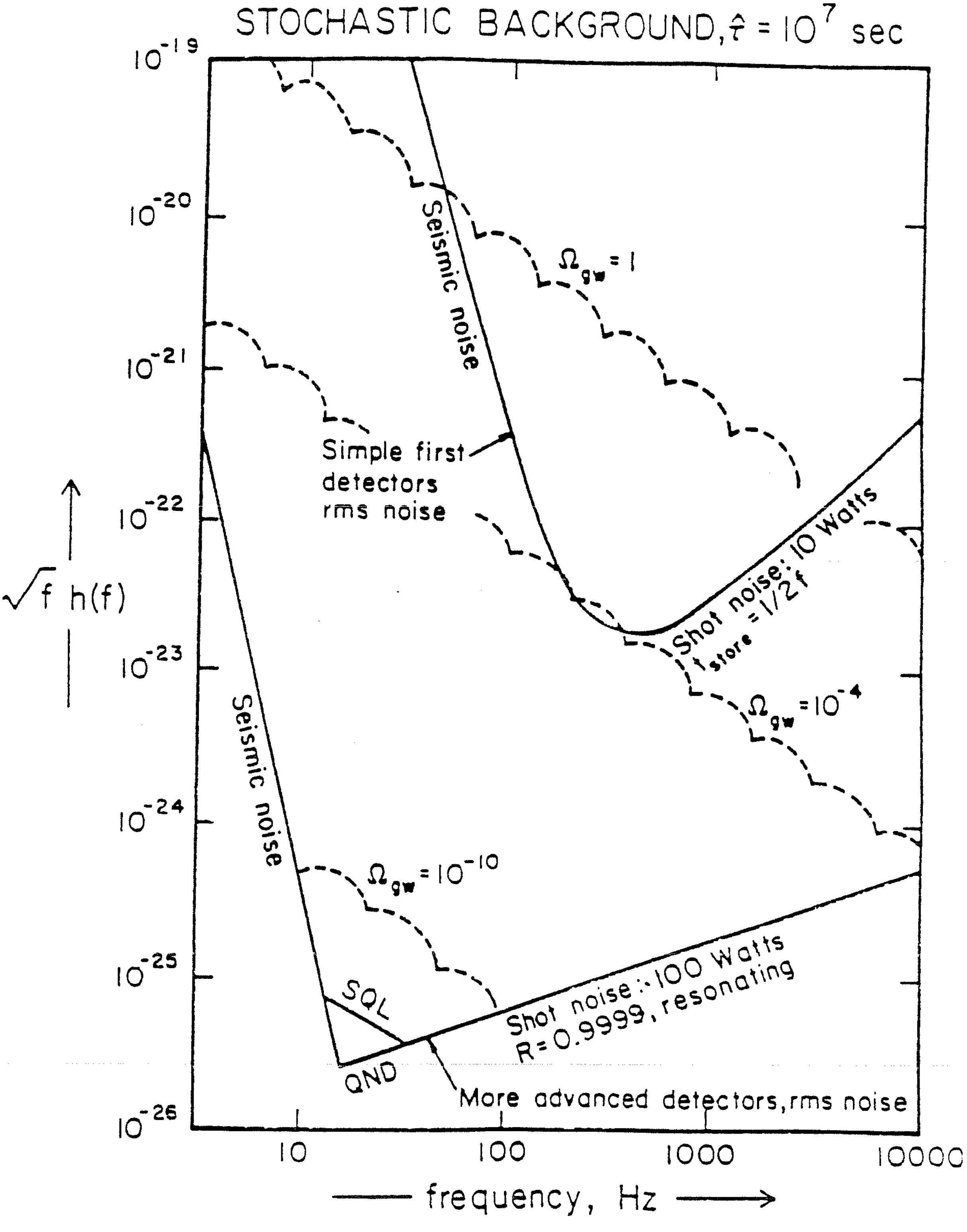


Figure 1.5. Same as Fig. 1-3, but for *stochastic background* of gravitational waves.

be mounted in the facilities with sensitivities roughly as shown by the upper solid curves of Figs. 1.3 - 1.5. Some technical specifications of such "Simple First Detectors" are spelled out in Sec. A.1 of Appendix A.

Prospects for Successful Detection. Section A.2 of Appendix A contains a detailed discussion of astrophysical sources of gravitational waves that could be detected with these simple first detectors. The strengths of the waves from some examples of such sources are plotted along with the detector sensitivities in Figures 1.3 — 1.5. Comparing the source strengths to the sensitivities one can conclude that the "simple first detectors" in the LIGO have a significant possibility of successful detection: see Appendix A for details. Moreover, the likelihood that there exist many strong sources that we have not thought of (cf. end of Sec. 1.4.1 above) enhances the possibility of success.

1.5.2 More Advanced Detectors

An important aspect in this project is the clear potential for major improvements in sensitivities beyond those of the "first simple detectors". Several methods for further improving sensitivity have been proposed - some using new concepts stimulated by the low optical losses demonstrated in our optical cavity experiments.

In the simple types of delay-line Michelson or Fabry-Perot interferometer systems outlined above the photon shot noise limits to sensitivity may be improved in two ways: by increasing the light storage time in the arms - until it approaches the period of the gravity wave signals; and by increasing the power in the light beams - until the quantum limit for the test masses is reached. Prototype experiments have already shown that optimizing the light storage time is entirely practicable for the gravity-wave periods of interest in ground-based experiments. In the Caltech Fabry-Perot prototype, storage times of 1 millisecond have already been obtained, which should scale to 0.1 seconds in a large system; and although large mirrors are required for long storage times in delay-line Michelson interferometers, storage times which should scale to several milliseconds have been reached. It is thus safe to assume that optimum storage times can be achieved. Reaching the optimum light power set by the quantum limit - or even to approach practical limits set by other stochastic noise sources - is more difficult. Suitably stable, continuous-wave, lasers capable of giving the required power (many kilowatts) at an appropriate wavelength are not yet available, and if banks of the type of argon laser currently used are employed the power consumption will become significant. Improved lasers are currently being developed, but at present we feel it prudent to envisage laser powers of not more than 100 watts for our planned experiments.

Fortunately, two methods for improving sensitivity without increase in laser power have been devised.[4] The first of these consists of a technique for recycling light through the whole interferometer many times, to increase the effective light power in the system.

Light Recycling Interferometer. Using phase modulation, it is convenient to operate high-powered interferometers with path lengths adjusted to give a dark fringe in the output from the beamsplitter. In this situation most of the light may leave the system through the other side of the beamsplitter, and it is proposed to redirect this light back into the interferometer to add coherently to the input beam. This effectively encloses the whole interferometer in an optical cavity which is in resonance with the laser light, as depicted - in principle only - in Fig. 1.6a. In the case of a delay-line Michelson interferometer two additional mirrors are used, with a photodiode D2 used to monitor rejected light and control the laser wavelength to minimize the rejected light intensity. In the case of a Fabry-Perot interferometer, the light storage time within the interferometer arms would be determined by choice of transmission of the cavity input mirrors. The light rejected by the cavities leaves the combining beamsplitter in the direction of the laser, and may be recycled by an additional mirror of suitable reflectivity, again with a monitoring diode D4 used to control the laser wavelength (or the optical path differences in the system) to maintain the resonance conditions. (For discussion of some practical aspects of such interferometers see Appendix B).

Recycling improves the performance of an interferometer by increasing the effective power available, without changing its frequency response. Another method for improving sensitivity still further for periodic or narrowband signals, by arranging a form of resonance between the light signal and the gravity wave, has also been devised.[4]

Light Resonating Interferometer. In this scheme the optical phase signal induced by the gravity wave is made to pass back and forth between the two arms of the interferometer in synchronism with the wave so that the amplitude of the signal builds up over the whole time that light may be stored within the system. Methods proposed for achieving this in delay-line and Fabry-Perot interferometers are indicated in outline in Fig. 1.6b. (More practical systems are described in Appendix B).

In the case of a delay line system, the delay time within each arm of the interferometer is made equal to half of the gravity-wave period, and light is arranged to pass from one arm to the other as shown, via coupling mirrors of high, but suitably chosen, reflectivity. Phase differences between light circulating in opposite directions build up over the light storage time.

In the case of a Fabry-Perot system, the optical cavities in the two arms are coupled together via the transmission of their input mirrors and by an additional mirror of high, suitably chosen, reflectivity. This system can be thought of as operating in a way similar to that of the delay-line system; or alternatively it may be considered that the lower of the two resonances of the coupled-cavity system is arranged to match the frequency of the laser light, and the upper resonance is made to match the upper sideband of the signal induced by the gravity wave, so that again there is an enhancement of the signal by the resonance.

In both of these resonating systems, the signal builds up coherently over

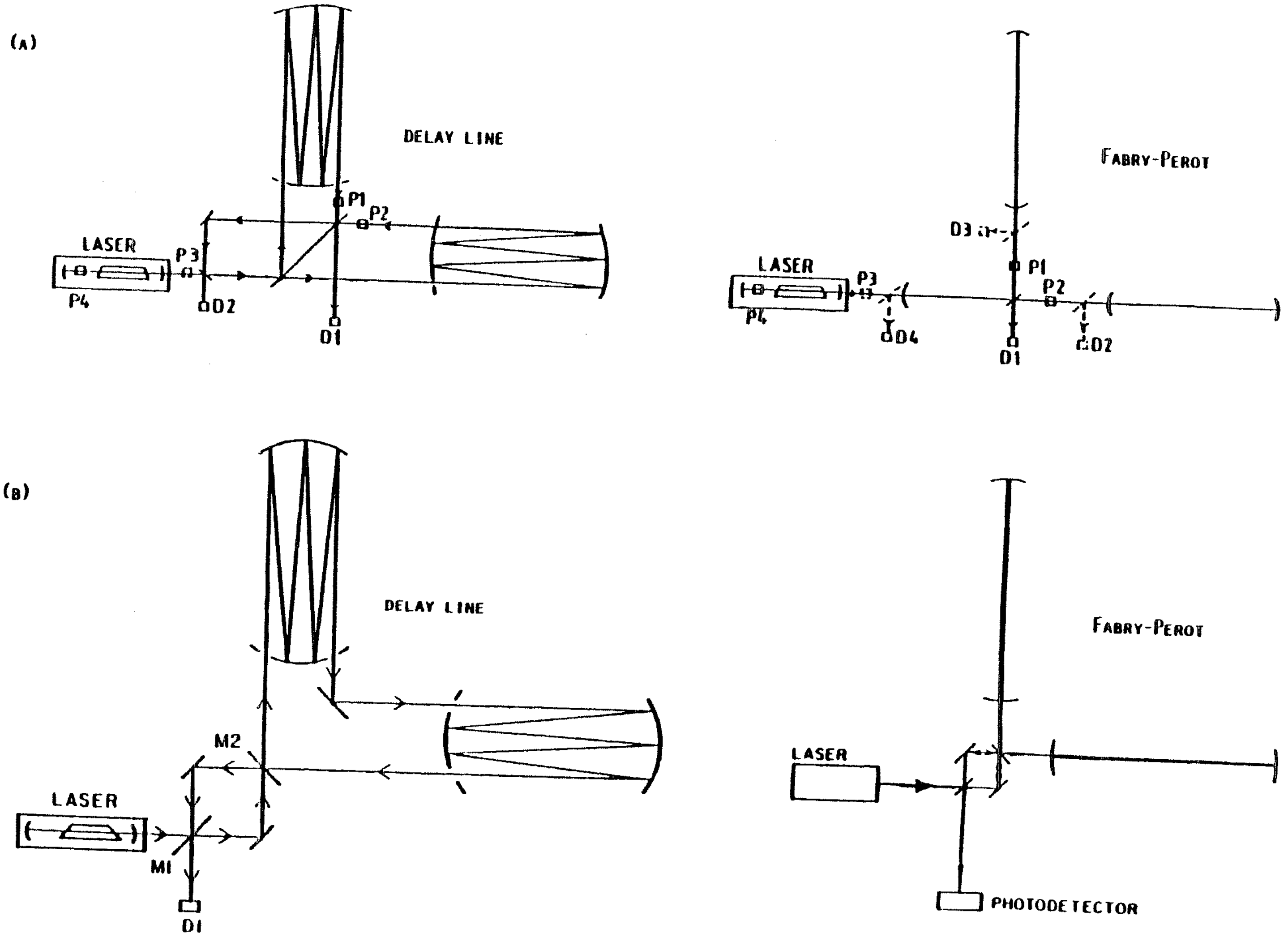


Figure 1.6. Two possible methods for enhancing the sensitivity of gravitational wave receivers built with delay lines and Fabry-Perot interferometers. (A)--Light recycling interferometers. (B)--Light resonating interferometers.

the overall light storage time, so an enhancement in sensitivity proportional to the storage time, and in general larger than that given by the wide-band recycling system, is achievable over a bandwidth equal to the inverse of the overall storage time centered at any chosen frequency.

Active Antiseismic Isolation. In the "first simple detectors" envisioned above, it was assumed that seismic noise is negligible above about 500 Hz. Recent tests of the passive antiseismic isolation in one of our prototype receivers (Appendix C.2) suggest that adequate isolation for these first simple detectors has been achieved already. However, because gravity wave sources are thought to be stronger at lower frequencies, it will be very important in more advanced detectors to push the antiseismic isolation to as low a frequency as possible. At lower frequencies it is more difficult to obtain adequate isolation by passive means, since the ground noise increases and the attenuation of simple, passive mass-spring isolators decreases. Fortunately, isolation can be improved by arranging a servo system to cause the suspension point of each test mass to track the motion of the mass below it. This type of active isolation system has been extensively developed at Glasgow, primarily for the horizontal degrees of freedom most relevant for gravitational wave antennas,^{5} and more recently at Pisa. An equivalent arrangement for vertical motions has been very successfully used at JILA for isolation of gravimeters,^{6} and a vertical system motivated by 1962 work of R. Dicke has been tested at MIT, where general analyses of some of these systems have been carried out. The existence of tilt components in the seismic noise complicates horizontal isolation schemes but a technique has been introduced at Glasgow in which tilt effects are eliminated by sensing motions relative to a reference body of large moment of inertia freely suspended at its center of gravity.

The improvement in isolation achieved by these techniques is limited in practice by mechanical resonance in the structures, and multistage isolation systems may be required for experiments at very low frequencies. Another type of active isolation that is convenient for LIGO receivers uses an auxiliary laser-interferometer system to monitor the distances between test-mass suspension points; see Appendix B for details. In principle such systems should be capable of giving good isolation at frequencies down to a few times the pendulum frequency of the test mass suspensions, but they will require much development to achieve this, and may become fairly complex.

Sensitivities of More Advanced Detectors in the LIGO. The "light recycling", "light resonating", and antiseismic isolation techniques just outlined show promise of greatly enhancing the performance of gravitational wave detectors over that of the "first simple detectors" of the last section. We anticipate perfecting these techniques in the proposed facilities; and that effort may well lead to "more advanced detectors" with sensitivities something like those shown in the bottom solid curves of Figures 1.3 – 1.5. For some technical specifications of such detectors see Sec. A.3 of Appendix A.

Prospects for Successful Detection with More Advanced Detectors Section A.4 of Appendix A discusses a variety of plausible gravity-wave sources, and one high-confidence source, which could be detected with the more advanced detectors. From that discussion it is evident that there is a very high probability of gravity-wave detection at the advanced-detector sensitivities.

Thus, if success does not come with the first simple detectors, we can be reasonably sure that continued efforts at improving the detector sensitivities in the LIGO will bring success at some point between the upper and lower solid curves of Figures 1.3 — 1.5.

2. The Conceptual Design of the LIGO

The key features of the conceptual design of the LIGO are presented in this section of the document.

The design is based on the studies described in Appendix E,

2.1. Essential features of the LIGO

The levels of gravity-wave sensitivity needed for the detection of gravitational waves, according to the estimates in Appendix A, cannot be achieved in vacuum systems as short as those now being used at Caltech and MIT. In fact, a high probability of unequivocal detection with the proposed Caltech/MIT LIGO requires the following essential features:

1. Two widely separated sites,
2. Arm lengths of order 4 kilometers at each site,
3. Vacuum pipe diameter of order 48 inches,
4. The capability of a vacuum level of 10^{-8} torr to accommodate the highest-sensitivity searches.
5. The capability of carrying out two simultaneous investigations (a gravity wave search and receiver improvement) at each site initially, and three or more later,
6. The capability to accommodate receivers of different arm length.
7. A minimum lifetime of the facilities of twenty years.

Justifications for these requirements are as follows:

1. *Two antennas at widely separated sites*

Multiple antennas situated at widely separated sites are essential for unequivocal detection of gravitational wave bursts. Present experience indicates that each antenna will exhibit a pulse noise spectrum which almost obeys a Gaussian distribution in amplitude after optimal filtering. The amplitude distributions typically have a non-Gaussian tail at large amplitude and low probabilities, exactly in the region of relatively low event rates where detection of gravitational wave bursts would be sought.

This non-Gaussian tail is generally associated with noise sources that are not fundamental, i.e. that in principle are removable — for example, seismic noise, acoustic noise, cosmic-ray noise, and the occasional release of strain in a test mass or support wire. The reduction of these types of noise is a problem in experimental design. If one knows the cause, the experimenter can choose to measure the noise source independently and remove its effect from the data; or he can design the apparatus so that it is insensitive to the noise source. Usually both things are done. The trouble comes when the rate of the noise events is low and the noise source was unanticipated, unfortunately a common occurence even with the most careful workers. These are the events remaining in the non-Gaussian tail after analysis. It is common experience for all of us that the most difficult thing to find and fix in a device or experiment is such an intermittent problem.

The best means of eliminating the large set of both known and unknown noise sources, due to the external environment of the apparatus and also to internal impulsive phenomena, is to operate at least two systems with comparable sensitivities at separations sufficiently large so that the extrinsic noise at the two locations is uncorrelated over the relevant observation times. Gravitational wave signals, however, would be correlated.

In the early phase of the search for gravitational wave bursts, it will be extremely important to have two sites in operation with overlapping sensitivity, frequency coverage and observation time. Besides the need for the experimenters themselves to have this diagnostic tool, universal acceptance of gravitational wave burst detection will depend in good measure on the fact that the same gravitational events have been seen in two places. The experiment strategy of a minimum of two antennas at separated sites is so crucial to the scientific success of burst detection by this project that we believe the investment made in interferometric gravitational wave detection may well not be justifiable unless there is a guarantee of this experiment strategy. To protect the investment, it is important that the two sites be under a common control in the same country, thereby making likely the simultaneous operation of antennas with comparable sensitivity, frequency coverage and operation time. The dangers of not having such common control include (i) funding difficulties in one of two countries that may have agreed to collaborate (as, for example, the United States' renegging in 1982 on a prior commitment to Europe for a companion to the European Solar Polar spacecraft (now called Ulyses); (ii) a slowness to transfer working technology from one site to another, e.g. due to the "not invented here" syndrome; and (iii) difficulties in scheduling common observation periods.

Some of the prior history in the field of bar detectors for gravitational waves illustrates these problems. Although Stanford had an operational cryogenic bar in 1980 with amplitude sensitivity 30 times better than the best room temperature bars, it was not until 1986 — six years later — that other bars of comparable sensitivity were operational in other groups, and a meaningful coincidence search for gravitational waves was carried out. The reasons, which are many, include funding difficulties in different countries and the fact that there was a long delay in transfering working technology from Stanford to other groups. The chances that the proposed new phase of gravitational wave detection will not be plagued by the same problem are much reduced by having at least one complete observational system under a common control in one country.

One hopes that the initial experiments will open the field of gravitational astronomy. If they do, then we will face the problem that the individual antennas have little directivity. At present the only method for establishing the position of gravitational wave burst sources is through measuring the differences in arrival time of the gravitational wave signals at antennas separated by continental baselines. Two antennas are not sufficient to unambiguosly determine the position of a source; at the minimum four antennas, well placed around the earth, are required. Furthermore, determinations of the propagation speed and polarization states of gravitational waves would benefit by a network of antennas. If funds and effort were unlimited the presently proposed effort could be faulted for not asking for the development of more than two antennas; looking into the future, it is the right thing to do. With the long term future in mind, we have been strongly encouraging and aiding our European and Japanese colleagues in their efforts to develop long baseline interferometric gravitational antennas.

2. *Arm lengths of order 4 kilometers at each site*

The choice of antenna arm length is not a simple issue. The optimum length of the arms of an interferometric gravitational wave antenna is equal to 1/2 the gravitational wavelength. Arms longer than this will not increase the gravity wave's measurable signals (the changes in the optical phase of the light traversing the arms). The optimum length is, however, impractical for a terrestrial observatory; a 1 kHz gravitational wave has a wavelength of 300 kilometers. More practical is a design in which the storage time of the light in the arms is increased, optimally to 1/2 of the gravitational wave period, by reflecting the optical beam back and forth along the arm many times. The response of such a "folded" antenna to a gravitational wave is much the same as the response of an optimum length antenna. The folded geometry does,however, place more demands than an optimum length antenna on the reduction of mirror losses, on the level of the residual gas in the arms and on the need to reduce the influences of stochastic forces on the end points defining the arms. Holding all other variables but the folded antenna's physical arm length constant, the scaling of the strain AMPLITUDE noise h with physical arm length, L ,varies as:

$1/L$ for

- most known stochastic forces acting on the antenna end points such as seismic, acoustic, thermal, and gravity gradients from objects at distances from a test mass less than or of order the arm length;

- the standard quantum limit;
- photon shot noise if the light storage time in the antenna arm is limited by poor mirror reflectivity or other factors to much less than 1/2 the gravitational wave period for burst sources;
- photon shot noise in a search for periodic sources with an optically resonant recycling system.

$1/L^{3/4}$ for

- statistical fluctuations in the index of refraction of the residual gas for fixed pressure and minimum optical beam size.

$1/L^{1/2}$ for

- photon shot noise using light recycling on burst sources assuming it is possible to achieve optimized storage time in the arms.

Independent of L for

- photon shot noise if it is possible to achieve optimized storage time but recycling is not used.

With these differing dependences on arm length of the various noise sources, the expected variation of interferometer sensitivity with length depends on which noise source will be the dominant one in the instrument, and is likely to differ from one instrument to another.

A major consideration influencing a decision on the length of the arms is the rate of detectable burst events. Once the interferometer sensitivities have reached a level where it is possible to detect sources at the distance of the Virgo cluster of galaxies (e.g. for the binary neutron stars, binary black holes, and supernovae discussed in Appendix A), the detectable event rate is expected to grow inversely with the cube of the amplitude sensitivity, h^{-3}. This is because the number of galaxies that can be monitored is proportional to the volume of the universe that can be observed, and the distance at which a specific kind of source can be detected is inversely proportional to the amplitude sensitivity. Under these circumstances the event rate varies as the inverse cube of the length-dependent factors listed above. For example, in the case of sensitivities limited by $1/L$-varying noise (seismic noise, acoustic noise, local gravity gradients, shot noise with resonant recycling, and standard quantum limit), *a factor 2 increase in arm length L produces a factor 8 increase in event rate.*

We have chosen arm lengths of order 4 kilometers at each site as a practicable compromise in the overall circumstances of this project for several important reasons.

1. IT IS EXTREMELY IMPORTANT TO BUILD A SYSTEM OF SUFFICIENT LENGTH TO HAVE THE CAPABILITY OF ACHIEVING A HIGH PROBABILITY OF SUCCESSFUL DETECTION. Although the probability of success is significant

at the level of the "first simple detectors" of figures 1.3 -1.5. a very high probability of success requires a sensitivity near that of the dotted line in figure 1.3. As is discussed near the end of Appendix A. this dotted line corresponds to a 90% confidence of detecting our only semi-guaranteed source: coallescing neutron-star binaries in distanta galaxies. for which the event rate increases as h^{-3}. With the quantum limit and seismic noise so near the dotted line, h is likely to scale as L^{-1}, so the event rate goes up as L^3. *A factor 2 difference in L then corresponds to a factor 8 difference in event rate, which* (by virtue of our present uncertainty in the actual event rate, cf. Appendix A) *corresponds to the difference between 50% and 90% confidence of detecting this semi-guaranteed source.* The location of the dotted line indicates that, even with 4 kilometer arms there may be little margin of safety in going after this semi-guaranteed source.

2. As seen from the scaling of the noise with arm length. the longer the arms the less stringent will be the demands on the receivers in order to achieve a given level of sensitivity. This is particularly important in the promising low frequency search where the stochastic forces on the antenna end masses are most difficult to control. A longer length also reduces the demands made on mirrors and in general. success in the search is expected to come more easily and quickly the longer the antenna arms.

3. Clearly one would want the arms to be as long as possible. but there are obvious constraints of cost. An approach that has been used is that the length of the arms should be large enough so that further improvement of the system performance by a significant factor requires a substantial cost increment. This implies that the system costs dependent on the arm length should be in reasonable proportion and not be dominated by those costs independent of the length.

4. To maintain costs at a reasonable level. it has been important to find sites which are sufficiently flat so that no tunnelling or large amounts of land removal become necessary. After an extensive search throughout the United States we have found that there are very few convenient sites that could accomodate arm lengths larger than 4 to 5 km economically.

3. *Vacuum pipe diameter of order* 48 *inches*

The vacuum pipe diameter is a critical parameter of the long baseline system which figures in both short and long range uses of the facilities. The vacuum pipes must be able to pass Gaussian optical beams without causing diffraction loss of the beams or being a serious source of scattered light. In particular, the pipes must be large enough so that motions of the pipe walls, when driven by seismic noise, do not add to the noise budget of the receivers through diffraction of the beams at the walls. This condition must be met with some margin for misalignment and settling of the tube supports.

The minimum size of pipe that could accomodate an extrapolation of the prototype-design delay-line Michelson interferometers to a 4 km length is 30 inches using 1/2 micron wavelength light. Although no decision can be made at present concerning the specific optical design of the initial interferometers to be used in the facilities, the delay line configuration is known to demand the largest diameter for a single receiver and thereby sets the conditions for the minimum tube diameter. The choice of 1/2 micron wavelength is predicated on present experience with the Argon Ion laser which is being used by all interferometric gravitational wave groups . The laser is energy inefficient, so it may be advantageous to use longer-wavelength, more efficient, and more powerful lasers, especially in the near infrared. The optical beam size scales as the square root of the wavelength so that using a 1 micron wavelength delay line system would require a minimum diameter of 43 inches.

The more compact geometries such as Fabry-Perot or tagged-beam interferometers could use smaller diameter tubes. However, a longer range goal for the facilities is to design them so that multiple investigations can be carried out simultaneously. Some of the single receiver designs, whether delay line or of the compact optical type, will be using multiple beams for seismic noise reduction as well as full and half length interferometers for diagnostic studies. The sensible choice for tube diameter is then not to constrain the possibilities at the outset unless there is strong economic reason to do so.

The overall system costs increase by roughly 8% in going from 30 inches to 48 inches so that tubing diameter is not a strong economic driver. The costs, of course, are not just in the tubing itself but in pumps, supports, valves and bellows. There is a breakpoint in the costs at 48 inches: with larger diameters, the costs of valves, bellows and the tubing itself grows faster because one exceeds industry standards.

4. *The capability of a vacuum level of* 10^{-8} *torr to accomodate the highest sensitivity searches*

The facilities should be designed so that fluctuations in the index of refraction of the residual gas in the interferometer arms will not become a limiting noise source. It is prudent in the vacuum system design to anticipate projected improvements in receiver sensitivity. Figures AA and AB show the limiting performance of an interferometer if the only noise source is the statistical fluctuations in the number of molecules in the interferometer beams, for the type of interferometer most sensitive to residual gas. The noise depends on the ratio of the molecular polarizability of the gas at the laser wavelength to the square root of the molecular thermal velocity. The major constituent (95 to 99%) of the residual gas in a clean stainless steel system is molecular hydrogen which diffuses out of the metal: and fortunately this gas has the least effect on an interferometer. The figures show the sensitivity limits set by residual hydrogen and nitrogen for burst sources and for periodic sources, compared with the sensitiviies determined by other factors. The important thing to notice is that the initial sensitivity goals ("simple first detectors") can be met, even in those interferometer designs most sensitive to residual gas fluctuations, by a very poor vacuum. The enhanced sensitivity goals ("more advanced detectors") will require residual gas pressures of hydrogen less than 2×10^{-8} torr and nitrogen at less than 10^{-9}. The goal is to design the vacuum system so that nothing in the construction or pumping strategy would preclude achieving these pressures. The system will be cleaned in the field and be bakeable to 150C. The anticipated outgassing rate after low temperature bakeout is expected to lie between 10^{-11} and 10^{-12} torr liters/second/cm^2 and improve with the square root of the pumping time. The permissable leak rate to attain the good vacuum levels for the enhanced sensitivity is 5×10^{-8} standard atmosphere cc/sec in each 100 meter section. Not acceptable

5. *The capability for two simultaneous investigations at each site initially*

The capability of carrying out two simultaneous investigations at each site initially is very important. This will permit the development of improved receivers as one investigation, while the first Joint Caltech/MIT gravity wave search is underway as the other (highest priority) investigation. The importance of this parallel mode of operation arises from the fact that, although some of the technology of improved receivers can be tested in other laboratories, the time-consuming integrated tests and debugging, especially of the optics, can be carried out only in the full scale vacuum system of the LIGO. This parallel mode of operation will permit at least one detection system to be on the air, searching for waves at all times.

The necessity for such a capability is made clear by twenty years of experience of research groups using single bar detectors for gravitational waves and also by the experience of groups working with single laser-interferometer prototypes: these groups have always been caught in the dilemma of whether to search, or to make technical improvements in the apparatus which would improve the sensitivity of the search. The natural direction, having only one apparatus, is to improve continually. As a consequence, to date there have not been many long-term, continuous searches carried out. It would be exceedingly unfortunate if, after spending the large amounts of money required for the LIGO and achieving at the outset sensitivities where there is significant hope of seeing something, the

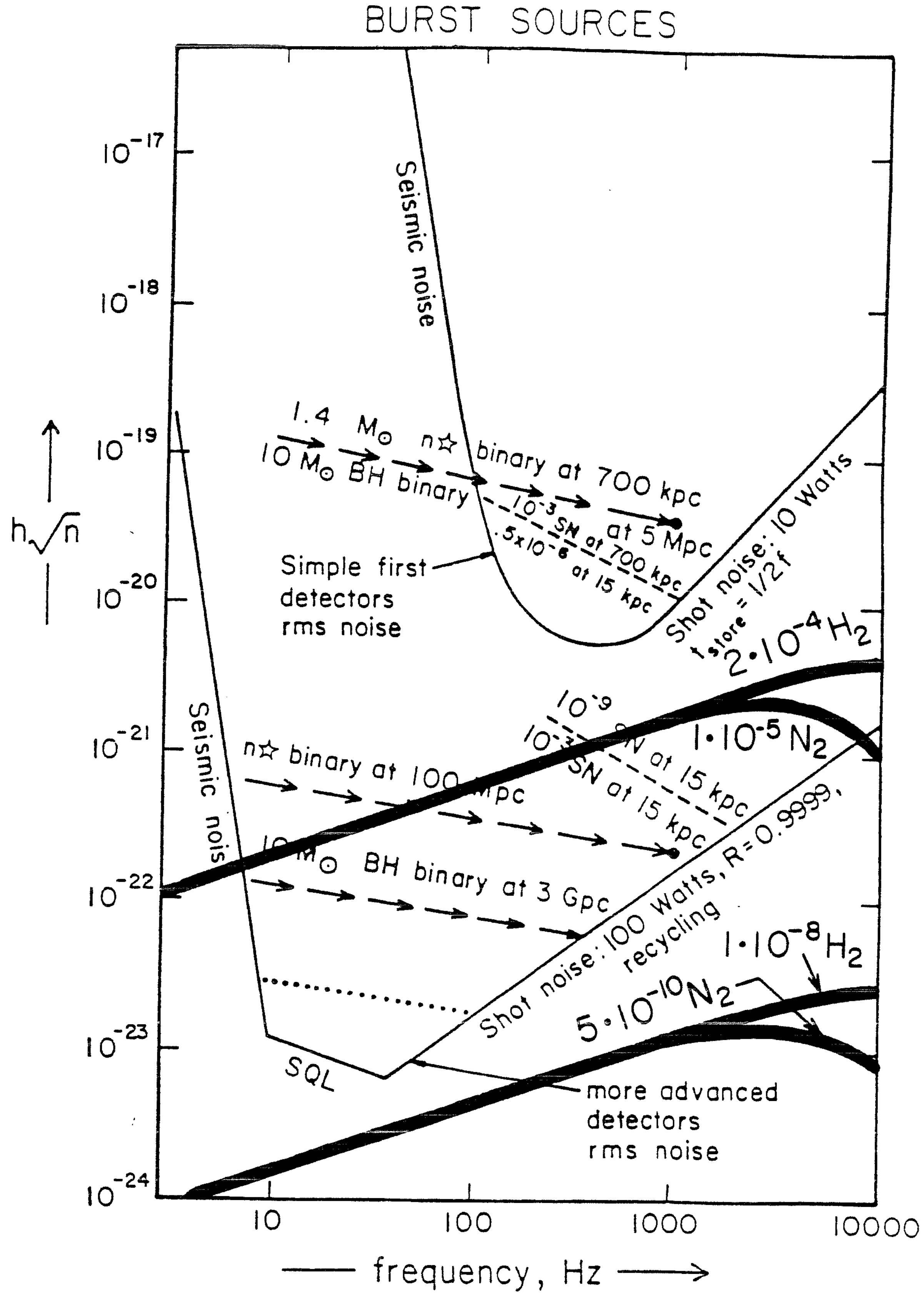


Figure AA. Noise due to fluctuations in the index of refraction of the residual gas in the interferometer arms -- shown in terms of its effect on receiver sensitivity in searches for bursts of gravitational waves: c.f. Fig. 1.3. Curves are shown for gas pressures of $2x10^{-4}$ torr and $2x10^{-8}$ torr of hydrogen (H_2), and $1x10^{-5}$ torr and $1x10^{-9}$ torr of nitrogen (N_2).

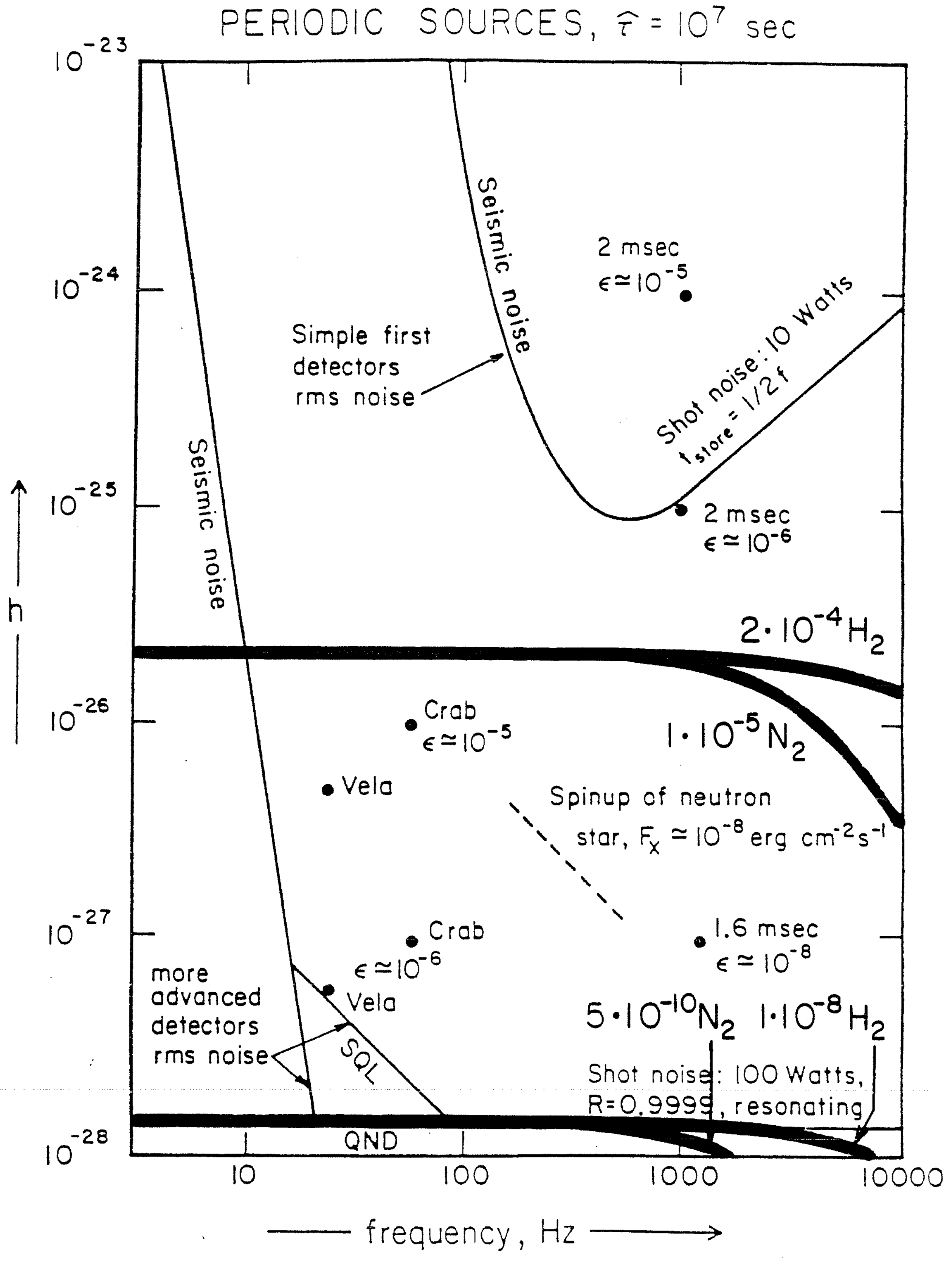


Figure BB. Same as Fig. AA, but showing the effects of residual gas on searches for periodic gravitational waves: cf. Fig. 1.4.

experimenters were still caught in this dilemma.

The LIGO should be easily upgradable to support a third independent investigation when funding and manpower permit, and to support additional simultaneous investigations later. If gravitational waves are not detected at the sensitivities of the first joint experiments, then three independent investigations would significantly speed up the subsequent advanced-detectors' search for gravity waves by permitting simultaneous, time-consuming searches with receivers optimized for different kinds of sources. Additional simultaneous investigations later will permit gravitational astronomy to become a research field like other branches of astrophysics with many independent and interesting research programs involving experimenters from a number of institutions.

6. *The capability for receivers of two different arm lengths*

The LIGO should be able to accommodate interferometers of two different arm lengths. The fact that gravity-wave signals in interferometers are proportional to armlength can be used as a partial discriminant between gravity waves and local disturbances at one antenna site, thereby reducing the spurious coincidence rate to a low enough value that two-site correlations can clearly identify gravitational-wave bursts. Two receiver beams sharing the same vacuum will also be very useful in diagnostic studies of the local noise sources, and are one way of measuring the noise due to fluctuations in the gas column density.

7. *A minimum lifetime of the facilities of 20 years*

The facilities being designed and constructed for the LIGO project are expected to be used in a succession of gravitational wave observations of continuously improving sensitivity as the technology of receivers advances. Specialized receiver systems with enhanced sensitivity for specific categories and types of gravity wave sources are contemplated. The facilities are not being constructed to carry out one make or break experiment. In many ways there is an analogy to an optical observatory. The big capital costs of an optical telescope are in the large mirrors, the pointing and control system, and the buildings that house them. The focal plane instrumentation is usually a small part of the initial cost. The focal plane instrumentation is, however, the source of the action; the cunning, ingenuity and inventiveness reside there. The scientific productivity of the telescope is in large measure dependent on improvements in this instrumentation as the technology advances. The receivers in the gravitational wave project are like the telescope focal plane instruments. The facilities are closer to the telescope itself.

The LIGO should be constructed as much as possible using established engineering practices familiar to contractors to minimize the risk and the chance of cost overruns. The LIGO facilities should not themselves become a new experiment.

The above essential features are incorporated in the following conceptual design of the LIGO:

2.2 Geometric layout of the vacuum system

The LIGO vacuum facilities at each site are in the shape of an "L" with each leg of the "L" being a 48 inch diameter vacuum tube of 4 kilometer length as shown in Fig. 1.1. The mirrors and test masses of the receivers are placed in vacuum chambers ("instrumentation chambers") with access to light beams traveling in the antenna arms. One version of the configuration of chambers in the central stations (at the intersection of the arms) is shown in Fig. 2.1a; an alternative version is shown in Fig. 1.1. A central 14-foot diameter chamber is placed directly at the intersection of the arms in both versions. This is the prime location for receivers of any type. The first joint Caltech/MIT receiver will be installed there. The remaining chambers in both versions are designed to give the facility the capability to carry out development of new receiver designs in such a manner as not to significantly interfere with searches being carried out in the central chamber. A decision on the best way to arrange for this capability will be made before the beginning of the final engineering design.

Figure 2.1b is a configuration of the central station in *later* stages of the development of the gravitational wave observatory. The initial building design and chamber configuration (Fig. 2.1a) are intended to anticipate and facilitate the addition of three instrumentation chambers to achieve this later configuration. This LIGO upgrade would enable further multiplexing of the arms to accommodate specialized and independent searches for and observations of gravitational waves. The particular configuration envisaged in Fig. 2.1b would position higher frequency gravitational receivers using small test masses in the front chambers and low frequency receivers, which will tend to have larger masses, in the rear chambers.

The central station, with its four instrumentation chambers initially, is the most complex part of the LIGO, as it is the location of the lasers, injection and exit optics and major part of the control and sense electronics for the interferometers.

Another station ("midstation") with one instrumentation chamber is placed halfway between the central station and the end station of each leg of the L. The two midstation chambers will house masses and mirrors forming the end points of the shorter (probably half length) interferometers. The midstation will be primarily passive, containing little optics or

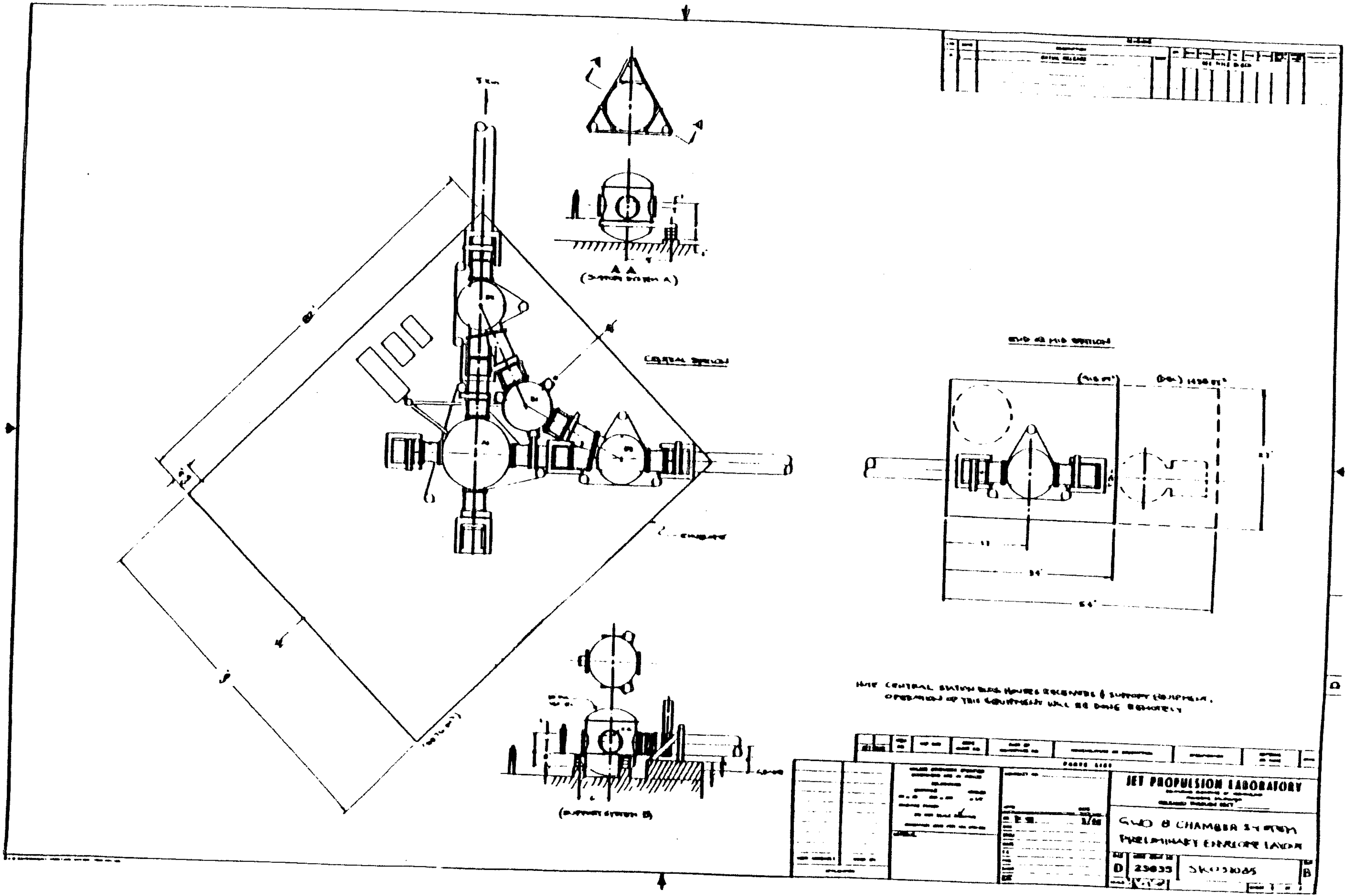


Figure 2.1(a) The corner, mid, and end stations of the LIGO shown with the configuration of instrumentation chambers that would be constructed at th. begining, according to one variant of

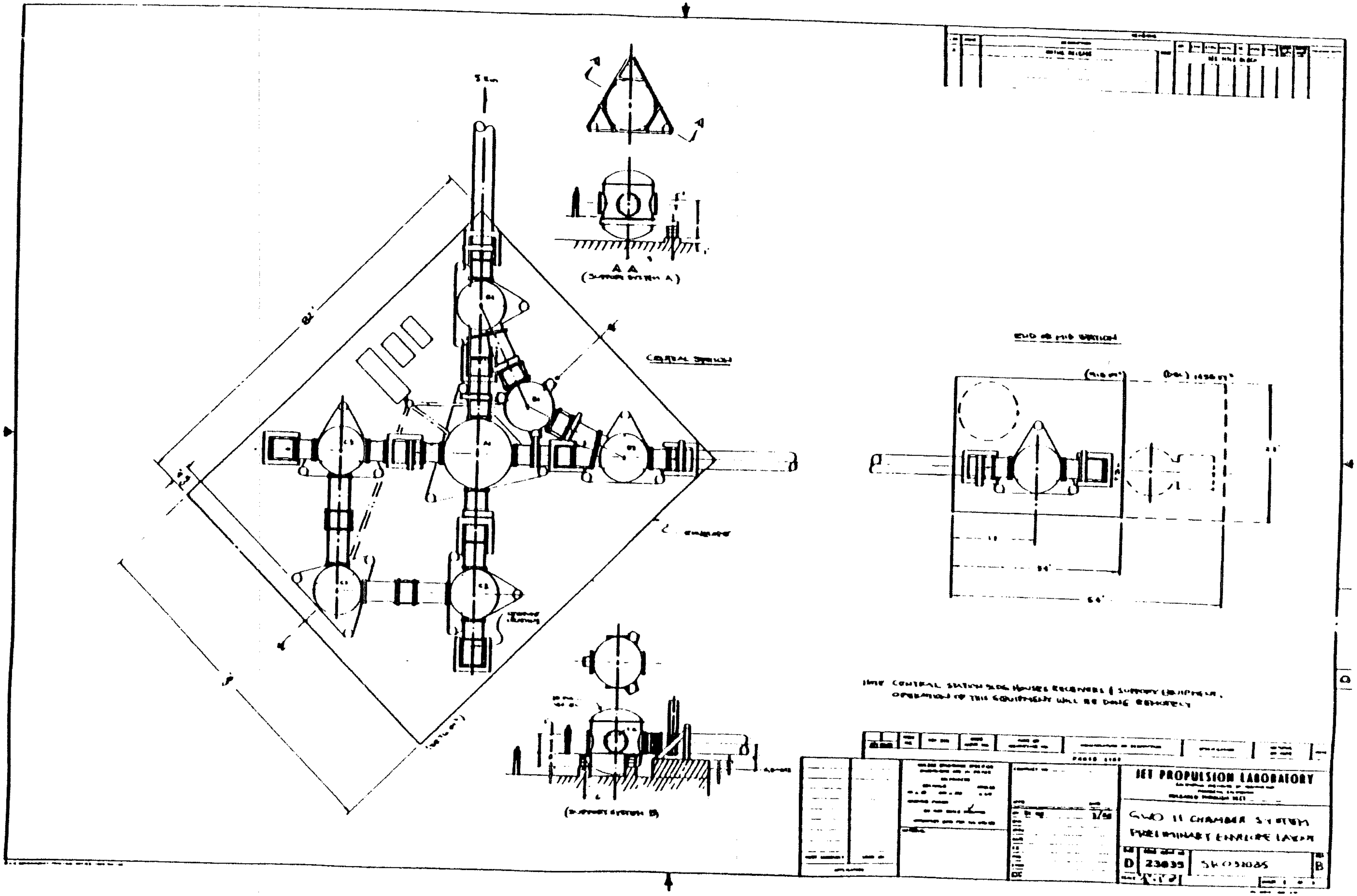


Figure 2.1(b) The corner, mid, and end stations of the LIGO shown at a later date, after the addition of three more chambers.

electronics. The instrumentation stations at the ends of the legs ("endstations") are also primarily passive.

2.3 Key features of the vacuum system

The vacuum system is the most costly part of the LIGO facility, and apart from the receivers it is that component of the facility requiring the most careful planning and design.

The function of the vacuum system is two-fold: 1) to reduce index fluctuations in the light paths along the arms and 2) to reduce the stochastic forces on the test masses and mirrors in the instrumentation chambers.

The vacuum system proposed for further study is made entirely of stainless steel tubing and bellows. The system is designed to be baked out at 150° C to attain pressures of 10^{-8} torr with a reasonable number of pumps. The pumping strategy is a hybrid of ion-chemisorption pumps and turbo pumps. Ion pumps are used to maintain the vacuum after initial pumpdown by the turbo pumps.

The instrumentation chambers are cylindrical stainless steel vessels designed to allow easy access to the receiver components. The main vacuum tubes are isolated from the chambers by gate valves to permit work on the receivers without having to bring the entire system to atmospheric pressure. Furthermore, the chambers associated with the capability for receiver development are valved to allow ready access without significantly disturbing the experiment in the central chamber.

2.4 Sites and Architecture

The specific design of the LIGO is dependent on the characteristics of the two sites where the LIGO will be built. We have chosen BLM-managed, Mojave-desert land at Hawes, California and the Blueberry Barrens of Columbia/Cherryfield, Maine as the prime sites. The facilities will be constructed primarily above ground at the California site and buried in Maine.

General considerations that apply to the design of the facilities at either site are:

1) The design must allow for the ability to find and repair vacuum leaks after construction.

2) Although seismic isolation of the tubing along the antenna arms is not required, the tubes should not be driven by the wind as this may cause noise due to the time-dependent scattering or diffraction at the tubing walls and internal baffles.

3) Thermal stability of the tubing is desirable in order to avoid: daily fluctuations in the outgassing, mechanical thermal distortions of the tubing, the possibility of temperature-driven outgassing bursts, and the acoustic and mechanical noise that might be transmitted to the instrumentation stations due to the possible stick/slip at sliding tube supports.

4) The vacuum system must be protected from vandalism, a problem even at continuously patrolled remote sites.

The conceptual design specifies a cover for the long evacuated tubes.

The buildings housing the instrumentation stations are planned to be prefabricated structures placed on concrete foundations. The chambers are placed on vibration isolation pads which in turn are anchored either to bedrock or to sufficiently buried casements so as to reduce the effect of differential expansion of the antenna arms due to surface temperature gradients.

Efforts will be made to not raise acoustic and vibrational noise in the instrumentation stations more than a few dB above the naturally occurring background at the sites in the 10 to 10,000 Hz band. The instrumentation stations are not intended to be general laboratory or operations buildings: those facilities will be provided by trailers or existing buildings at the sites.

2.5 Power, cooling, and facility instrumentation

Power is readily available at both sites. Present estimates indicate an average demand of 2 MW at each site for lighting, pumps, lasers, and instrumentation. The lasers require closed cycle cooling systems configured to dissipate 0.3 MW maximum; the laser cooling is capable of expansion to 0.6 MW by addition of cooling towers.

The facilities are to be designed so that the receivers can be readily interfaced to them and so that housekeeping and environmental information can be easily folded into the receiver output data streams for correlation and veto analysis. The two facilities are also to include data links to the home institutions and to each other.

Appendix E provides some of the history leading to this conceptual design. The accompanying document "Description of LIGO Design and Project Plans" describes the conceptual design and functional requirements for the facilities more fully.

APPENDICES

APPENDIX A
ASTROPHYSICAL SOURCES OF GRAVITATIONAL WAVES COMPARED WITH DETECTOR SENSITIVITIES

In Sec. 1.5 we describe two kinds of gravitational-wave detectors that might operate in the LIGO: "Simple first detectors" and "more advanced detectors." In this appendix we shall give some technical specifications for such detectors and shall compare their sensitivities with the anticipated strengths of gravity waves from a variety of astrophysical sources.

A.1. Sensitivities of Simple Types of First Detectors in the LIGO

The Caltech and MIT gravity wave groups have furnished NSF with a list of "Milestones" which they expect to achieve between now and the target date for final approval of the LIGO facilities construction (June 1987); see Appendix I. The milestones are designed to guarantee that, even if no further progress were made on detector technology between the time of approval of construction and the completion of construction, receivers could be mounted in the facilities with sensitivities roughly as shown by the upper solid curves of Figs. 1.3 - 1.5. These curves, labeled "Simple first detectors - rms noise", correspond for example to arm lengths of 4 km and to receivers (Michelson or Fabry-Perot interferometer systems) with the following characteristics:

$$P_0\eta \equiv \text{(laser power)} \times \text{(photo detector efficiency)} = 10\,\text{Watts}\,,$$

$$t_{\rm store} \equiv \text{(light storage time in interferometer)} = \frac{1}{(2 \times \text{frequency})}\,,$$

$$b \equiv \text{(number of bounces of light)} = 30 \times (1\,\text{kHz}/\,\text{frequency}),$$

seismic noise negligible above 1 kHz and totally debilitating below 100 Hz.

For such receivers the rms photon shot noise as a function of frequency is given by the following formulae,[7] which correspond to the right-hand straight segments of the upper curves in Figs. 1.3 - 1.5:

$$X(f) = \begin{bmatrix}\text{spectral density}\\ \text{of displacement noise}\end{bmatrix}^{1/2} = \frac{\pi}{2}\left[\frac{\hbar\lambda c}{2b^2\eta P_0}\right]^{1/2} \simeq 7 \times 10^{-17}\,\frac{\text{cm}}{\text{Hz}^{1/2}}\left[\frac{f}{1\,\text{kHz}}\right].$$

$$h = \frac{2}{L}\sqrt{f}\,X(f) \simeq 1\times10^{-20}\left(\frac{f}{1\,\text{kHz}}\right)^{3/2} \quad \text{for bursts of duration } 1/f\,.$$

$$h = \frac{2}{L}\frac{1}{\sqrt{\hat{\tau}}}X(f) \simeq 1\times10^{-25}\left(\frac{f}{1\text{kHz}}\right) \quad \begin{array}{l}\text{for periodic waves with}\\ \hat{\tau} = \text{(averaging time)} = 10^7\ \text{sec}\,.\end{array}$$

$$\sqrt{f}\,h(f) = \frac{2}{L}\frac{\sqrt{f}\,X(f)}{(\pi f\hat{\tau})^{1/4}} \simeq 3 \times 10^{-23}\left(\frac{f}{1\text{kHz}}\right)^{5/4} \quad \begin{array}{l}\text{for stochastic waves with}\\ \hat{\tau} = 10^7\ \text{sec}\end{array}$$

where

L = (armlength) = 4 km. λ = (wavelength of light) / 2π = 0.1 μm.

f = (frequency of gravitational waves).

At frequencies below 1000 Hz the sensitivities shown in Figs. 1.3 - 1.5 are worse than these shot-noise limits because of seismic noise.

A.2. Sources that Could be Detected with these First Simple Detectors

Over the past fifteen years there have been extensive theoretical studies of the gravitational waves to be expected from astrophysical systems. These studies, based on the best information available from electromagnetic observations of the universe (radio, millimeter, infrared, optical, ultraviolet, X-ray, gamma-ray), have been summarized in the proceedings of a number of workshops and summer schools,[8] and in review articles.[9] The discussion of gravitational-wave sources in this appendix is drawn from those reviews and from the original literature.

The sensitivities of current gravity wave detectors are good enough that they could detect astrophysical sources without violating any of our cherished beliefs about the universe around us,[11] though detection is quite unlikely. The improved sensitivities of the LIGO's "first simple detectors", as described above, are in the range where the prospects of success are reasonable (a few tens of per cent), but not high. Examples of the sources that could be detected with these first simple detectors are the following:

Supernovae. Type II supernovae are believed, with a high level of confidence, to be created by the gravitational collapse of the cores of massive, highly evolved stars; and type I supernovae may, though this is controversial, result from stellar collapse of white dwarfs that have accreted considerable mass from very close companions. In addition to these two types of optically observed supernovae, there may well be stellar collapses that produce little optical display ("optically silent supernovae").

The strengths of the gravitational waves from supernovae can be characterized by the fraction of a solar rest mass of energy carried off by the waves (the "efficiency" $\Delta E / M_{\odot} c^2$):

$$h \simeq 5 \times 10^{-22} \left(\frac{\Delta E / M_{\odot} c^2}{10^{-3}} \right)^{1/2} \left(\frac{15\ \mathrm{Mpc}}{r} \right) \left(\frac{1\ \mathrm{kHz}}{f} \right)^{1/2} .$$

$$f \equiv \begin{pmatrix} \text{frequency at peak} \\ \text{of spectrum} \end{pmatrix} .$$

If the stellar core remains nearly spherical during collapse, its efficiency will be exceedingly small; but if the core is rotating rapidly enough that centrifugal forces flatten it and produce triaxiallity before the collapse reaches nuclear density, the efficiency may be as large as 10^{-3} (reference 12). If type I supernovae do involve collapse, they probably rotate rapidly and have the $\sim 10^{-3}$ efficiency. Most type II supernovae might rotate slowly and have efficiencies many orders of magnitude smaller than 10^{-3}; but it is possible that many rotate rapidly.

As shown in Fig. 1.3, the "first simple" detectors could detect a supernova in our own galaxy with an amplitude signal-to-noise ratio of 5 (that required for a one-sigma detection of a very rare event), if the supernova has an efficiency of 0.5×10^{-6} or larger; and it could detect a supernova in the Andromeda galaxy (700 kpc from Earth), if the efficiency is 1×10^{-3}. The rate of type II supernovae out to Andromeda is about one every 10 or 20 years; that of type I is about the same; and the rate of silent supernovae could be as high as the highest rates estimated for pulsar births, one each four years. As the detector sensitivity pushes the observed region of space from Andromeda on outward by another factor 20, the event rate will go up proportional to the amplitude sensitivity; and thereafter it will go up as the cube of the amplitude sensitivity (the difference being due to the clumping of galaxies).

The upshot of these numbers is that the first simple detectors are in a range where supernovae of high efficiency ($\sim10^{-3}$) *might* be seen once every few years, and where modest further improvements of sensitivity will push the event rate up significantly.

Coalescence of compact binaries (neutron stars and black holes). Since a large fraction of all stars are in close binary systems, the dead remnants of stellar evolution may contain a significant number of binary systems whose components are neutron stars or black holes and are close enough together to be driven into coalescence by gravitational radiation reaction in a time less than the age of the universe. The binary pulsar is an example of such a system..

As the two bodies in a compact binary spiral together, they emit periodic gravitational waves with a frequency that sweeps upward toward a maximum,

$$f_{\max} \simeq 1\,\mathrm{kHz} \quad \text{for neutron stars ;}$$

$$f_{\max} \simeq \frac{10\,\mathrm{kHz}}{M_2/M_\odot} \quad \text{for holes with the larger one having mass } M_2 .$$

Since the details of this frequency sweep are well known from the theory of binary stars,[13] the experimenter can search for such sweeps in his data, thereby increasing his amplitude signal-to-noise ratio by the square root of the number n of cycles of the waves over which he observes. Since the number of cycles spent near frequency f is

$$n \equiv \frac{f^2}{df/dt} = \frac{5}{96\pi}\,\frac{M}{\mu}\left(\frac{c^3}{\pi GMf}\right)^{5/3},$$

$$\mu \equiv \frac{M_1 M_2}{M_1 + M_2} = \begin{pmatrix}\text{reduced}\\ \text{mass}\end{pmatrix}, \quad M \equiv M_1 + M_2 = \begin{pmatrix}\text{total}\\ \text{mass}\end{pmatrix}.$$

and the amplitude at that frequency, rms averaged over all detector orientations and binary orientations, is

$$h = \frac{8}{5}\,\frac{G\mu}{c^2 r}\left(\frac{\pi GMf}{c^3}\right)^{2/3}, \quad r \equiv (\text{distance to source}) .$$

the effective signal strength is

$$h\sqrt{n} \simeq \sqrt{\frac{2}{15\pi}}\,\frac{G(\mu M)^{1/2}}{c^2 r}\left(\frac{c^3}{\pi G M f}\right)^{1/6}.$$

Because of their broad-band frequency sensitivities, laser interferometer detectors will be able to study the details of the frequency sweep of the waves, and the details of the final splash waves and ringdown waves produced in the coalescence. For some predictions of the characteristics of these waves see reference 14.

As shown in Fig. 1.3 the inspiral-and-coalescence signal would be detectable by the first simple detectors, with an amplitude signal-to-noise ratio of 5, if the binary were made of two 1.4 solar-mass neutron stars at twice the distance of Andromeda, or two 10 solar-mass black holes at seven times the distance of Andromeda. The birth rate of such binaries today probably does not exceed one each thousand years out to such distances. On the other hand, galaxies such as our own are surrounded by massive dark halos that might be made of remnants of an ancient population of stars ("Population III") which formed, burned, and died while galaxies were first forming.[15] It is quite possible, though not highly likely, that one per cent or more of the mass of these halos wound up in compact binaries that spiral together in times of order the age of the universe; in this case, the event rate for coalescences would be of order one per year or more.[15]

As for supernovae, so also for coalescing binaries, as the detectors improve beyond the first simple one, the event rate will go up initially linear with amplitude sensitivity; then cubically.

Pulsars. A pulsar (rotating neutron star) emits periodic gravitational radiation as a result of its deviations from axial symmetry. The strongest waves are likely to come off at twice the rotation frequency, though waves can also be produced at the rotation frequency plus and minus the precession frequency.[16] At twice the rotation frequency the amplitude of the sinusoidal waves depends on the pulsar's ellipticity ε (more precisely, the ratio ε of the nonaxisymmetric part of its moment of inertia to the axisymmetric part):

$$h \simeq 10^{-19}\varepsilon\,\frac{(f\,/\,1\,\mathrm{kHz})^2}{(r\,/\,10\,\mathrm{kpc})}, \qquad f \equiv \text{(gravitational wave frequency)}.$$

Data collected with the first simple detectors for other purposes (e.g. supernova searches) can also be Fourier analyzed to search for pulsar signals. As indicated in Fig. 1.4, by integrating for 100 days one could detect a pulsar with rotation period 2 msec (gravity-wave frequency 1 kHz) and ellipticity 2×10^{-6} at the distance of the galactic center. Little is known as yet about the number of such rapidly rotating neutron stars in our galaxy. However, if one per cent of all neutron stars were born rotating this rapidly or faster and with surface magnetic field strengths of 3×10^{11} Gauss or less and with ellipticities of 2×10^{-6} or larger, then there would be one or more such detectable pulsars in our galaxy today.

Stochastic background. Because all plausible sources of stochastic background are cosmological, it is convenient to characterize the background at a given frequency f by the total gravity-wave energy density in a bandwidth $\Delta f = f$ divided by the energy density required to close the universe. In terms of this ratio, denoted Ω_{gw}, the square root of the spectral density of the wave amplitude, $h(f)$, is given by

$$h(f) \simeq (8\times10^{-19}/\sqrt{\mathrm{Hz}})(1\,\mathrm{Hz}/f)^{3/2}\,\Omega_{gw}{}^{1/2}\,.$$

This root spectral density, multiplied by the square root of the frequency to make it dimensionless, is plotted as a series of dashed curves in Figure 1.5 for a wide range of frequencies and for Ω_{gw} equal to 1, 10^{-4}, and 10^{-10}.

Figure 1.5 shows that a stochastic background with $\Omega_{gw} \gtrsim 10^{-4}$ in the several-hundred-Hertz range would be detectable by the first simple detectors with 100 days of integration. This is a rather interesting wave strength:

Stochastic background from Population III stars. Population III stars, if they existed (see above), may have produced in their death throes gravitational waves that superimpose today to form a stochastic background. Bond and Carr[13] and others have deduced from current observations and theory that Ω_{gw} for such a background cannot exceed $\sim 10^{-3}$; but values as large as $\sim 10^{-4}$ are plausible and would be detectable.

Stochastic background from inflation, strings, phase transitions, and other phenomena in the very early universe. The density fluctuations from which galaxies formed are known to have had a magnitude $\delta\rho/\rho \sim 10^{-4}$ to 10^{-6}. A number of proposals have been made in recent years as to how these density fluctuations might have originated: e.g. quantum mechanical fluctuations amplified by inflation, cosmic strings, and phase transitions. These processes typically (but not always) produce, along with galaxy seeds, a "Zel'dovich spectrum" of gravitational radiation -- i.e. a spectrum with Ω_{gw} independent of frequency in the frequency bands of interest for gravity wave detectors; and the amplitudes of the waves correspond to Ω_{gw} as large as $\sim (\delta\rho/\rho)_{\text{galaxy seeds}} \sim 10^{-4}$ to 10^{-6}, or as small as 10^{-14} – depending on the scenario. Thus, the first simple detectors will just enter the interesting region; and subsequent improvements in sensitivity will push down through that region with $\Omega_{gw} \propto$ (amplitude sensitivity)^2. (We note in passing that in the next few years pulsar timing measurements will also push down through this interesting region, but at much lower frequencies $f \lesssim 10^{-7}$sec.)

A.3. Sensitivities of More Advanced Detectors

The "light recycling," "light resonating", and antiseismic isolation techniques outlined in Sec. 1.5.2 show promise of greatly enhancing the performance of gravitational wave detectors over that of the "first simple detectors" described above. We anticipate perfecting these techniques in the proposed facilities; and that effort may well lead to "more advanced detectors" with characteristics something like the following:[17]

$P_0\eta$ = (laser power) × (photodetector sensitivity) = 100 Watts ,

R = (mirror reflectivity) = 0.9999 ,

light recycling used for burst searches,

light resonating used for periodic and stochastic searches,

seismic noise negligible above 10 Hz but debilitating below 10 Hz.

For such apparatus the rms noise levels as functions of frequency are given by the lower solid curves of Figures 1.3, 1.4, and 1.5 (labeled "possible later experiments"). The shot noise limits of these figures were computed from the following formulae[17]

$$h \simeq \pi\left[\frac{\hbar\bar{\lambda}(1-R)f^2}{L\eta P_0}\right]^{1/2} \simeq 1.6\times10^{-22}\left(\frac{f}{1\,\mathrm{kHz}}\right) \text{ for bursts ,}$$

$$h = \frac{\pi}{L}\left[\frac{\hbar\bar{\lambda}c(1-R)^2}{\eta P_0\hat{\tau}}\right]^{1/2} \simeq 1.4\times10^{-28} \text{ for periodic waves ,}$$

$$\sqrt{f}\,h(f) = \pi\left[\frac{\hbar\bar{\lambda}cf}{\eta P_0}\right]^{1/2}\left[\frac{2(1-R)^3}{L^3 c\,\hat{\tau}}\right]^{1/4} \simeq 1.8\times10^{-25}\left(\frac{f}{1\,\mathrm{kHz}}\right)^{1/2} \text{ for stochastic waves ,}$$

where

ηP_0 = 100 Watts , $R = 0.9999$, $\hat{\tau} = 10^7$ sec , $L = 4$ km , $\bar{\lambda} = 0.1\,\mu$m.

The segments of the sensitivity curves labeled "SQL" are determined by the "standard quantum limit" for a free-mass detector – which sets in when the stored laser power becomes so great that light-pressure fluctuations compete with photon shot noise:[18]

$$h \simeq \frac{1}{\pi L}\left(\frac{2\hbar}{Mf}\right)^{1/2} \simeq 1.2\times10^{-24}\left(\frac{1\,\mathrm{kHz}}{f}\right)^{1/2} \text{ for bursts,}$$

$$h \simeq \frac{1}{\pi L}\left(\frac{2\hbar}{Mf}\right)^{1/2}\frac{1}{(f\hat{\tau})^{1/2}} \simeq 1.2\times10^{-29}\left(\frac{1\,\mathrm{kHz}}{f}\right) \text{ for periodic waves,}$$

$$\sqrt{f}\,h(f) \simeq \frac{1}{\pi L}\left(\frac{2\hbar}{Mf}\right)^{1/2}\frac{1}{(\pi f\hat{\tau})^{1/4}} \simeq 3\times10^{-27}\left(\frac{1\,\mathrm{kHz}}{f}\right)^{3/4} \text{ for stochastic waves,}$$

where

M = (mirror mass) = 10^6 g , $\hat{\tau} = 10^7$ sec , $L = 4$ km .

For periodic and stochastic waves the standard quantum limit can be circumvented by splitting each mirror-carrying mass into two parts with a suitable spring between them.[19] However, it is not yet clear how practical this is, so the "later" sensitivities of Figures 1.4 and 1.5 are shown both with and without the standard quantum limit. For burst waves nobody has yet devised a scheme for circumventing the standard quantum limit in laser interferometer detectors (though a potentially viable scheme does exist for bar detectors) [20]

A.4 Sources that Could be Detected with The More Advanced Detectors

As the detector sensitivities in the proposed facilities gradually improve, they will move downward from the upper solid curves of Figures 1.3 - 1.5 to the lower solid curves. It is almost certain that at some point during those improvements – possibly right at the beginning, and conceivably toward the end – gravity waves will be detected and will begin to be used both for tests of fundamental physics and as probes of the universe (Sec. 1.4). As an indication of the very high probability of success, we shall compare the sensitivities of the "more advanced detector designs" (lower solid curves) with current estimates of source strengths:

Supernovae. With the needed amplitude signal to noise ratio of 5, the more advanced designs could detect supernovae with efficiencies 10^{-9} in our Galaxy, and 10^{-3} in the Virgo cluster of galaxies. This is adequate to be quite promising, but in view of the low event rate in our galaxy and the many orders of magnitude uncertainty in supernova wave strengths, it is far from adequate to guarantee success.

Coalescence of Neutron-Star Binaries. **Here we have a near-certain guarantee** of success: Clark, van den Heuvel, and Sutantyo[21] have deduced, from observations in our own galaxy, that to see three coalescences of neutron-star binaries per year, one must look out to a distance of 100^{+100}_{-40} Mpc (90% confidence). Figure 1.3 indicates that with the more advanced detectors, the resulting waves could be detected with an amplitude signal-to-noise ratio of 5 (the minimum needed to pull such a rare event out of Gaussian noise) out to a distance of 1.5 Gpc, i.e. half way to the edge of the observable universe. Thus, the advanced detectors would be 15 times more sensitive than needed, according to Clark, van den Heuvel, and Sutantyo, for an event rate of 3 per year; and their predicted event rate would be one per hour.[21]

Coalescence of Black-Hole Binaries. The more advanced detectors could see black-hole coalescences throughout the universe so long as the more massive of the two holes did not exceed $1000M_{\odot}/(1+Z)$, where Z is the holes' cosmological redshift. Unfortunately, so little is known about the number of black holes and black-hole binaries in the universe that the event rate could be anywhere between zero and many per day. Current fashion would suggest an interestingly high rate.

Pulsars. Figure 1.4 shows that the "advanced" detectors could detect the Crab and Vela pulsars if their ellipticity is 3×10^{-7} or larger, and the 1.6 msec pulsar (PSR1937+21) if its ellipticity is $\gtrsim 1\times10^{-9}$. It is quite possible that these ellipticities lie in these ranges; for example, the observed slowdowns if due to gravitational-radiation-reaction correspond to ellipticity $\sim10^{-3}$ for Crab and Vela, and 5×10^{-9} for PSR1937+21. However, it is also possible that the ellipticities are below the observable range.

Spinup of a neutron star. It is fashionable to believe that the 1.6 millisecond pulsar acquired its fast rotation by spinup due to accretion in a binary system. Such spinup is subject to the "Friedman-Schutz instability",[22] wherein, when the star reaches a critical rotation rate of order that observed for the 1.6 millisecond pulsar, the bulk of the accretion energy stops spinning up the star and starts pouring out as gravitational radiation. The radiation is produced by density waves which circulate around the neutron star's outer layers at a different speed from the star's rotation, and which thus radiate at a different, lower frequency. (This is a special case of a general class of gravitational-radiation-reaction instabilities discovered by Chandrasekhar[23], which was one of the bases for Chandrasekhar's Nobel Prize.) Wagoner[24] has shown that the frequency of the resulting gravitational radiation will be a few hundred Hertz, and that its amplitude (which is proportional to the square root of the accretion-produced x-ray flux F_x) will be

$$h \simeq 3\times10^{-27}\left(\frac{300\,\mathrm{Hz}}{f}\right)\left(\frac{F_x}{10^{-8}\mathrm{erg/\,cm^2\,sec}}\right)^{1/2}$$

As shown in Fig. 1.4 the "advanced" detectors could detect such a source if its X-ray flux were $\geq 3\times10^{-10}$ erg cm^{-2} sec^{-1} (Sco X-1 is 600 times brighter than this; many others are 10 times brighter). The number of such sources is unknown; it could well be large, and it could be zero.

Stochastic Background. Figure 1.5 shows that the "advanced detectors" could detect a stochastic background in the 10 to 100 Hz band with cosmological density parameter $\Omega_{gw} \gtrsim 10^{-11}$. When one recalls that the cosmologically interesting region begins at 10^{-4}, one sees that even if nothing is seen, it will be possible to totally rule out a number of plausible hypotheses for the seeds of galaxy formation and scenarios for Population III stars. Moreover, it is worth recalling that the cross section for gravitational waves to interact with matter is so small that waves created in the big bang at the "Planck time" of 10^{-43} seconds are likely to have propagated unimpeded from then until now. Thus, such waves are a potential direct observational link (the only such direct link) to the era when the initial conditions of the universe were set; and if no more that 10^{-11} of the universe's energy went into such waves with present-day frequencies 10 to 100 Hz (perfectly plausible), the waves could be detected and studied by the advanced receivers.

Sensitivities Required for High Probability of Detection.

Of all the above sources, the one in which we can have greatest confidence is the coalescence of neutron-star binaries. To have 90% confidence of seeing 3 or more such events per year, one must look out to 200 Mpc distance;[21] and to have 90% confidence of seeing the wave burst in the presence of detector noise, one must have an amplitude signal to noise ratio of 10. These requirements correspond to the sensitivity of the dotted line near the bottom of Fig. 1.3. Moreover, at this sensitivity it seems quite likely that some of the other sources described above will be detected. Thus, we regard this as a benchmark sensitivity level at which the probability of detecting gravity waves is very high.

Appendix B.

NEW CONCEPTS IN INTERFEROMETRIC GRAVITATIONAL WAVE DETECTION TECHNIQUES

B.1. Introduction.

The gravitational wave detection facilities whose design is proposed here represent a considerable step up in scale from present instruments, and the corresponding step up in sensitivity is, we believe, sufficient itself to fully justify the project. We anticipate, however, a much bigger improvement in overall performance than this, for these facilities will enable a number of new concepts to be exploited which should greatly enhance experiment sensitivity and scientific productivity. Many of these ideas were initially conceived in early work in Glasgow and in more recent work at Caltech where available vacuum systems are too small in baseline or in beam pipe diameter to make them practical; but they could in principle bring major benefits in a system of the scale of the proposed LIGO.

Some of the concepts have already been briefly outlined in earlier sections of this Proposal: here we will give more details to indicate how these schemes may be carried out in practice, and we will introduce some additional concepts.

B.2. New Interferometer Concepts

(a) Enhancement of Sensitivity by "Light Recycling"

The basic idea here has already been outlined in Section 1.5.2. The optimum storage time for light in the arms of a multireflection interferometer corresponds approximately to half the period of the gravity wave, and if the mirrors used have low losses, corresponding to a time constant much longer than this, then most of the light entering the interferometer system leaves it from the unused side of the beamsplitter. This light may be returned to the system by an additional mirror, and if the optical paths and the transmission of this mirror are correctly adjusted to maximize the total stored light flux then a useful improvement in the photon shot noise limit to sensitivity may be obtained without degrading the bandwidth of the system.[4] Delay-line Michelson and Fabry-Perot versions of this arrangement are shown, in principle, in Figure 1.6A (Section 1.5.2).

In practice it will be important to minimize optical losses in all components within the whole resonant system. We know that losses in small diameter mirrors currently used in the Caltech prototype are sufficiently small. In the prototype interferometers we have used a high frequency phase modulation technique to shift the sensitive phase measurement away from frequencies where intensity noise from the laser is important, and in one simple arrangement this is done by pockels cell phase modulators (indicated by P1 and P2 in Figure 1.6A). Unfortunately some of these modulators have losses of a few percent, and they may exhibit refractive index changes and other problems at high light intensities. We therefore propose to use a different modulation technique in a recycling interferometer, and one possible arrangement is shown in Figure B.1, for the case of a Fabry-Perot system. Here the main interferometer is unmodulated, and a low-intensity auxiliary beam coherent with the input beam is phase modulated at a suitable radio frequency and caused to interfere with the residual output, which is also arranged to have very low intensity. With suitable control of optical phase, amplitude and depth of modulation of the auxiliary beam (using monitoring photodiodes omitted from the diagram for simplicity) this arrangement can provide the type of low-loss system required. A similar arrangement can also be used with a recycling delay-line Michelson interferometer.

Figure B.1 also illustrates the use of separate test masses supporting just the cavity mirrors at the inner ends of the two interferometer arms. This enables the critical test masses to have a simple compact geometry which makes it possible to arrange that the lowest internal mechanical resonance in these masses occurs well above the gravitational wave frequencies of interest, and has a high quality factor. Effects of internal thermal noise are thus minimized near the gravitational wave frequencies. This technique, suggested from Caltech and Munich independently, has proved very effective in reducing noise in prototype interferometers.

(b) *Enhancement of Sensitivity for Periodic Signals*

A technique for improving the photon shot noise limit to the sensitivity of an interferometric detector for periodic gravitational waves has been outlined in Section 1.5.2. In this technique[4] the optical phase signal is made to interchange between the two arms of the interferometer in synchronism with the gravitational wave inducing it, so that the signal builds up linearly with time over the total time that light is stored within the system. Methods for achieving this in both delay-line Michelson and Fabry-Perot interferometers are illustrated, in principle, in Figure 1.6B.

As in the other interferometers it is useful to employ a high-frequency modulation technique to reduce effects of laser intensity noise, and it is desirable to keep any modulation Pockels cells out of the main high power beams. One possible arrangement for in optically resonating Fabry-Perot system is indicated schematically in Figure B.2 and again a similar method can be used in a delay-line interferometer.

In analyzing the operation of the Fabry-Perot system, the two optical cavities may be considered as a coupled system with two resonant modes. The lower resonance may be chosen to match the frequency of the laser light, and the upper resonance arranged to match the upper sideband of the signal induced by 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 optically

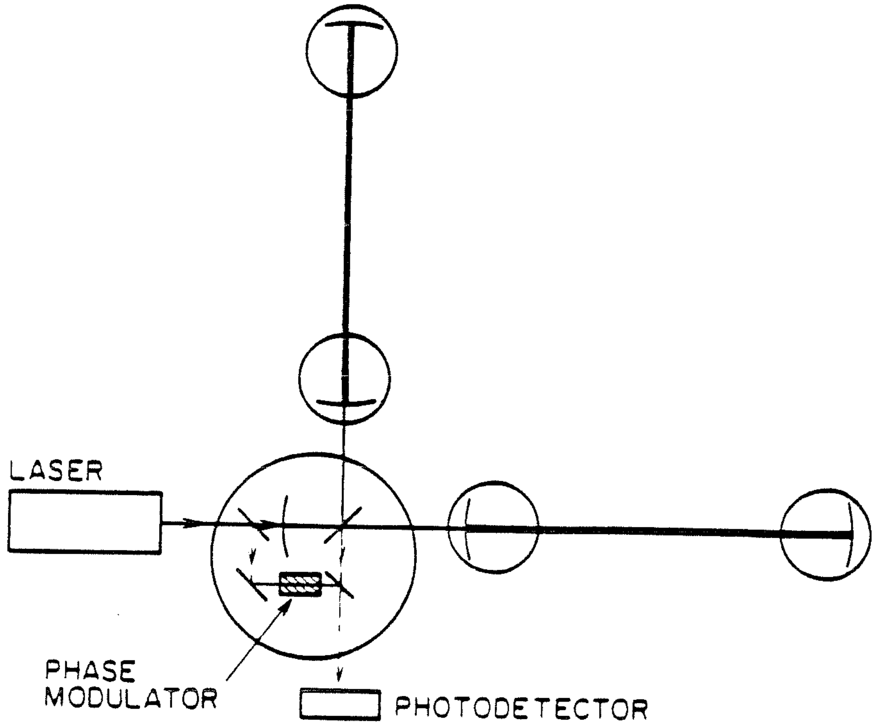


Figure B.1 A practical method of recycling light within a Fabry-Perot cavity in which the Pockels cell modulator is placed outside the cavities to reduce losses.

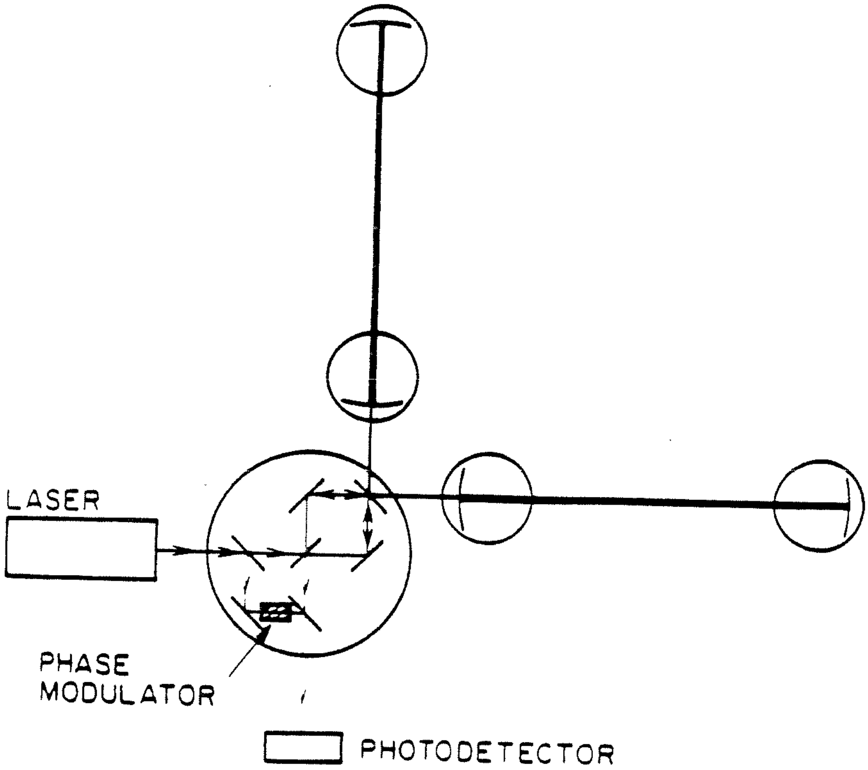


Figure B.2 A low-loss method for enhancing the sensitivity of a Fabry-Perot antenna for periodic signals.

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 a fixed frequency signal such as a millisecond pulsar might be enhanced by two orders of magnitude, corresponding to a power sensitivity improvement by a factor of 10000.

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 losses to arm length, so low loss mirrors are even more important here than for pulse searches. This type of search also benefits most rapidly from increases in interferometer baseline, and if stochastic noise forces acting on the test masses can be made small enough to be unimportant then the requirements of periodic gravity wave searches using resonant interferometers are themselves strong reasons for making the baseline of a gravitational wave interferometer as long as practicable.

The bandwidth over which resonant enhancement takes place is determined by the overall light storage time, and in practice is likely to be a few Hertz. In a search for a periodic signal of known frequency a suitable coherent integration would be preformed in the analysis of the data from the interferometer to narrow the effective bandwidth and enhance sensitivity further.

(c) An Alternative Interferometer System

The techniques for enhancing interferometer sensitivity described above were initially conceived under the stimulus of the realization that mirrors of the type developed for laser gyroscopes could give extremely long light storage times if applied to long-baseline Fabry-Perot cavities; but, as shown, the ideas are applicable to Michelson interferometers also. In fact the basic Fabry-Perot and delay-line Michelson interferometers have many common properties - as well as individual advantages and disadvantages. Other multireflection systems are useable, however, and it may be noted that a third type of interferometer, the frequency-tagged interferometer, was recently suggested independently 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 "compact delay-line" type of interferometer has significant advantages over the systems already being developed. It may prove useful should light scattering be an unmanageable problem or if difficulties arise in achieving high power simultaneously with good frequency stability. This concept is mentioned here in part to indicate that new ideas continue to arise in this field, and we feel it is important that the large-scale vacuum facilities being proposed be made sufficiently flexible to accommodate a wide range of optical systems.

B.3. Techniques for Improving Discrimination Against Other Phenomena

We now move from new optical techniques capable of giving greatly improved sensitivity in the interferometers which form the heart of the detectors, to further new methods for significantly improving the detection system as a whole.

Effective discrimination against all kinds of spurious phenomena is a critical aspect of any gravitational wave experiment. A prime technique has been, and remains, the use of two or more detection instruments at widely separated sites. This is crucial in establishing the existence of gravity wave bursts and furthermore is required for gaining information on the positions of gravitational wave sources. The coincidence method can be usefully supplemented by detection techniques which themselves give discrimination against spurious disturbance at each site. Several new methods for improving this aspect of the experiments have been arrived at during the course of the interferometer development at Glasgow, Caltech, and MIT, and we will briefly summarize here some which may improve experiments done using the proposed facilities.

(a) Reduction of Seismic Noise 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 layers 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 with existing passive suspension systems. In addition to the development of active seismic isolation systems discussed in the main body of ~~the proposal~~ this document, another method for improving rejection of seismic noise was proposed in 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 more easily obtained by this method than by other active systems, 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 proposed for the LIGO.

(b) 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 (at low frequencies) changing gravitational gradients due to moving local objects. Monitors for many of these phenomena will be used in the LIGO to reject 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.

If the rate of spurious pulses is high, cross correlation of data from only two detectors may be inadequate and there may be a need for increasing the number of independent detectors. The obvious solution, given an unconstrained budget, would be to construct independent detecting systems at the same and at many different sites. In the absence of many sites, however, one can still improve the discrimination somewhat, as well as the capability to perform diagnostic studies of noise sources, by running 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 accommodate two or more separate interferometer beams 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, which for a large-amplitude gravity wave should be in the ratio 1:2, can discriminate against many types of spurious phenomena. In particular, bursts of gas from the vacuum pipe walls and changes in gravitational gradients from local moving objects would give strain signals in the two interferometers typically not in this ratio; 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, 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.

B.4. On the Design and Uses of the LIGO at Later Stages

A key aspect of our present conceptual design of the LIGO is the requirement (Sec. 2.1) that it be easily upgradable to support three or more simultaneous investigations -- largely by the construction of additional instrumentation chambers in the vacuum system. In this section we shall describe some of our tentative thoughts about the design and uses of the LIGO after such upgrades have been performed.

If it turns out that the strengths of the gravitational waves are near the lower solid curves of figures 1.3 - 1.5 ("advanced detector" curves) rather than near the upper solid curves ("first simple detector" curves), then the LIGO facilities may still be in a search phase when they reach an upgraded form. In this section we shall focus attention largely on this possibility – so that the reader can see that in the most pessimistic of situations there is a great richness of possibilities inherent in the proposed LIGO.

(a) Operation of Several Interferometers within a Single Vacuum System

The evacuated beam pipes for a long-baseline interferometer and the civil engineering associated with them dominate the cost of the whole system, so it is desirable to use them as intensively as practicable. The half- and full-length interferometer system outlined above [Sec. B.3(b)] is a special case of a more general concept of multiple use of beam pipes which has gradually developed along with the practical development of Fabry-Perot interferometers with their compact beams. 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 masses for an interferometric detector depends on the time scale of the signals being sought. This is because 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 B.2.(a) and (b) 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. Schematic diagrams of possible arrangements are shown in Figures B.3 and B.4.

It may be useful to comment briefly on the arrangement shown in Figure B.4 - which is just an illustrative layout. The system shown accommodates three sizes of test masses, for different frequency ranges, with a full- and a half-length interferometer for each range. In each interferometer the central mass is split up into three parts. The prime location is at the intersection of the long beam pipes, and in this arrangement the support masses for the beamsplitters of two of the interferometers are located there, with the corresponding test masses located in the adjacent tanks, forward of the central tank. Two further sets of tanks are shown here: tanks housing smaller, high-frequency test masses forward of the central tank, and tanks housing larger low-frequency test masses behind it. Beamsplitter assemblies are housed in a third tank in each set, located on the diagonal plane of symmetry between the two arms. This type of layout maximizes the particularly valuable space on the diagonal plane, which is required for optical elements such as beamsplitters which must be equidistant from their associated test masses. The widths of the pipes on the diagram are greatly exaggerated to make the beam paths clearer, and although the diagram may look cluttered, the number of test masses and beams shown could be easily fitted in with beam pipes 48 inches in diameter, arms 4 km long and light of wavelength 514 nm, using Fabry-Perot or compact delay-line optics.

In fact there is room, when required, for additional beams associated with at least two further sets of masses, which could be accommodated by adding a further set of three tanks in front of the corner assembly, and another set of three tanks behind it. A tank to give more room for test masses at the end and

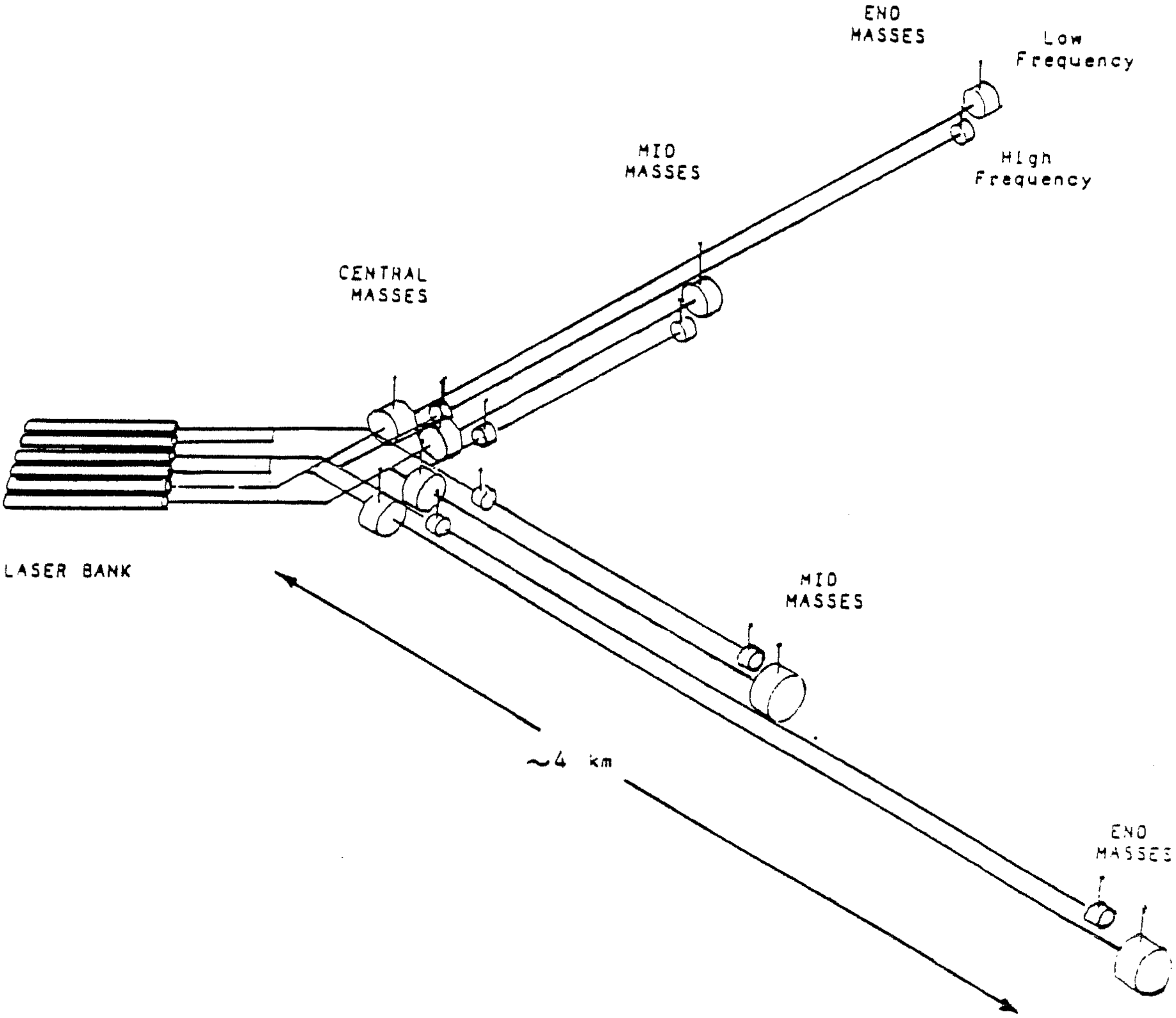


Figure B.3 Example of a possible type of multiple interferometer system. Initially only some of the masses might be installed. Further masses—and possibly more than those shown here, to facilitate periodic searches—might be added later. (Note diagram is highly schematic and not to scale: light beams would be closely packed to fit within the single vacuum pipe for each arm.)

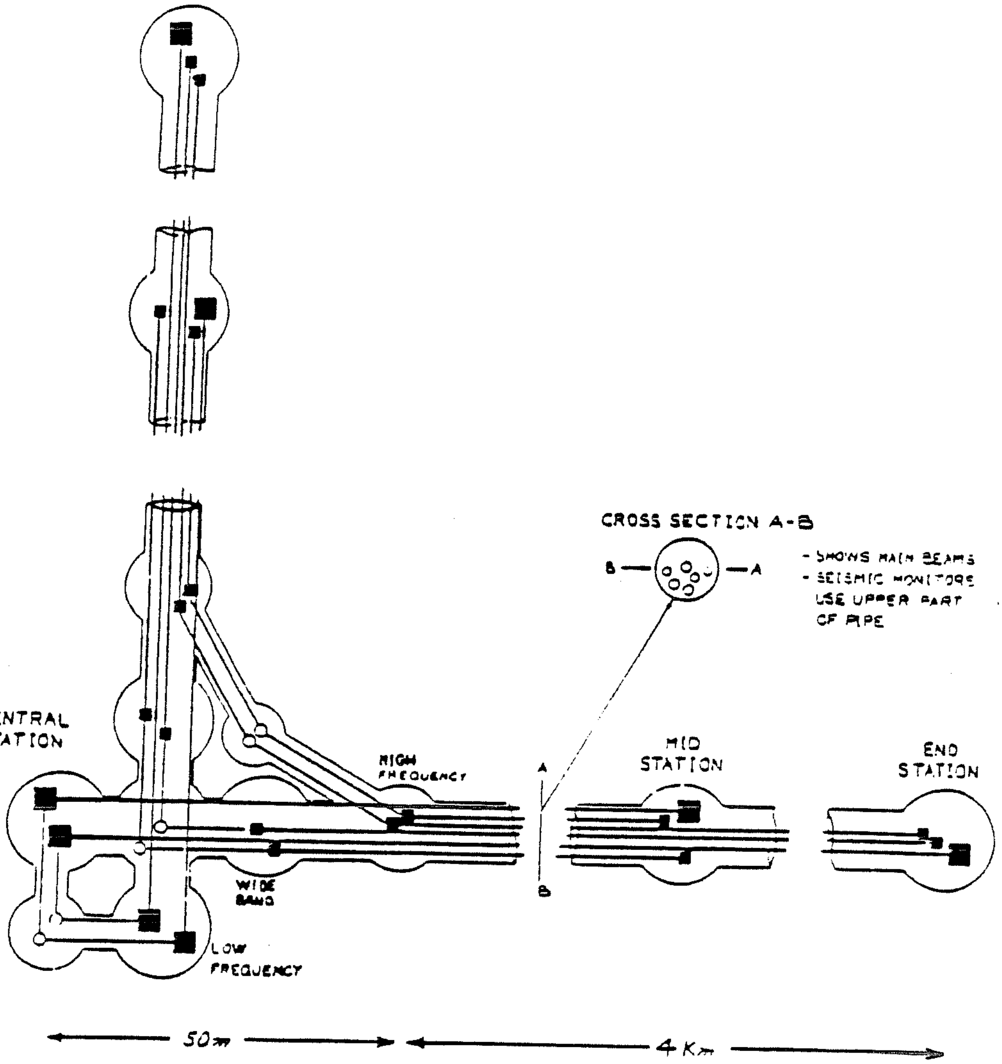


Figure B.4 An example of how large diameter (>1 m) pipe can be exploited to operate many interferometers simultaneously. Depicted here are three seperated detectors, optimized for low frequency (< 100 Hz), high frequency (> 1kHz), and wideband operation. Each detector consists of four interferometers full-length and half-length for main beams monitoring the suspended masses as well as auxilliary beams for monitoring the suspension points.

mid stations might be added also. Such a full utilization of the beam pipes would probably only be reached at a late stage in the use of the installation, and would require some sharing of seismic monitoring beams among different sets of test masses. We certainly are not proposing that a system as elaborate as this be built early in the development of the LIGO; however, when planning facilities of this type it is important to consider the possibilities for future expansion.

(b) Optimization of System Design for Various Phases in its Operation

The experimental work we foresee for the LIGO might be regarded as having two partially overlapping phases: the first phase being the exploratory search phase leading to the unambiguous detection of gravitational radiation from one, or more, types of source; and the second being the detailed study and investigation of the gravitational wave signals and the development of gravity wave astronomy as a mature subject. Throughout each phase there would be a continuing development and refinement of interferometer designs to give successive improvements in sensitivity and performance.

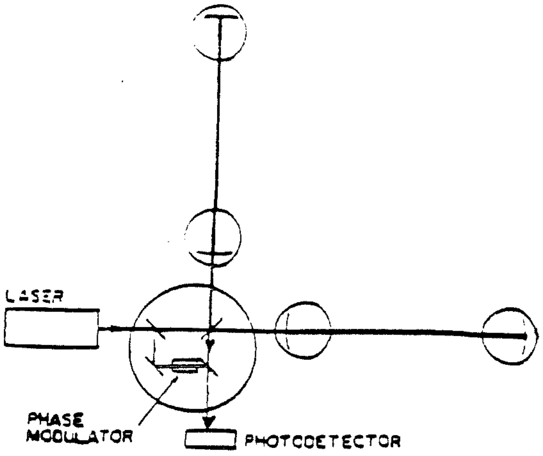
In planning the facilities we place prime importance on the first phase, the search phase, and on methods for achieving the discovery of gravitational radiation with minimum overall cost. Once the waves are clearly detected we would expect that there will be little difficulty in justifying what additional funding may be required for the effective and rapid development of the field, and for the present we let that second phase look after itself.

Our present expectations about gravitational wave sources and anticipated detector performance, summarized in Section 1 of this Proposal, indicate that the probability of discovery of gravity-wave signals is likely to depend strongly on the sensitivity of the search performed. And it may be noted here that the achieved sensitivity of an experimental search does not just depend on the sensitivity per unit bandwidth of the detectors themselves: it is a function also of the duration of the experiment, or, more generally of the amount of information analyzed. Increasing either search duration or number of detectors employed may improve the overall sensitivity or depth of the search. Thus increasing the number of vacuum tanks and operating interferometers in the facilities may significantly improve the chances of detecting gravity waves.

Arriving at an optimum balance between all the parameters describing the facilities involves many factors, some not accurately known. And using more interferometers does increase receiver construction costs somewhat - although we would expect to minimize interferometer development effort and construction costs by designing an interferometer with many common elements, so that with only minor changes it can be used in different types of experiments - see Figure B.5. From a preliminary analysis taking all the factors into account, one of the PI's (RWPD) concludes that for a search phase three sets of operating interferometers at each facility may be near optimum; and if gravitational waves are not detected in the initial variant of the LIGO, we would plan to add instrumentation chambers to permit such operations.

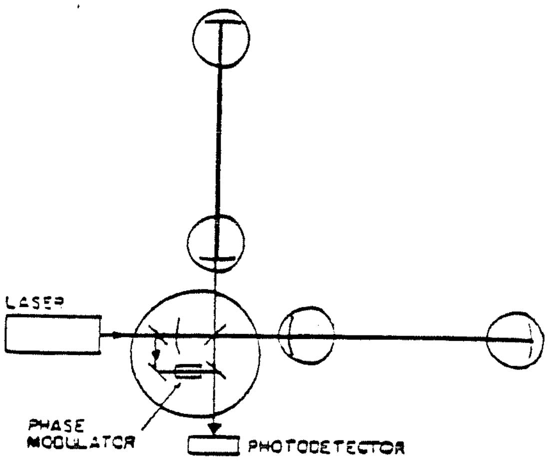
(c) Note on Overall System Outlined here

Putting together the various new experimental techniques and ideas outlined above, along with encouraging results from prototype experiments with low-loss mirrors, leads to a concept for a complete interferometric gravitational wave detection system with very interesting features: high sensitivity (bottom curves of Figures 1.3, 1.4, and 1.5), 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 long-range goal for our proposed LIGO facilities.



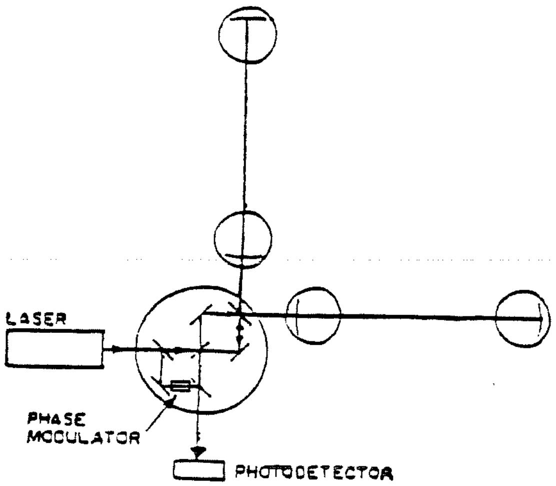
(a)

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 B.5 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.)

APPENDIX C
PROTOTYPE RECEIVER RESEARCH AT MIT AND CALTECH

C.1 The MIT Prototype Receiver

The prototype interferometric antenna at MIT is a Michelson interferometer with 1.5 meter arms in which the beams are folded to increase the light storage time. The antenna is operated to hold a single fringe by means of feedback to optical and mechanical controllers. The feedback signal is the antenna output. A schematic of the apparatus is shown in Figure C.1.1.

C.1.1 Description of the Apparatus

C.1.1.1 Light Source

The light source is an argon ion laser operating at 514 nm. The laser is operated in a single radial and longitudinal mode, and the light output is 1/2 watt. After leaving the laser the instantaneous line width of the light is broadened to a Lorentzian line of about 1 GHz width using an electro-optic modulator driven by periodic random noise. This frequency broadening suppresses the interference modulation of the main beam in the interferometer by scattered light. The scattered light will generally have taken different times than the main beam to reach the output of the interferometer. Due to the frequency broadening the interference between the scattered light and the main beam will undergo rapid phase fluctuations which result in an amplitude noise spectrum that can be made as small as the shot noise in the scattered intensity. The technique requires that the interferometer be held near the zero path length difference fringe. The precision of the path length equality is determined by the amount of scattering. The amplitude stabilizer which is shown in Figure C.1.1 was found to be unnecessary, and it has been removed.

The laser light is injected into the interferometer by way of an assembly of spatial mode matching lenses and a single mode optical fiber. The fiber, a few meters long, serves to isolate the laser's mechanical noise from the interferometer and, more importantly, to reduce the noise from laser beam position and angle fluctuations that would be converted to phase fluctuations at the output of the interferometer due to imperfect alignment of the instrument.

C.1.1.2 Interferometer

The optical cavities in the interferometer arms are defined by spherical mirrors which are attached to masses suspended on pendula with periods of two seconds. At frequencies large compared to the pendulum resonance frequencies, the masses are free in inertial space and isolated from external acoustic and seismic perturbations. Capacitive displacement sensors for all six degrees of freedom of each of the three masses are used to drive electrostatic controllers to critically damp the pendula without adding noise in the gravitational wave frequency band. The interferometer is operated in a vacuum of 10^{-7} mm Hg, maintained by ion pumps, to reduce gas pressure fluctuation forces on the masses and index of refraction changes in the optical paths.

On entering the vacuum, the light is split by a 50/50 beam splitter and then enters the interferometer arms through holes in the mirrors. The light traverses each arm 56 times and emerges through the same hole by which it entered. The multi-pass geometry, formed by spherical mirrors, is called a Herriott delay line. The number of beam transits is determined by the mirror radii and their separation. When properly aligned, the optical path length is first order sensitive to mirror displacements along the optic axis, but sensitive to all other motions only in second order. After leaving the delay line the light passes through AD*P electro-optic modulators (Pockel's cells), one in each arm, and then is recombined. The beam from the symmetric output port of the interferometer is measured at a photodetector. The beam from the antisymmetric output port is coupled into a single mode optical fiber. This serves to increase the interferometer contrast by spatially filtering the output beam. At present, the interferometer contrast with the output coupler is 99.3%. The output of this fiber is then measured at a photodetector.

C.1.1.3 Fringe Interrogation and Servo System

In order to determine the fringe motion a 5.3 MHz phase modulation is impressed onto the beams by the electro-optic modulators. When the interferometer is at a symmetry point of a fringe the photodetector output contains only signals at even harmonics of this frequency. If the fringe moves from the symmetry point the photocurrent contains a signal at the fundamental with amplitude proportional to the fringe motion and phase determined by the direction. These signals, after synchronous detection and filtering, are returned to the electro-optic phase modulators and the mass electrostatic controllers to hold the interferometer on a fixed fringe. This servo loop signal is used as the interferometer data output. The fringe interrogation scheme serves to move the fringe signals above the 1/f noise in the laser amplitude, amplifiers and photodetectors. The technique of locking to a fringe suppresses the effect of gain variations and laser amplitude fluctuations. It also enables the interferometer to operate near the condition for equal optical path length in the two arms which is required to reduce the noise due to laser frequency fluctuations.

C.1.1.4 Data Collection

The data taking system operates at data sampling rates up to 100 kHz to magnetic disk and up to 20 kHz to disk or magnetic tape. The data are taken with two A/D's. A slow A/D, multiplexed to sample 64 channels, is used to take data from slow servos such as the mass dampers. A fast A/D samples the output of the interferometer and can be multiplexed to eight channels. For diagnostic purposes, the data taking system is sometimes bypassed in favor of a frequency analyzer connected to the data output of the interferometer.

C.1.2 Present Performance and Data Analysis

Figure C.1.3 shows a recent frequency spectrum of the noise output from the MIT prototype interferometer. The spectrum shows a noise plateau of 5 x 10^{-15} cm/$\sqrt{Hz}$ at frequencies above 3 kHz. This spectrum was taken with 9 mA of photocurrent, and the shot noise limit under these conditions was calculated to be about 2 x 10^{-15} cm/$\sqrt{Hz}$.

Fifteen hours of data collected in June, 1985, have been analyzed for gravitational wave signals. This data sample has a strain sensitivity of 5 x 10^{-14} for burst sources at periods of less than one millisecond and 2 x 10^{-19} for periodic sources. Burst searches were accomplished by fitting to pulse templates. The data after filtering had a gaussian distribution to 6σ and a non-gaussian tail at this level. The analysis for periodic sources is being completed on a subset of this data with a strain sensitivity of 10^{-18} for sources with periods of less than 300 μs, and about 10^{-17} for sources with periods between 300 μs and 1 ms.

C.1.3 Current Efforts and Near-Term Plans

C.1.3.1 Improvements to 1.5 Meter Prototype

Efforts to understand and to reduce the sources of noise in the 1.5 meter prototype will continue. There is clearly excess noise above the calculated shot noise level. In the past half year a detailed program has been carried out to determine the sources of the noise in various frequency bands of the noise spectrum shown in Figure C.1.3. The method has been to excite noise driving terms so that their effect (transfer function of the noise to the output of the interferometer) can be determined. For example, the low frequency (f $\leq$ 100 Hz) noise is entirely attributable to building noise fed through the suspension system. Noise at frequencies between 100 Hz and 2 kHz is primarily due to acoustic coupling through acoustically driven misalignment of the input optics. The noise above 2 kHz is due in part to the excess amplitude noise impressed upon the light by the random phase modulation needed to suppress scattering in the apparatus. Continuing work in the 1.5 meter prototype is primarily dedicated to reducing noise at frequencies above one kilohertz. New optical components will be installed in the 1.5 meter prototype before work begins on the five meter prototype. These new optical components will reduce loss and scattering, hopefully improving the performance at frequencies above one kilohertz. To improve the low frequency performance will require work on damped suspension systems and better acoustic isolation, which are difficult to implement in the existing small prototype. These will be done in the new five meter system when it becomes available.

C.1.3.2 The 5 Meter Prototype

A new prototype interferometer is under construction at MIT. This new interferometer will have vacuum tanks which are large enough to permit development and testing of large scale optical components and suspension systems. A decision has been made to build the new interferometer within the present laboratory, and thus to limit its arm length to five meters, rather than to build a longer interferometer at a more remote location. This will be the last prototype interferometer built at MIT before the large baseline interferometers are constructed in Maine and California.

The new prototype will serve as a test of some of the vacuum technology presently planned for the LIGO project. In particular, the cleaning techniques, pumping strategy and vacuum seal technology will be investigated. In addition to the three vacuum tanks which will be placed in a Michelson configuration, there will be a fourth vacuum tank for suspension components that need to be tested in vacuum. The new prototype is being designed to accomodate both Nd:YAG lasers at 1.06 micron and argon lasers at 514 nm.

C.1.3.3 Optical Component Research

Two Nd:YAG lasers are in operation. A rod laser, operating at eight watts in a single spatial mode, shows performance approaching shot noise at frequencies above one megahertz at a detected optical power of approximately 50 milliwatts. A slab laser is being developed in a collaborative effort between MIT/Caltech and GE. To date, the slab laser has achieved a power output of 40 watts multi-mode at a wavelength of 1.06 micron. The problem of frequency stabilizing the slab laser is under investigation. One possibility is to use a small, diode-pumped laser as a frequency reference.

Optical fibers with core diameters of 10, 12.5, and 15 microns have been developed. These large core diameters are needed to handle the higher optical intensities which are generated. The 10 micron fibers are single mode at 514 nm, and work is continuing to demonstrate single mode behavior of these fibers at 1.06 micron with Nd:YAG lasers.

Electro-optic modulators which can handle high intensities are under study. KTP has been characterized, and it appears to be suitable for the high frequency modulators used in an interferometer. Large crystals are unavailable at present, but they are expected to become available in the near future. Older crystals exhibit an unacceptably high absorption due to iron impurities, but the newer crystals which are being manufactured do not have such high impurity concentrations.

Integrated optics chips using waveguide optics are under development for use as position sensors. these will have applications in both active and passive suspension systems which require high sensitivity (10^{-13} cm/$\sqrt{Hz}$) combined with large dynamic range. The development of these devices is being carried out in conjunction with Dr. Leonard Johnson at Lincoln Laboratory. Tests of a Mach-Zender interferometer integrated optics chip have demonstrated shot noise limited performance at 2.5 milliwatts driven by a 1.3 micron diode laser. Chips using the same technology are being made at Lincoln for the position sensors. These will be phase modulated Michelon interferometers containing graded index lenses, a beamsplitter, phase modulators and fiber pigtails, all mounted in the same chip. Hopefully, this technology will eventually become sufficiently inexpensive so that active isolation systems can use them for each degree of freedom.

Several efforts are under way toward the development of components exclusively for the LIGO. The optical properties of long delay lines are being investigated. The delay line used in the existing prototype interferometer relies upon geometric separation of the beams in a circular pattern on the mirrors using a reentrant path. If this geometry is scaled to a four kilometer delay line, then the mirrors need to be 62 or 87 cm in diameter for 0.5 or 1 micron light, respectively. The equal path length condition would require that the mirror sagitta be equal to about 100 Angstroms, and the angle between entrance and exit beams would be of order 100 microradians. Alternative delay line geometries are being studied via computer modeling. For example, non-reentrant delay lines can be made by separating the entrance and exit apertures, but this results in the loss of some of the symmetry advantages of the reentrant delay line. Delay lines which fill the mirror space more efficiently can be made using astigmatic mirrors.

Mirror manufacturers have been consulted about the problems involved in making mirrors with the figure tolerances and mechanical properties which are required. Silicon, which exhibits high Q and high transverse speed of sound, may be a suitable material. Silicon blanks are being ground (at no cost to the collaboration), and scattering measurements will be performed at MIT. A potential solution to the figure tolerance problem is to servo the mirror figure, and this will be tested in the five meter prototype.

The problem of scattered light in a large delay line is under study. Scattering problems are potentially more serious in large interferometers than in the 1.5 meter prototype because of the small angles involved. A stationary interferometer will be constructed to test the effect of scattered light, and the problem of light scattering in a large baseline interferometer is being approached both analytically and through the development of a Monte Carlo program.

C.1.3.4 Suspension Research

The auxiliary tank of the new vacuum system will be used to test suspension systems. One goal is to develop a compound system with electronic damping to hold a mirror mass as large as one ton. The system is designed to measure vibration isolation transfer functions by driving the point of support with an electromagnetic shaker. This technique will determine the resonances and second order couplings in the candidate suspension design for the prototype and the LIGO. Associated with this research is a study of the Q of fiber suspension elements as a function of stress.

Under active development is a servoed magnetic suspension to be used as the first stage of a compound isolation system. One of the reasons for this development is to eliminate the need for high vapor pressure elastomers as acoustic noise isolators.

Research on active suspensions will also be carried out in the auxiliary tank. Preliminary work on a single degree of freedom active system was completed several years ago. The new development is to use the interferometer mirror itself as the inertial reference in such a suspension system.

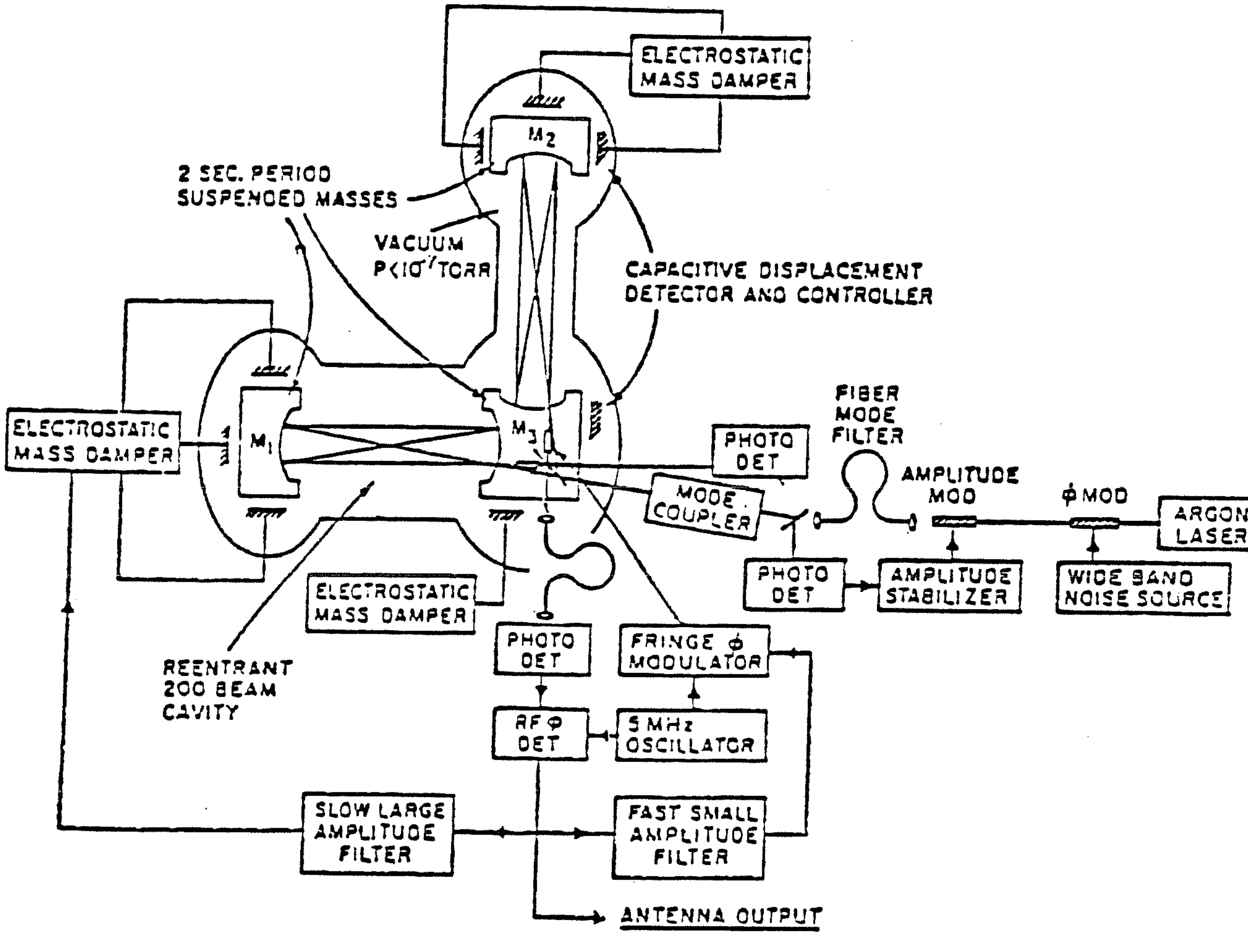


Figure C.1.1. A schematic of the MIT delay line interferometer gravity antenna prototype.

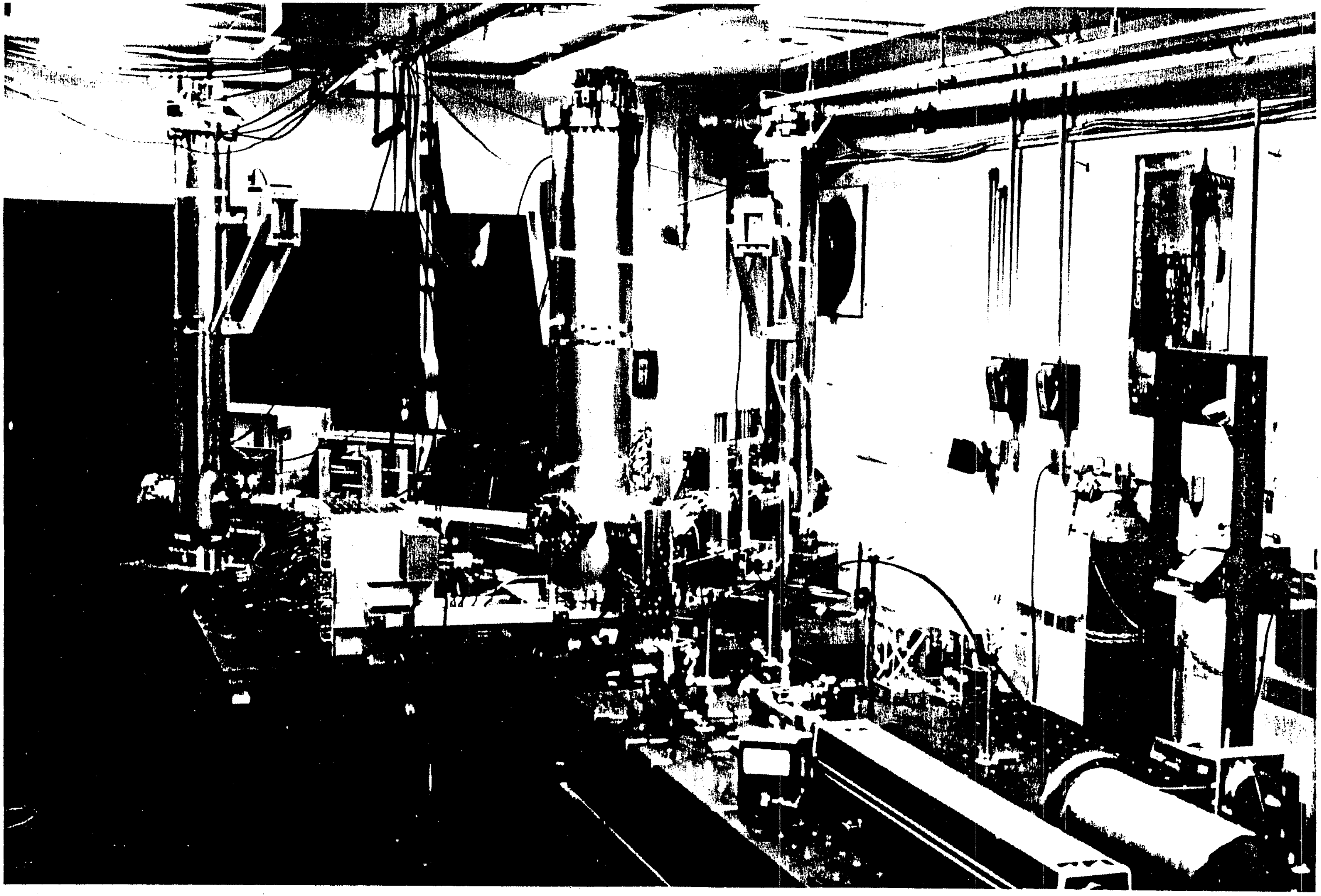


Figure C.1.2 The MIT Prototype Antenna

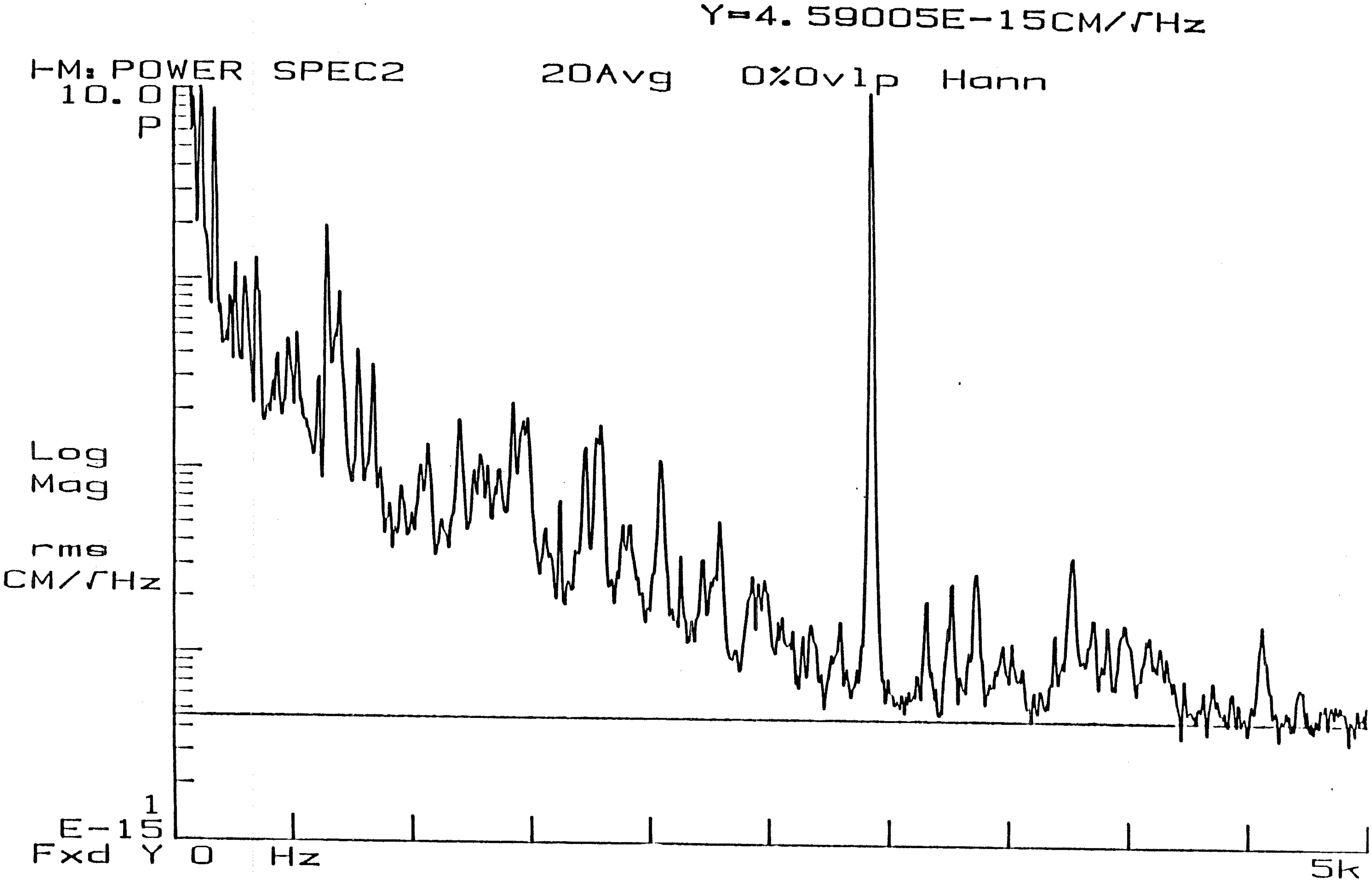

Y=4.59005E-15CM/√Hz
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Figure C,1,3

C.2 The Caltech Prototype Receiver

Background and Description of the 40-meter Interferometer

The Gravitational Physics group at Caltech started in 1979 when one of the P.I.'s of the present proposal took up a post there. The initial experimental work grew out of earlier work on laser-interferometers for gravitational-wave detection at the University of Glasgow. Experiments began with the construction of 10-meter long Fabry-Perot cavities and the development of laser stabilization techniques,[25] followed by construction of a full prototype laser-interferometer gravitational-wave detector with arms 40 meters long in a specially designed building. Most of the Caltech experimental work has been carried out with the latter instrument, which we now describe[26].

The Caltech prototype antenna (Figure C.2.1) 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 one-second pendulum period. Light from an argon-ion laser of wavelength 514 nm enters the antenna at the corner of the L, where it is split, forming two optical cavities. An incident gravity-wave changes the length of the two arms differently, and alters the optical phase difference between the 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, ground to a curvature radius of 62-meters, are coated for the highest reflectivity currently available. Piezoelectric transducers between the mirrors and masses are used to fine tune the cavity length and to calibrate the gravity-wave detector.

The optical paths between the cavity mirrors are spanned by stainless steel pipes of 20 cm diameter (see Figure C.2.2), evacuated to 2×10^{-5} torr, well below the vacuum required to eliminate noise from residual gas that might be observed with the prototype. Pipe flanges are joined with metal seals, so the pressure can be reduced further by subjecting the entire vacuum system to a bakeout.

In operation, phase sensitive servos keep the two cavities in resonance. An electro-optic cell applies phase modulation at radio frequency to the light before it enters the cavities. The light reflected directly from the input

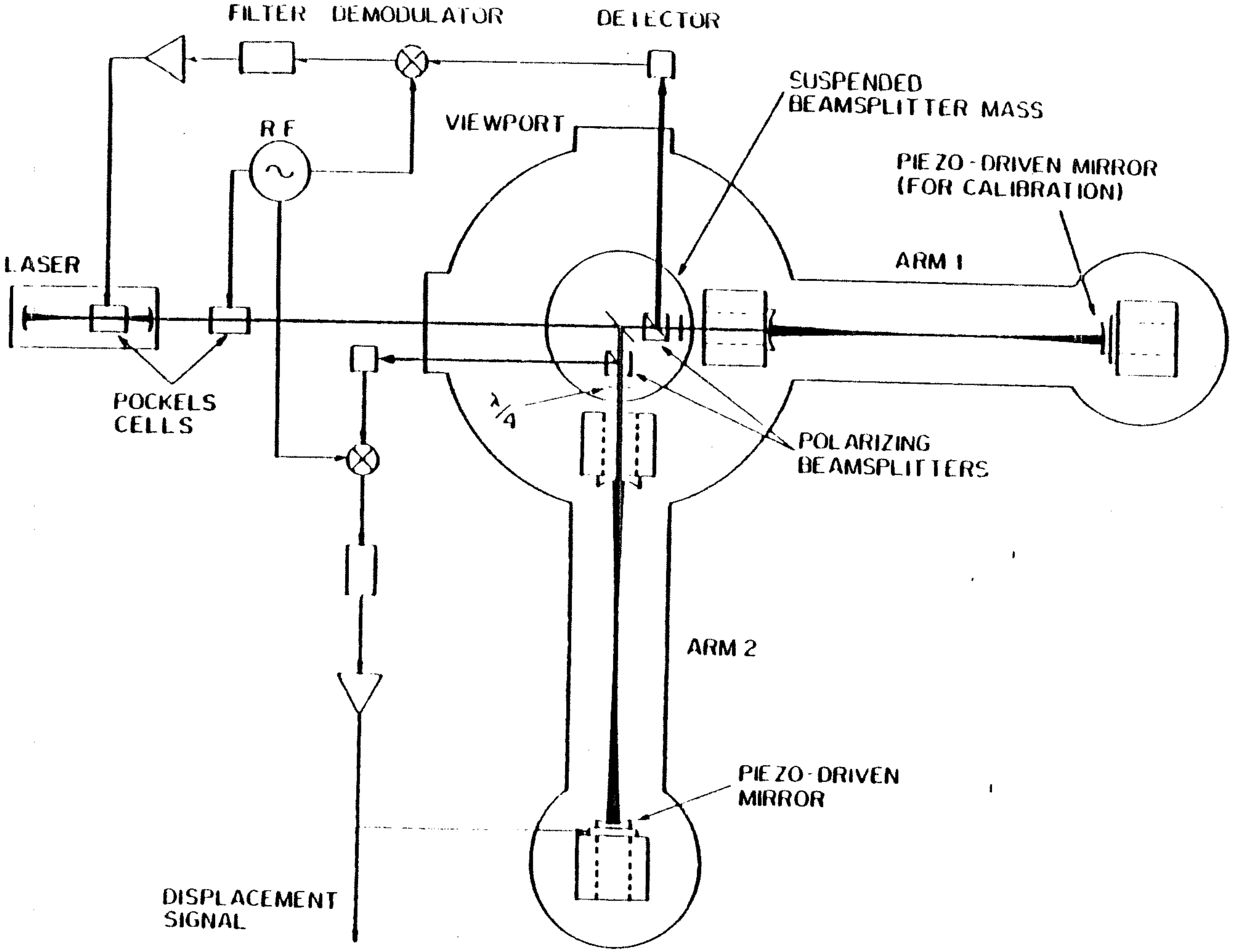
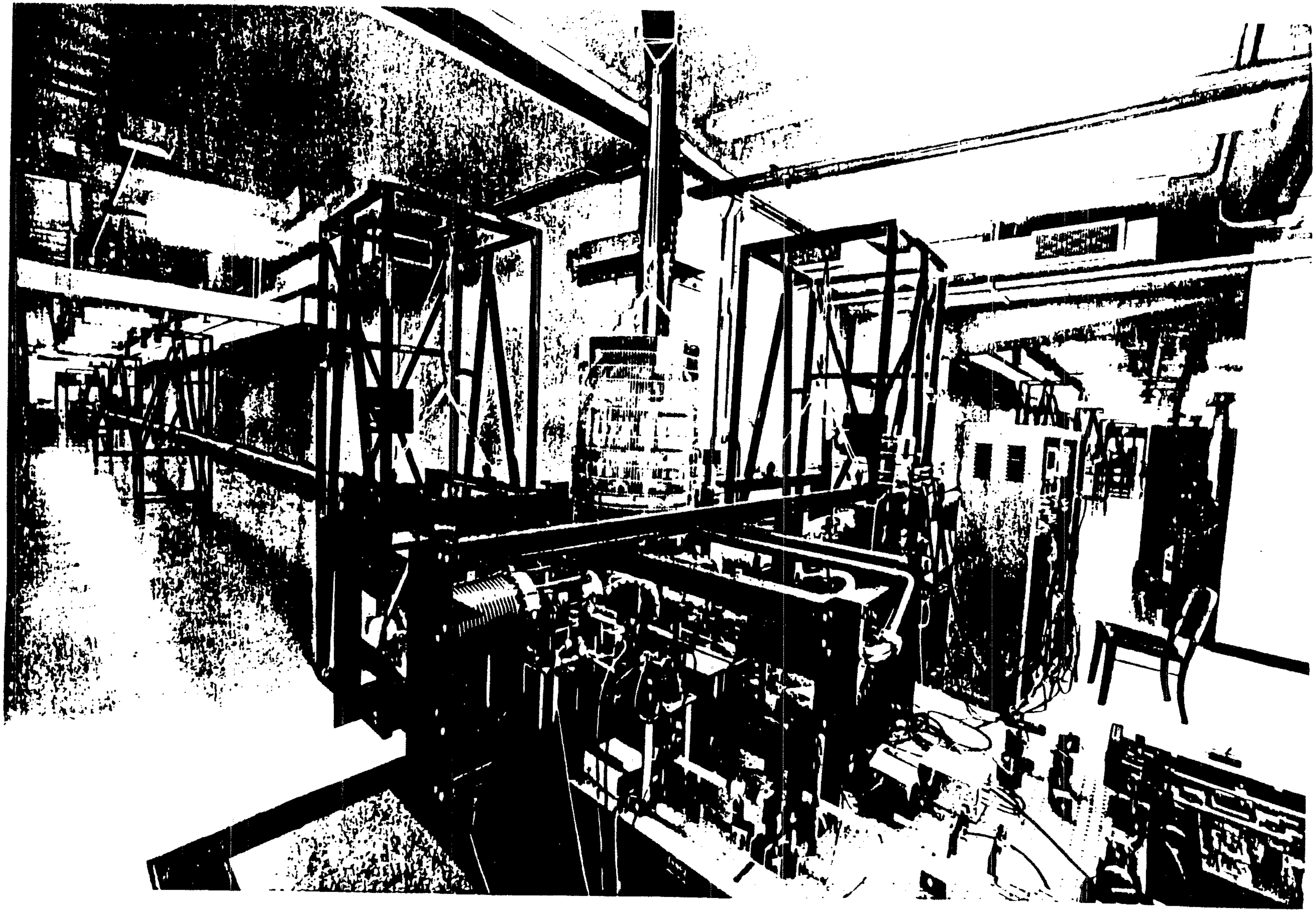


Figure C.2.1 Schematic diagram of the Caltech 40 meter prototype. The interferometer uses five suspended masses inside the vacuum chamber -- four to carry the mirrors which define the ends of the two arms and one to carry the beamsplitter and associated optics. Radio-frequency phase modulation is used 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.

Figure C.2.2. View of Caltech 40-meter prototype laser interferometer gravitational wave detector. Parts of the optical system, and associated electronics, extend off the right-hand side of the photograph. (This photograph was taken with an ultra-wide-angle lens, to show both arms of the interferometer. It may be viewed in correct perspective by placing the eye, aided by lens of power about 6 diopters, 10 cm from the page.)



mirrors has sidebands due to the modulation, but within the narrow (200 Hz) bandwidth cavities the modulation sidebands average to zero. 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 using 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 below 30 Hz and fed back to coil-and-magnet transducers near the suspension points, fixing the angular degrees of freedom of the masses to within a microradian. Longitudinal motion is measured by ground-referred optical sensors mounted below each test mass to detect the shadow of the test masses in the illumination field of modulated LED's; these sensors are used for cold damping of pendulum motion by feedback applied to piezoelectric stacks in contact with blocks attached to the tops of the clusters of suspension wires. Additional feedback signals, derived from the interferometer output, are applied to the same transducers to maintain optical resonance and to provide fine control of the longitudinal position of the test masses.

Several stages of seismic 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. An additional external layer of isolation is kept in reserve: the optical tables rest on commercial air mounts which have been tested but found unnecessary at current sensitivity. A four-layer stack of alternating lead and rubber inside the vacuum isolates against seismic disturbances above the stack's resonance frequency of approximately 5 Hz.

The 40-meter detector was used in March 1983 for a very speculative search for gravitational radiation from the millisecond pulsar [27]. The detector operated 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. In the ensuing 3.5 years, the sensitivity of the Caltech detector has improved by approximately three orders of magnitude.

Present Performance

The first sensitivity goal of the prototype at Caltech 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 $= 4 \times 10^{-5}$) give a cavity storage time long enough to exhibit maximum sensitivity at all frequencies above 200 Hz. Mirrors with higher reflectivity will not be needed until advanced optical schemes (such as light recycling) are employed.

Performance is indicated in Figure C.2.3, which shows the frequency spectrum of the noise output of the Caltech prototype interferometer, calibrated in $m/\sqrt{Hz}$ and in strain/$\sqrt{Hz}$. This spectrum was accumulated with approximately 3 milliwatts of light incident on each photodiode. The high-power (5 watts single-mode) argon ion lasers now in use allow over two orders of magnitude increase in power, but the noise is independent of power above 1 millwatt, where the noise observed above 500 Hz is equal, within a factor of two, to the calculated and measured photon counting fluctuation (shot noise). The displacement sensitivity between 500 Hz and 3 kHz is $2 \times 10^{-17} m/\sqrt{Hz}$, and the strain sensitivity is $5 \times 10^{-19}/\sqrt{Hz}$.

Improvements Underway

The source of the noise in excess of shot noise is under investigation. Several instrumental and physical effects have been found *not* to be a source of noise, including

- Electronic noise in the amplifiers and photodetectors
- Frequency or intensity noise in the highly stabilized lasers
- Seismic noise
- Ambient acoustic noise in the laboratory
- Noise generated by turbulence in the laser water cooling system
- Thermal noise from low-order resonances in the test masses
- Noise imposed by the mass orientation and position servos
- Optical feedback, which, if not blocked, can induce parasitic resonances
- Noise due to residual gas in the beam pipes or in the vicinity of the vacuum chambers

These and other possible sources of noise are checked routinely, especially whenever improvements are made in overall sensitivity. Also, a series of sensitive benchtop measurements indicates that the piezoelectric ceramic transducers used for cavity length control are not inherently noisy at frequencies of interest, even when low- frequency signals up to one kilovolt in magnitude (as used when locking the cavity) are applied.

The test of seismic isolation, conducted by shaking one of the optical tables with a large commercial vibration transducer, revealed that noise due to ambient seismic motion at Caltech is at least two orders of magnitude lower than other noise sources, as indicated in Fig. C.2.3. (The sensitivity of the seismic isolation measurement was limited by a small amount of acoustic feedthrough, and the isolation is likely even better than depicted.) The seismically excited motion of the test masses is independent of interferometer length, and scales as background seismicity. If the present seismic isolation system were used in a receiver several kilometers long located at one of the remote sites discussed in Section 2.4, where the ground is typically ten times quieter, it would be adequate for detection of millisecond-bursts with strain amplitudes as small as 10^{-22}. Improved methods of isolation have been designed and tested, and the proposed facilities will probably have better isolation than the present prototypes. Nevertheless, it is significant that the simple passive isolation used in the Caltech prototype is good enough to achieve a sensitivity above 1 kHz surpassing the prediction for the most advanced detectors discussed in section 2, and that this extrapolation follows directly from laboratory measurements.

The list of sources of noise that have not yet been ruled out is shorter:

- Thermal noise in the joints between the test masses and the mirrors
- Fluctuations in the geometry of the laser beams relative to the test masses
- Noise associated with nonlinear phenomena in optical fibers

The group at the University of Glasgow was the first to recognize the relevance to noise performance of the method of bonding mirrors to test masses. Experiments done at Caltech suggest large thermal noise from the bonding material can couple directly into the mirror displacement. Preliminary measurements with a low-loss, hard bonding technique indicate a significant reduction in this source of noise.

The other two items, geometry fluctuations and optical fiber noise, are related because fibers are used to reduce the fluctuations in the light injected into the interferometer. The fiber can itself be a source of noise; three mechanisms by which fibers can produce noise have been identified: 1) By conversion, via slight misalignment, of geometry fluctuations into intensity fluctuations. This is especially important if the beam geometry fluctuates at the modulation frequency, as has been observed in the light following the phase modulator. 2) By nonlinear processes within the fiber, such as stimulated Brillouin scattering. 3) By parasitic interferometers formed between the fiber ends and other components in the optical chain. Arrangements with zero, one, and two (one before and one after the phase modulator) fibers have been used, with intensity modulation servos at the

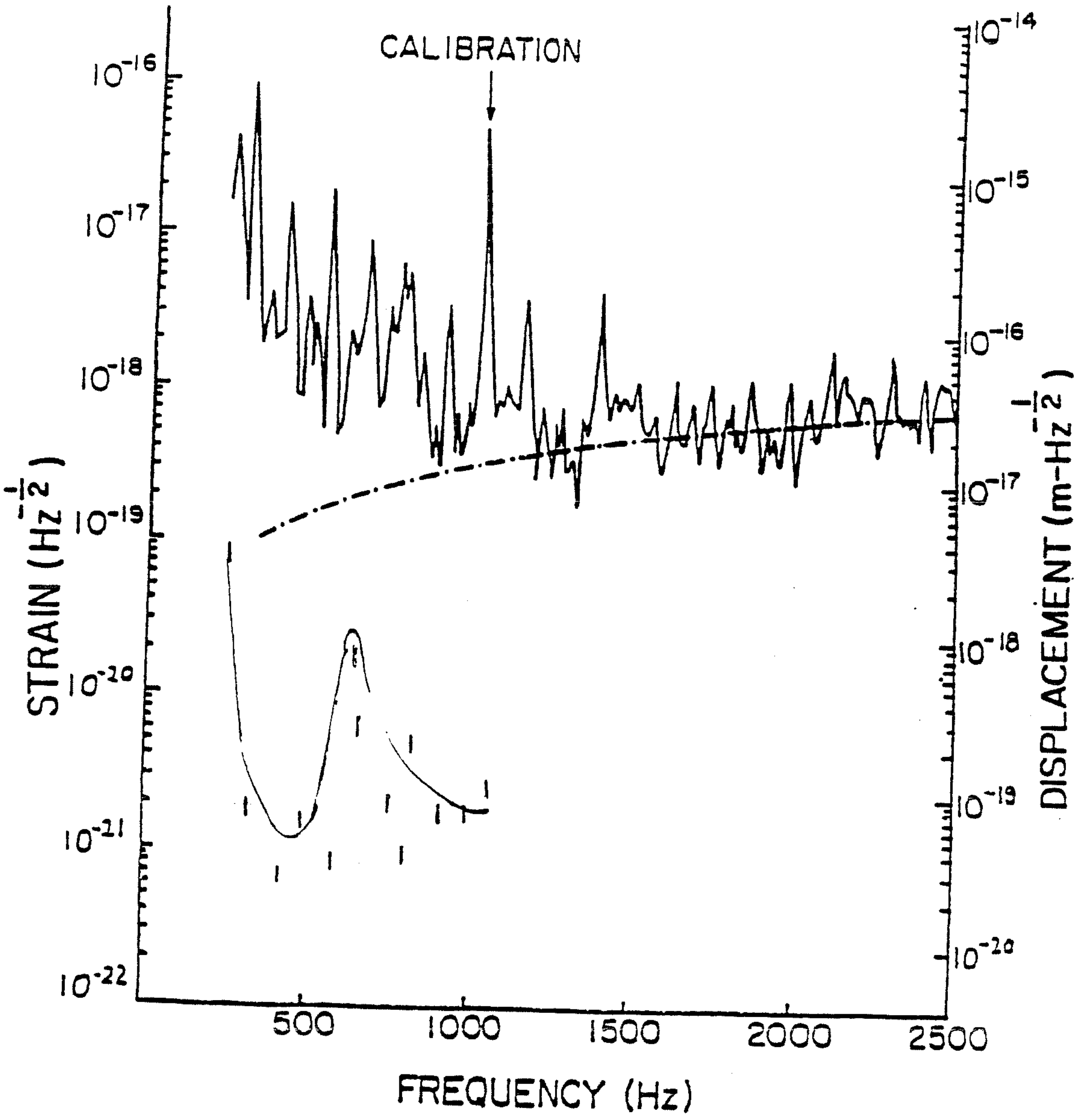


Figure C.2.3. Noise spectrum of the Caltech prototype antenna, calibrated in strain (Hz $^{-.5}$) and displacement (m-Hz$^{-.5}$). The upper curve is the measured noise. The portion of the spectrum below 250 Hz was not well calibrated in this measurement and has been deleted. Many of the peaks below 1 kHz are multiples of the line frequency and may be due to pickup in the electronics. The dashed curve shows the calculated shot noise for the light power (2 mW) and fringe visibility (0.65) of the interferometer at this measurement. The lower curve indicates the small fraction of noise attributable to seismic disturbance. The seismic curve was measured by shaking one of the end masses at a series of fixed frequencies, measuring the coupling to the gravity wave signal, and scaling to the ambient seismic noise in the Caltech laboratory. The peak near 700 Hz is probably due to a resonance in the suspension wires.

fiber input and sensing at the fiber output, resulting in beams with stable geometry and constant (within the servo bandwidth) intensity. The best configuration appears to be one fiber, placed between the laser and the phase modulator. As an alternative to fibers, a high-finesse, thermally stable frequency reference cavity now under construction can be used as a mode cleaner to reduce fluctuations in beam geometry.

Three lines of investigation, all at advanced stages of development, are important for achieving the best performance from LIGO-scale detectors, as well as for improving the prototype.

- A wavefront sensing technique for automatic alignment of cavities
- Coherent addition of stabilized lasers
- An anti-seismic interferometer to sense motion of the suspension points

The alignment system uses the variation of the phase across the wavefront reflected from the input of the cavity mirrors (a superposition of the laser light and light leaking from the resonating cavity) to derive signals for controlling the orientation of both test masses. Supplementing the 40-meter optical levers with this system improves the low frequency stability by a factor of 5.

The addition of stabilized lasers has been demonstrated, though not yet used in the detector. The relative phase of the beams from two argon ion lasers, incident from orthogonal directions on a 50% beamsplitter, was adjusted to give a low level of light (sensed by an r f photodiode) out one port of the splitter, and the remainder of the incident light out the other port. This technique can be extended to add linearly the power from any number of lasers.

The anti-seismic interferometer, a simple one-bounce system now under construction, will sense changes in the separation of suspension points due to seismic noise that penetrates the isolation or due to thermal drift. The interferometer output will be fed back to the suspension points, reducing low frequency relative motion of the test masses by a large factor.

APPENDIX D
PROTOTYPE RECEIVER RESEARCH IN EUROPE

D.1 The Max Planck Institute for Quantum Optics

The 30 meter laser interferometer begun in 1982 at the Max Planck became operational this year and incorporates all the improvements that the Garching group has developed in the past ten years. The interferometer,[28] a Michelson delay line, operates with 200 mW of interferometrically modulated power and uses 110 mirror passes for an effective optical path of 3.3 km. The displacement noise of this apparatus is shown in figure D.1.1. One of the innovations in this interferometer is the separate suspension of each mirror and the beam splitting mass by wire suspensions to reduce the thermal and acoustic noise generated by a complex central mass. They have also introduced an optical fiber to clean up the spatial modes of the laser beam and have coupled the fiber directly to the beam splitter block to minimize the relative motion of the injected beam relative to the interferometer.

The group has completed a proposal to the Max Planck Society to study the design of a long baseline antenna which can achieve a strain sensitivity of 10^{-21} rms at 1 kHz. The present conceptualization of this antenna assumes an antenna arm length of 3 km with 0.75 m diameter tubing at a pressure of 10^{-6} torr. They are considering an equilateral triangle configuration beginning with two sides of the triangle, and in later phases of their program to constructing the third side. Their concept is to bury the entire apparatus in a 2m high tunnel bermed with 1 meter of earth.

D.2. The University of Glasgow

Experimental work on gravitational-wave detection began at Glasgow around 1970, with development of wide band resonant bar gravitational-wave detectors by one of the present P.I.'s and colleagues. Extensive coincidence pulse[29] and cross correlation[30] searches were made with a pair of detectors, which recorded one possibly interesting pulse signal in two years of operation. Efforts then shifted to development of laser-interferometer detectors, initially with a 1-meter prototype detector[31] using multireflection Michelson interferometer optics, built with 0.3 ton test masses and the isolation and vacuum system of an earlier "divided-bar" gravitational-wave detector. Much work on high-Q suspensions and electrostatic feedback systems was done, and noise studies revealed the importance of scattering at the multireflection mirrors. The Fabry-Perot gravitational-wave detector system was devised at this point,[32] primarily to avoid the scattering problems of delay lines, and the second Glasgow interferometer, with 10-meter Fabry-Perot cavities, was built.

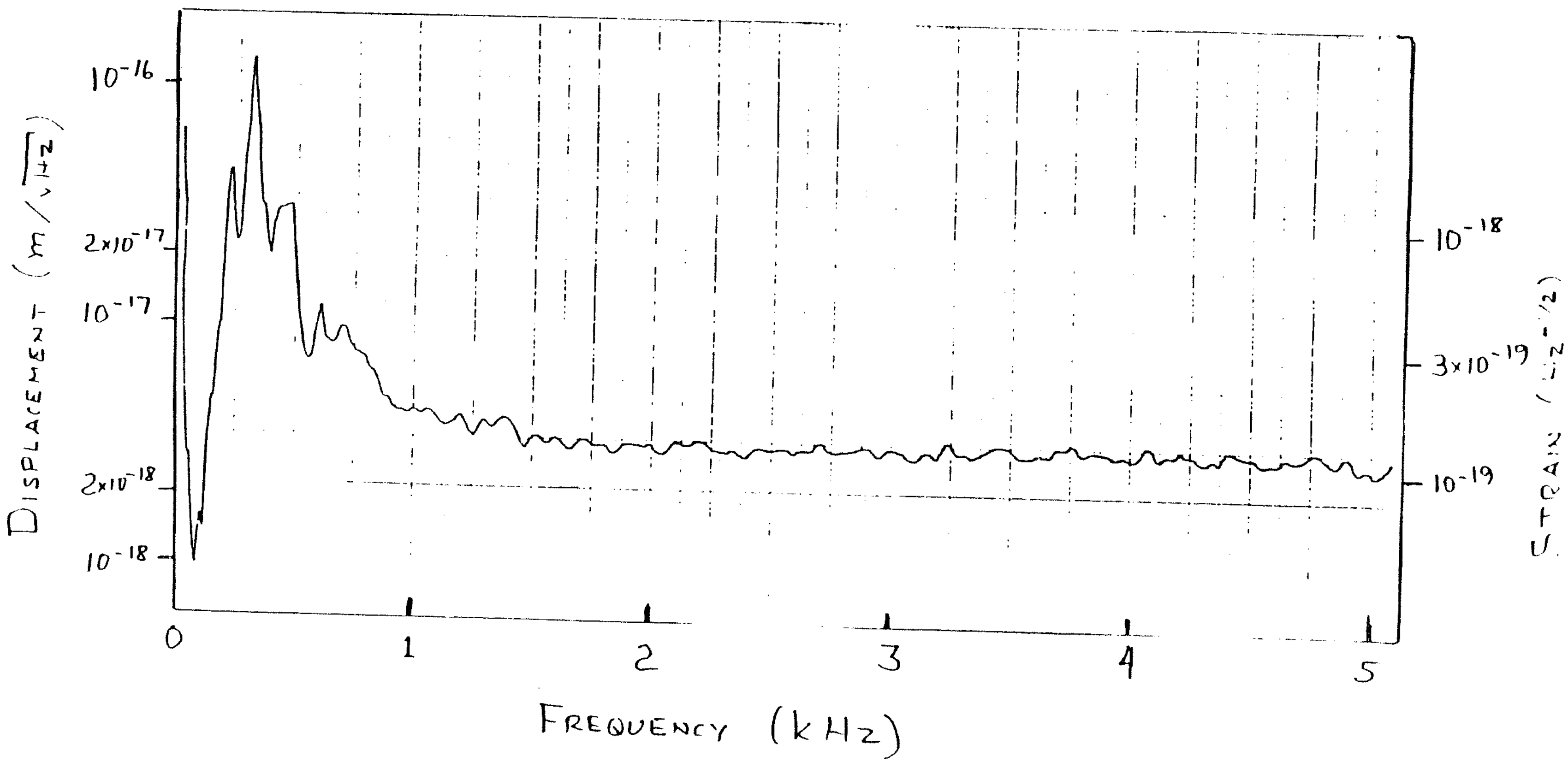


Figure D.1.1 Displacement Noise in the 30 Meter Prototype at the Max Planck Institute in February 1986

The technique of laser stabilization by monitoring the phase of light reflected from an optical cavity was devised in this work, and developed both at JILA (Colorado) and with this 10-m interferometer. Design of test masses has gone through three generations with this apparatus, the current test masses being simple bronze spheres with inset mirrors supported by 4-wire suspensions from tilting, rotating, and translating control blocks driven by electromagnetic and piezoelectric transducers. At the central station a separately suspended and servo-controlled structure supports the optics for splitting, recombining, and controlling the main beams, including Pockels cells, polarizers, position-sensitive photodiodes, and a separate "mode-cleaning" optical cavity for reducing geometrical fluctuations in the laser beam. The position and direction of the input laser beam is controlled by auxiliary servo systems using fast and slow piezo-driven mirrors.

Mirrors with relatively large losses have been mostly used in this interferometer, but good sensitivity has been achieved.[29] A significant improvement in performance has been obtained recently by improved bonding of the mirrors to the test masses. A recent measurement of displacement noise is shown in Figure D.2-1.

A considerable amount of experimental and theoretical work on active seismic isolation techniques has been done at Glasgow (see Section 1.5.2 and Appendix D). This led to an actively-isolated and servo-stabilized test mass at the end of one cavity of the 10-m interferometer, with tilt isolation using a freely suspended reference arm. Active seismic isolation has not been applied to the other test masses in the system, however, although active feedback damping is used for all of the masses.

Recent work at Glasgow includes development of a laser stabilization technique aimed at giving maximum continuous power from a high-power argon laser. To avoid the losses and damage experienced with electro-optical devices in the laser cavity a high-speed piezo mirror developed by the Orsay group provides first-order stabilization, with subsequent phase correction by a Pockels cell outside the laser. Results are encouraging.[33]

There is close collaboration between the Glasgow and the Caltech groups, and as the Glasgow interferometer project began several years earlier than the Caltech one many of the relevant techniques have been developed first there. By concentrating efforts on slightly different aspects in the two groups a very beneficial collaboration has been achieved, and, it is hoped, will continue.

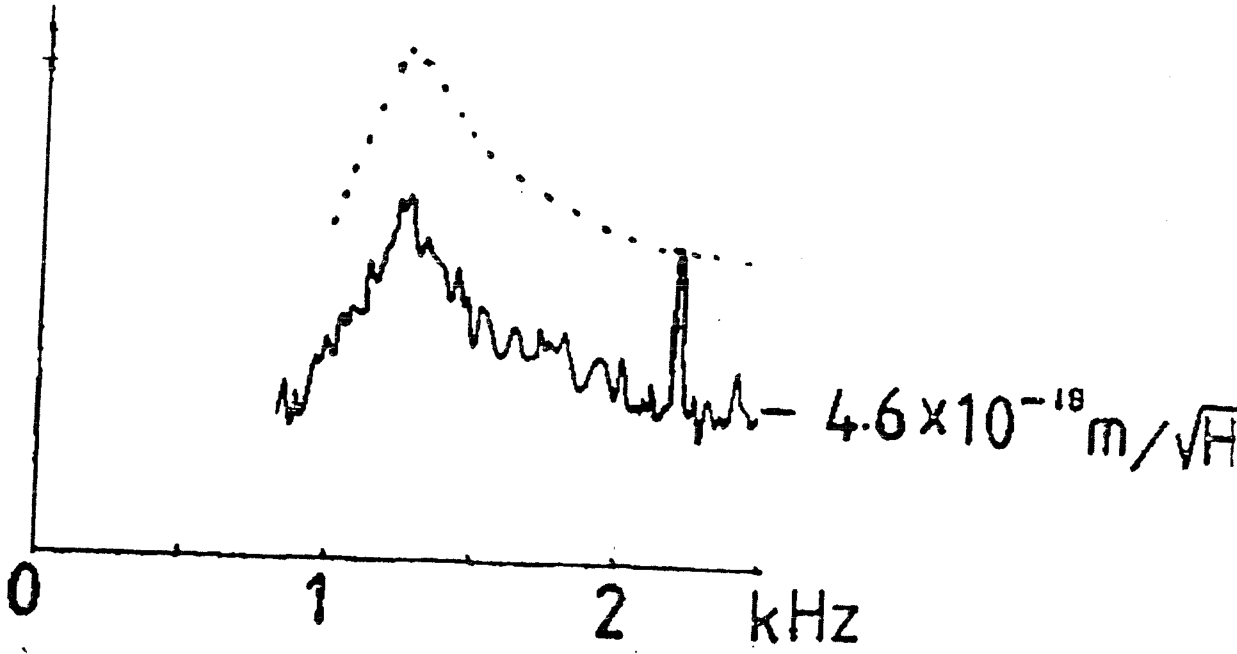


Figure D.1-2. Displacement noise in the 10 meter prototype at Glasgow University in September 1986 (solid curve). The dotted curve is a contour of constant displacement noise, approximately 1×10^{-16} m/$\sqrt{HZ}$. The actual noise (solid curve) at 1kHz is 1×10^{-17} m/$\sqrt{Hz}$. (The raised section of the two curves in the kilohertz region is a feature of the present servo system and does not correspond to increased displacement noise.)

D.3. CNRS / Orsay

A group at CNRS/Orsay in France is developing high-power lasers and associated optics appropriate for use in interferometric gravity wave detectors. They have succeeded in injection-locking a low-power phase stabilized Argon ion laser to an unstabilized laser, producing 1.5 Watts of single-mode light. This technique can be extended to lock several high-power lasers, whose outputs can be added coherently before exciting an interferometer. Another route to high power under investigation by the Orsay group is the development of stabilized solid-state lasers. The group is planning the construction of a six-meter prototype gravity wave detector, and is currently working to demonstrate optical recycling.

APPENDIX E

COST AND FEASIBILITY STUDIES WHICH HAVE BEEN CONDUCTED FOR THE LIGO AND FOR ITS CONCEPTUAL DESIGN

The initial study of a full scale laser interferometer gravity-wave detection system was undertaken by MIT with Stone & Webster, an A & E firm, and A. D. Little, the consulting firm. The objective was to establish the feasibility and rough cost of a full scale, 5-km* long system. For the sake of brevity this is referred to as the MIT Study in subsequent paragraphs. No specific optical configuration or experimental strategy was assumed during this study. It was intended to serve as a resource base for the development of a more detailed study of these systems. The results have been used by the Caltech/MIT Research Groups to develop more detailed cost estimates and implementation strategy. This latter effort was carried out in 1984 and 1985 by a team of engineers from the Ground Antenna and Facilities Section of the Jet Propulsion Laboratory operating under the guidance of the joint Caltech and MIT research groups and a Project Manager.

During the past two years we have been building on the material developed during the MIT study to further expand the implementation options. Questions of construction strategy were reexamined, and a detailed study of candidate sites for antenna construction was completed. To enhance and focus the JPL study, a set of Functional Requirements has been developed to establish a basis for the system design. A conceptual design for the LIGO facilities was developed that incorporated the functional requirements, and the characteristics of the facility sites. Finally, based on the specific construction or implementation approaches at the two sites selected, a preliminary cost estimate was prepared. This estimate, given in Appendix H is being used as a baseline against which new implementation approaches are measured.

E.1 MIT Study

To understand the factors which would dominate the cost and practical difficulty of designing and constructing a large scale interferometer system, the first phase of the study focused on three areas: the vacuum system, investigated by a group at Arthur D. Little (ADL); construction and installation of the antennas and their ancillary facilities, studied by Stone and Webster Engineering; and possible sites for the system, identified and studied in a preliminary way by Stone and Webster. The results of this effort were summarized in "A Study of a Long Baseline Gravitational Wave Antenna System",[34] copies of which are available from MIT on request.

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*The sites had not been chosen at the time of this study. A reduction of the length to 4 km was subsequently forced by the properties of the Cherryfield site.

E.1.1 ADL's Study of the Vacuum System

The ADL group was asked to design a vacuum system which would operate at a pressure of 10^{-6} torr and which could be upgraded later to a pressure of 10^{-8} torr. The costs which they derived were a function of the vacuum pipe diameter and length.

Aluminum and stainless steel are the two materials suitable for the vacuum pipe. Aluminum appeared to have the edge because of lower cost, although it was recognized that there is a smaller experience base in aluminum vacuum systems. A particular trouble was that at that time there were no suitable aluminum bellows and that aluminum-to-stainless transitions would have to be used wherever bellows were requred.

An important result of the ADL Study is that the pipe diameter is not a major cost driver when viewed in the context of total facility costs, as long as industry standard sizes are specified. For example, an increase in pipe diameter from 24" to 48" results in an approximate overall cost increase of only 15 percent.

A pumping strategy consisting of mechanical roughing and ion-getter pumps was selected as the approach used in developing the required vacuum. The ion pumps are highly reliable, have minimal maintenance requirements, and do not cause mechanical vibrations that could affect the measurements being made. The roughing pumps selected are designed to reach pressures of 10^{-4} torr before the ion pumps are energized.

Instrumentation vacuum chambers, in which the test masses would be installed, were also designed. These chambers are stainless steel cylinders that can be baked at high temperatures to drive out retained gaseous contaminants to allow the system operating pressures to ultimately reach 10^{-8} torr. They were designed to afford complete access to the test masses as well as allow quick access for minor adjustments. The largest chambers contemplated in this study had a diameter of 14'. The instrumentation chambers are isolated from the main vacuum pipes by gate valves.

E.1.2 The Stone and Webster Study of Construction Strategies

Several concepts for the construction, involving both vacuum pipe diameter and length, were studied. Since the sites were not specified, only "generic" costs could be derived. The cost model that was developed included elements that were proportional to antenna length and elements that were independent of length, such as buildings, power, and laser cooling.

Several installation options were studied. The least expensive and highest risk idea was to place the insulated vacuum pipe on supports above grade. At a somewhat higher cost, the vacuum pipe could be protected from the elements by enclosing it in a partially or completely buried culvert. The most expensive approach studied involved the implementation of the systems in a mine (such as

Figure E.1 Optimal Orientation of LIGO at Edwards AFB, Palmdale, Ca.

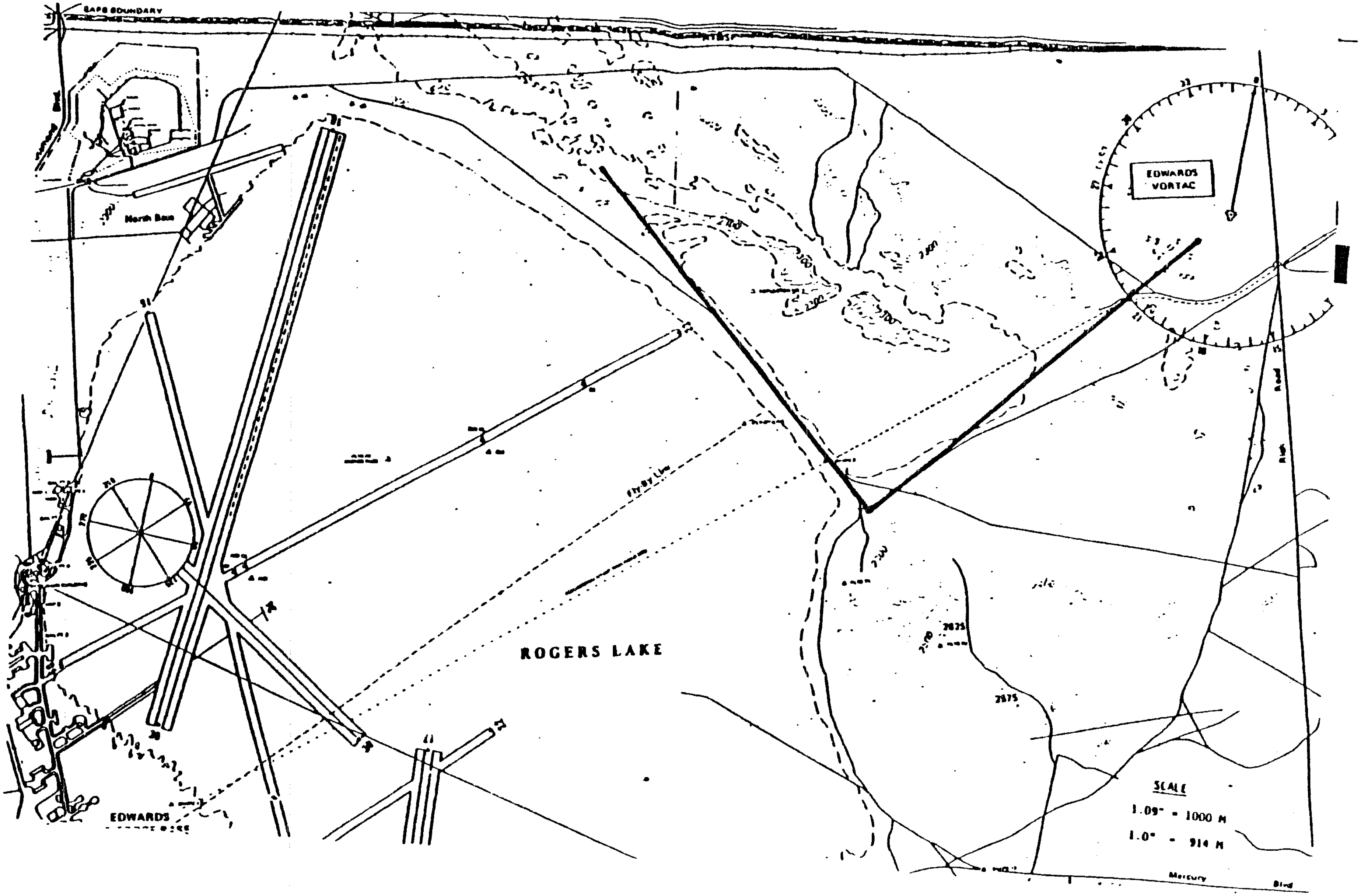
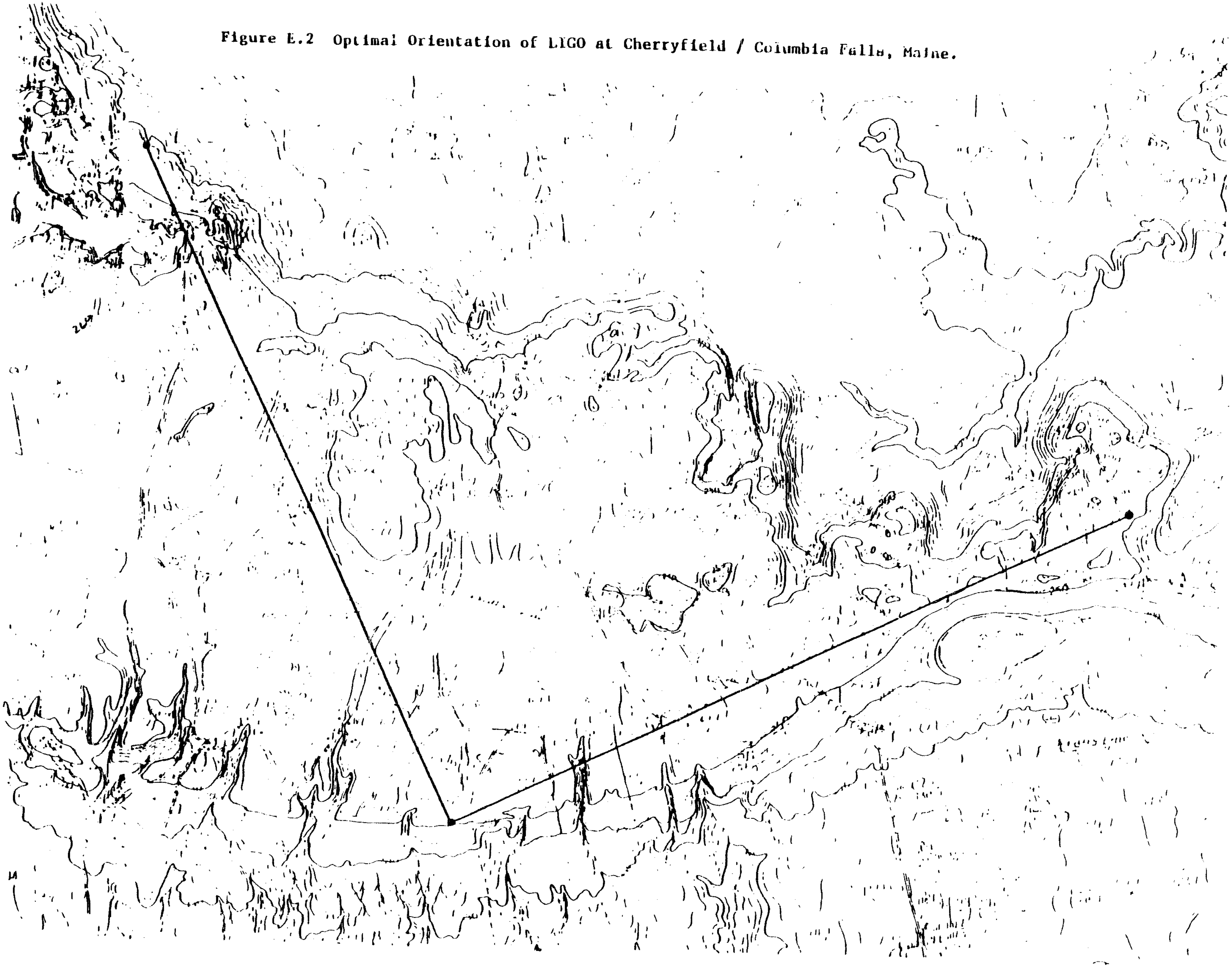


Figure E.2 Optimal Orientation of LIGO at Cherryfield / Columbia Falls, Maine.



a salt mine, which is dry and constructed in a grid-like "room and pillar" arrangement). The consideration of this latter approach was dropped when the potential cost became apparent, although this implementation would offer a benign environment to the type of instrumentation proposed for the LIGO.

E.1.3 The Stone and Webster Site Survey

The purpose of this preliminary site survey was not to pick the actual locations for an antenna installation but rather to identify the criteria for suitable sites and to produce a list of places with those attributes. Because of its preliminary nature, no site visits were included in the study. For surface sites, the desirable criteria included: flat topography, low number of roads and houses, accessibility to labor, transportation, power and water, remoteness from anthropogenic sources of vibration and noise, and low probability of large seismic events.

The list of possible sites concentrated on developed facilities owned by governmental agencies, such as national laboratories and military bases, in the hope that it would be easier to gain access and take advantage of pre-existing shops and power distribution systems. Over a dozen potential sites were identified during this survey, including one of the prime sites, Edwards Air Force Flight Test Center, California, and the two principal backups, the Idaho National Engineering Laboratory, near Idaho Falls, and the NASA Deep Space Network Facility (Goldstone) at Fort Irwin, California.

The survey of mines disclosed a number that could hold a small antenna system, but none that were adequate for the required 5-kilometer length. some investigation was made of the possibility of extending the tunnels in these mines, but the attendant costs would have been difficult to predict, and the rate at which the mine face can be extended is quite slow. For this reason, we determined that there were no suitable mine sites available for this program.

E.2 The Preliminary Benchmark Design

On the basis of the work by the industrial consultants, the Caltech and MIT Team prepared a "strawman" design for presentation to the NSF Advisory Committee for Physics and to the Gravitation and Cosmology Subcommittee of the NAS Physics Survey in the fall and winter of 1983-1984. It appeared prudent to recommend a below ground culvert type installation since the antenna would be subject to much less disturbance from temperature fluctuations, sunlight, wind, rain, and vandalism, and would in turn have less impact on the environment. The arm length was fixed at 5-kilometers as the longest affordable, although scientific considerations would argue for a longer antenna. The site had not been chosen at this time. The present length of 4 km is determined by the properties of the Cherryfield site. The pipe diameter was chosen to be 48 inches, the largest size compatible with commercially available vacuum equipment. The decision to use 48 inch pipe was based on several factors: it gives the most flexibility for multiple use of the vacuum installation: it has adequate leeway in alignment; and it is sufficiently large not to preclude the use of Nd:YAG or other lasers with longer wavelengths than the Argon lasers currently in use in the existing small scale prototypes at Caltech and MIT.

This preliminary benchmark design was estimated to cost approximately $56 Million (in 1982) dollars for the permanent facilities and the first two receivers. Almost all of the estimated cost was for the two facilities, the cost of the receivers being small in comparison.

E.3 The JPL Study and the Present Conceptual Design

While the MIT study established the overall costs of many of the elements of a full scale system, it did not fix the design. In addition, research and development efforts being conducted by the Gravity Wave Groups at Caltech and MIT resulted in requirements that were not addressed in detail in the MIT Study. As a result a work order to JPL was issued to expand upon the earlier feasibility study and to investigate the potential sites that were located during the MIT Study so that the facility costs could be reestimated. These activities, being conducted by JPL, are under the cognizance of the Project Office at Caltech.

JPL was asked to study the implementation approaches and costs of a variety of LIGO concepts. After considerable study a set of requirements was established for further studies. The first of these was that each facility of the LIGO be initially capable of supporting two separate, non-interacting experiments. Furthermore, the facilities should be designed in such a manner that they can be easily upgraded without requiring major modifications or expense to accommodate additional experiments. The motivation for this requirement is that one should plan at the outset to be able to simultaneously observe with one experiment while developing the next generation receivers as well ultimately to have the capability for multiple searches. In later phases of gravitational wave astronomy, it is anticipated that research groups at Caltech, MIT, and other institutions would want to carry out a number of specialized searches and observations using the LIGO facilities.

A second requirement is that the facilities be able to operate interferometers of different lengths simultaneously in order to improve the rejection of local noise and to give the facilities the capability to carry out specific observations.

A third requirement is to design the facilities to achieve a pressure of 10^{-8} torr at the outset. This is driven in part by the expectation that receiver sensitivity will improve rapidly. Another consideration is that the acceptance tests of the vacuum subsystem should prove that the system is capable of attaining this pressure.

Beyond examining the impact of these suggestions for the vacuum system design, it was deemed worthwhile to reexamine the whole system cost. This effort included a critical study of some of the important cost-drivers, such as the covered installation of the system, the vacuum pipes and some facility elements not addressed by the MIT Study.

The outputs of the JPL Study are described in the accompanying document, *LIGO Design and Project Plans*.

APPENDIX F
MEMORANDUM OF UNDERSTANDING BETWEEN CALTECH AND MIT

In November 1984 the Administrations of the California Institute of Technology and the Massachusetts Institute of Technology agreed to the following memorandum of understanding for the joint research and development program that underlies this proposal:

MEMORANDUM OF UNDERSTANDING BETWEEN CALTECH AND MIT ON A JOINT PROJECT TO CARRY OUT GRAVITATIONAL WAVE RESEARCH

1. The California Institute of Technology (Caltech) and the Massachusetts Institute of Technology (MIT) hereby agree to establish a joint research program to detect cosmic gravitational radiation and use it for research in physics and astronomy. This document states the agreed upon principles for this joint enterprise.

2. The gravitational wave research program involves three main types of apparatus: gravitational wave receivers, the vacuum facilities which house the receivers, and prototypes for the receivers.

   a) The vacuum facilities will consist of large vacuum systems, buildings and other equipment to be agreed upon, located at two sites separated by roughly 1000 kilometers or more. Each vacuum facility will be designed to support several receiver elements simultaneously.

   b) Each receiver element will consist of a laser interferometer which monitors the separation of freely suspended masses that are perturbed by a passing gravitational wave.

   c) Prototype receivers are laser interferometer systems used in design studies and proof of concept for the development of future receiver elements.

   Caltech and MIT hereby agree (1) jointly to design, construct and operate the vacuum facilities; (2) jointly to design and construct at least two receiver elements, one to be installed at each site; (3) jointly to carry out a search for gravitational radiation using these receiver elements. It is further agreed that (4) the construction and experimentation on prototypes will be carried out independently by Caltech and MIT, but with close communication between the two research groups; (5) Caltech and MIT are both free independently to design, construct, and operate additional receiver elements in the vacuum facilities with the proviso that the additional receiver elements do not significantly compromise the development and performance of the joint receiver elements and their observations, which will have the highest priority.

3. Proposals for funding the design, construction, operation, and enhancement of the vacuum facilities and joint receiver elements will be submitted jointly by Caltech and MIT to the National Science Foundation. Proposals for support of the gravity research groups of the two institutions will be submitted independently by Caltech and MIT.

4. The management structure for the joint work will be as follows:

a) All matters of scientific and fiscal policy will be decided by the members of the gravity research groups of the two institutions with final responsibility and authority in the hands of a Steering Committee. The Steering Committee will consist of three members: the two Co-Principal Investigators Ronald W. P. Drever and Rainer Weiss, and Kip S. Thorne. The Steering Committee will appoint one of its members as Chairman. The Steering Committee will endeavor to reach all decisions by consensus. In the event that a consensus cannot be reached, an issue will be decided by majority vote.

b) The Steering Committee will appoint a Principal Scientist for Joint Construction, who will act on its behalf on a day to day basis for the design and construction of the vacuum facilities and the construction of the joint receivers. This Principal Scientist does not have the power of decision on major issues, which must be brought to the Steering Committee. The choice and role of this Principal Scientist will be reconsidered at the time of the decision on the conceptual design of the joint receivers.

c) The Steering Committee will appoint a Principal Scientist for Experimental Techniques and Planning. This Principal Scientist will have the responsibility to develop, coordinate and propose plans for: experimental strategies and techniques, and conceptual designs of joint receiver elements. He also will act as a resource for the scientists and encourage cooperation on related research. This Principal Scientist does not have the power of decision on major issues, which must be brought to the Steering Committee. The choice and role of this Principal Scientist will be reconsidered at the time of the decision on the conceptual design of the joint receivers.

d) The design and construction of the vacuum facilities and construction of the joint receiver elements will be managed by a Project Manager. The Project Manager is responsible to the Steering Committee but interacts on a day to day basis with the Principal Scientist for Joint Construction. The Project Manager will be a nonvoting observer at Steering Committee Meetings, with the exception of executive sessions.

e) Certain portions of the joint project, by agreement of the members of the two gravity research groups, will be selected to be responsibilities of individual group members.

f) The President of each institution will designate a cognizant administrative contact, who will have responsibility for any institutional commitments and interinstitutional relations connected with this agreement.

5. After their construction, the vacuum facilities will be operated and maintained jointly by Caltech and MIT. Decisions concerning the allocation of space and time in the facilities to scientists at Caltech, MIT or other institutions will be made by the Steering Committee.

6. All non-review-article publications describing the joint gravity-wave searches will be co-authored by all the scientists of both gravity research groups.

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