Proposal to the National Science Foundation for a Grant to Support

A DETAILED ENGINEERING DESIGN STUDY AND DEVELOPMENT AND TESTING OF COMPONENTS FOR A LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

to be carried out jointly by the

California Institute of Technology

and

Massachusetts Institute of Technology

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APPENDIX IV

NATIONAL SCIENCE FOUNDATION

PROJECT SUMMARY

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

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

California Institute of Technology	Massachusetts Institute of Technology
Division of Physics, Mathematics, and Astronomy	Department of Physics

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PRINCIPAL INVESTIGATOR(S)

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TITLE OF PROJECT A DETAILED ENGINEERING DESIGN STUDY AND DEVELOPMENT AND TESTING OF COMPONENTS FOR A LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

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

The experimental development of laser interferometer techniques for detection of gravitational radiation, together with new concepts for enhancing sensitivity, has reached a stage where interferometer systems with arm lengths of order 4 km should be capable of detection and measurement of expected gravitational wave signals from various astronomical sources. Observation of this radiation would provide new tests of general relativity theory and also lead to an important new tool in physics and astronomy, capable of giving information on collapse processes, black holes, and other astrophysical phenomena unobtainable in any other way. This joint project of the California Institute of Technology and the Massachusetts Institute of Technology will carry out feasibility studies and an engineering design of a Laser Interferometer Gravity-Wave Observatory (LIGO) for such observations. The LIGO will include large vacuum systems at two separated sites, to permit use of coincidence techniques for identifying signals, and will be sufficiently flexible to accommodate a joint Caltech-MIT gravitational wave detection system and a variety of other detectors. The construction of the LIGO will be the subject of a later proposal.

NSF Form 4 (7-83)

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 detailed engineering design 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 proposal requests funds to carry out the final engineering design of the LIGO. The proposal also requests funds for the development and testing of several key components required for the LIGO, and of several key commercial components of the full-scale gravity-wave detectors to be installed in the LIGO.

The aim of the proposed work is to bring the LIGO design and cost estimates into a sufficiently advanced state that the LIGO can be evaluated by the NSF for construction.

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 proposal.

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 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.

This proposal's final design and component-testing studies will take one year. While those studies are underway, the Caltech and MIT research groups will continue to develop and improve the prototype gravity-wave receivers on which they have been working for many years; that receiver development is supported by separate grants from NSF to Caltech and MIT. A joint Caltech-MIT proposal for the construction of the LIGO and of the first joint receivers to be installed in it will be submitted to NSF in August 1986. The present plans call for beginning construction of the LIGO in November 1987 and completing it at both sites in 1989. The first joint Caltech-MIT detector would then be in operation in 1990.

1.3 The Organization of this Proposal

The body of this proposal (Secs. 2 through 5) focuses on issues central to the specific work being proposed: Section 2 presents our present conceptual design of the LIGO; Section 3 describes the proposed development and testing of components for the LIGO and its full-scale receivers; Section 4 describes the proposed detailed engineering design study for the LIGO; and Section 5 presents the budget for this proposal.

The work proposed here is only one component of the Caltech/MIT gravity-wave research program. Other aspects of that program – some of them central to its ultimate success – are described in appendices. The appendix material includes the following:

- A description of gravitational wave sources that might be seen with detectors in the LIGO, and a detailed comparison of the sources' expected strengths with the detectors' projected sensitivities (Appendix A).
- Brief descriptions of some concepts for advanced receiver technology (Appendix B), of prototype receiver research that is being carried out at Caltech and MIT (Appendix C) and elsewhere in the world (Appendix D); and a list of receiver-research milestones which have been presented to the National Science Board for their use in evaluating past and future progress at Caltech and MIT (Appendix I).

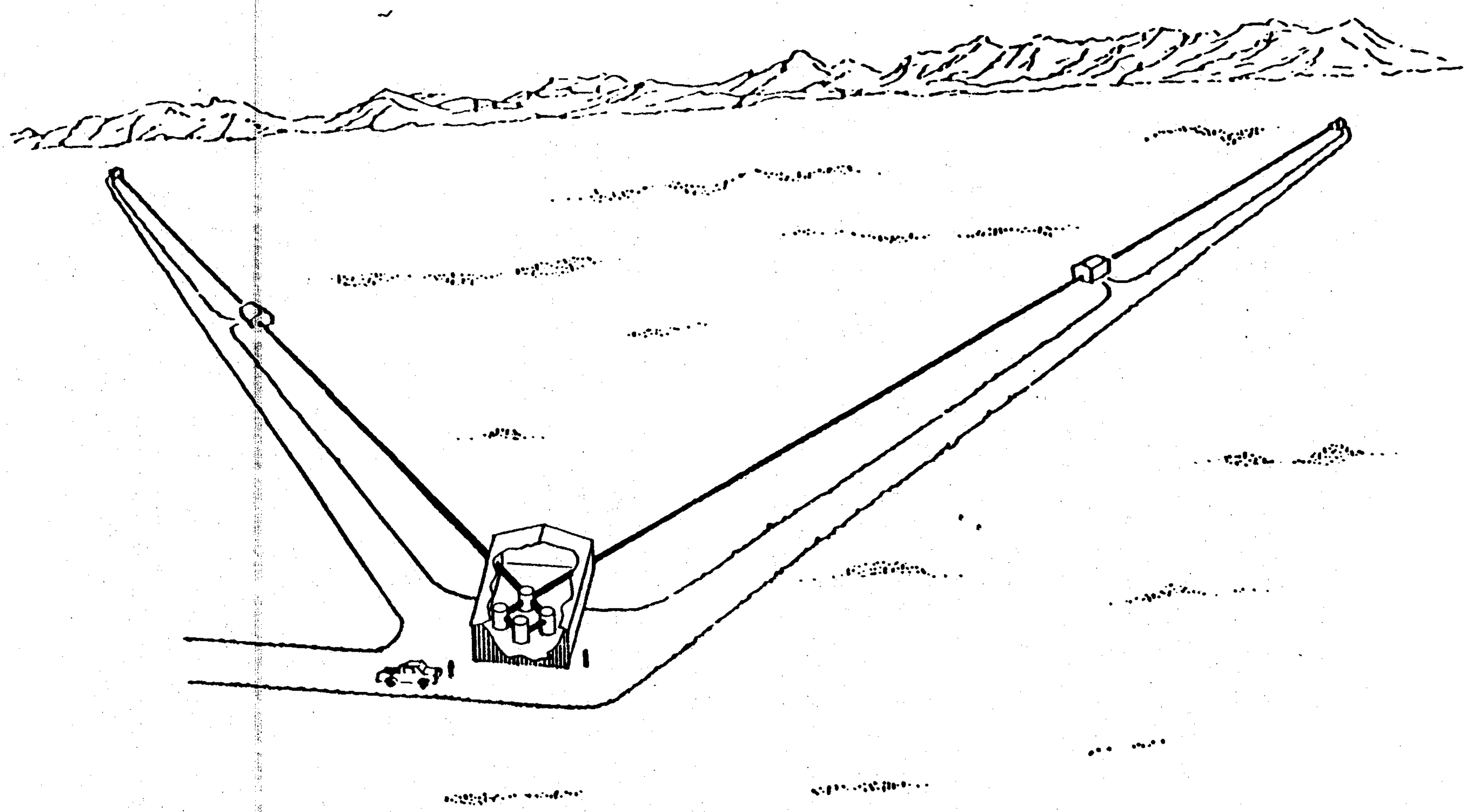


Figure 1.1 Artist's impression of one variant of the above-ground, west-coast site of the Laser Interferometer Gravitational Wave Observatory.

- Descriptions of the extensive past and present feasibility, design, and cost studies for the LIGO (Appendix E).
- The present, tentative version of the functional requirements for the LIGO (Appendix F); these, when completed, will be the input for the proposed detailed engineering design.
- A summary of milestones that will occur during the LIGO development effort (Appendix G).
- A description of our present vision of the "implementation" of the detailed engineering design (i.e., construction of the LIGO), which will be the subject of our next joint proposal to NSF; and details of the current cost estimates for the implementation (Appendix H).
- The Caltech/MIT memorandum of understanding under which this project is carried out (Appendix J).

Before turning to the details of the LIGO's conceptual design (Sec. 2) and of the proposed work (Secs. 3, 4, 5), we shall describe briefly the payoffs for physics and astronomy that would result from gravitational-wave detection (Sec. 1.4), and the gravity-wave detectors that might operate in the LIGO and their prospects for successful detection (Sec. 1.5).

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.

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.

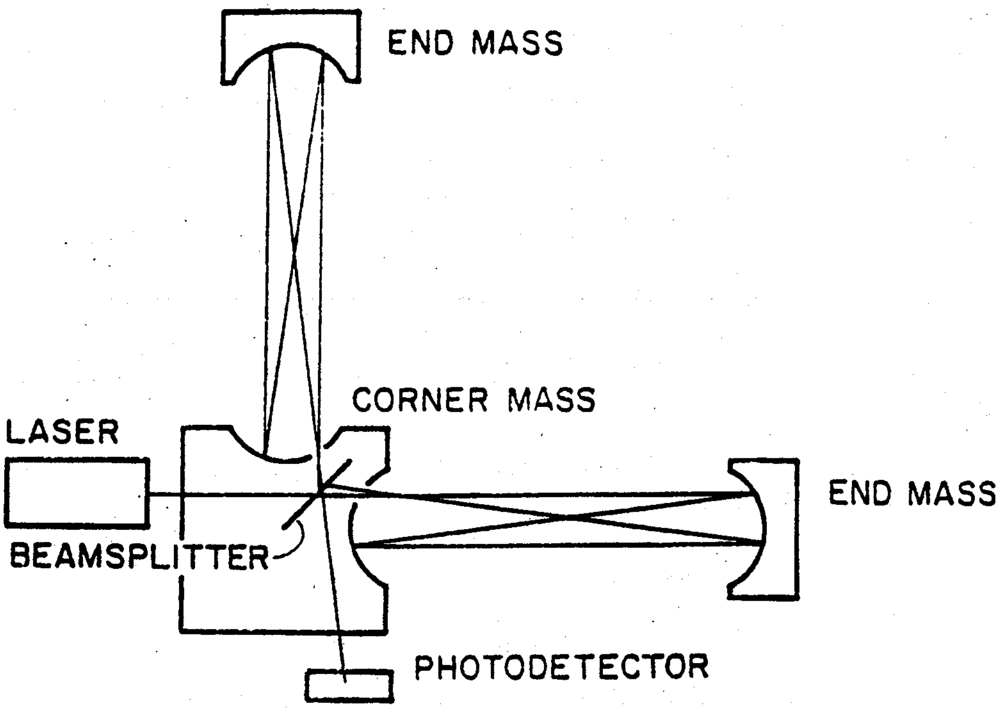
1.5 Gravity-Wave Detectors in the LIGO and their Prospects for Successful Detection

1.5.1 Simple First Detectors

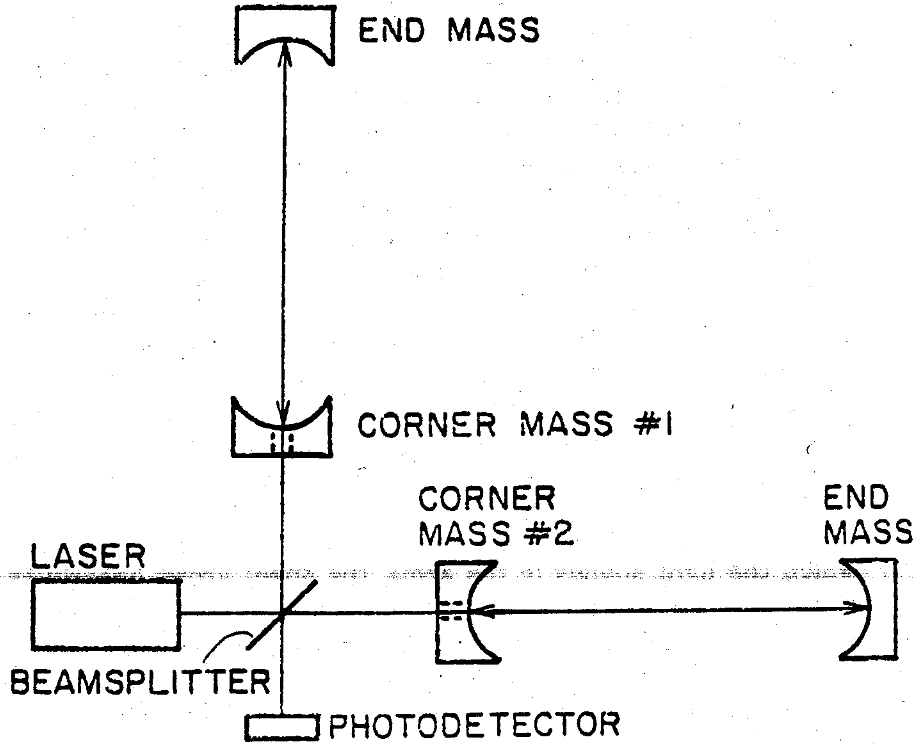
Description of Laser-Interferometer Gravity-Wave Detectors.

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 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 (June 1987); see Appendix G. 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

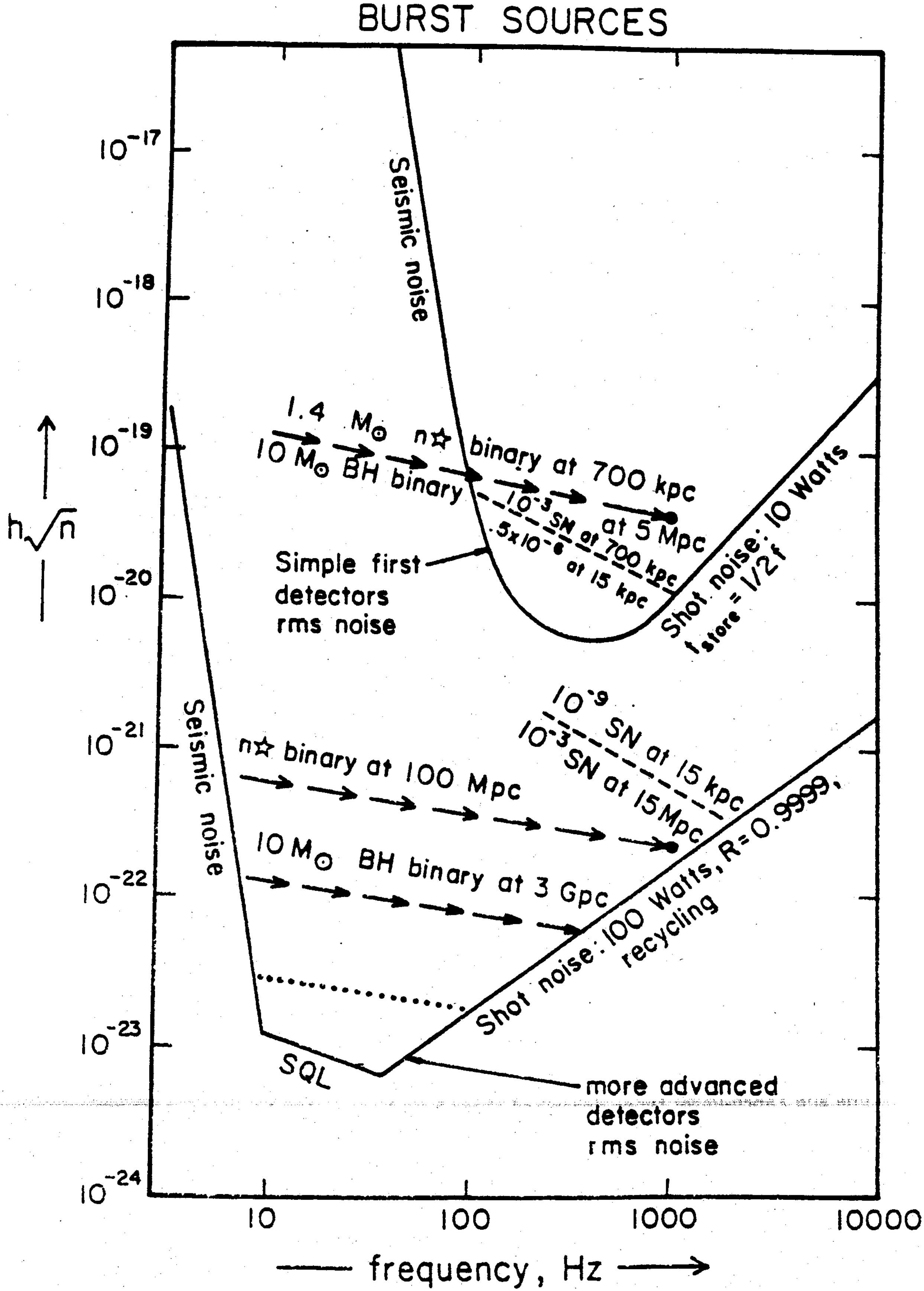


Figure 1.3. Comparison of predicted gravity wave strength for *burst* sources (Appendix A) with possible detector sensitivities in the LIGO (text and Appendix A).

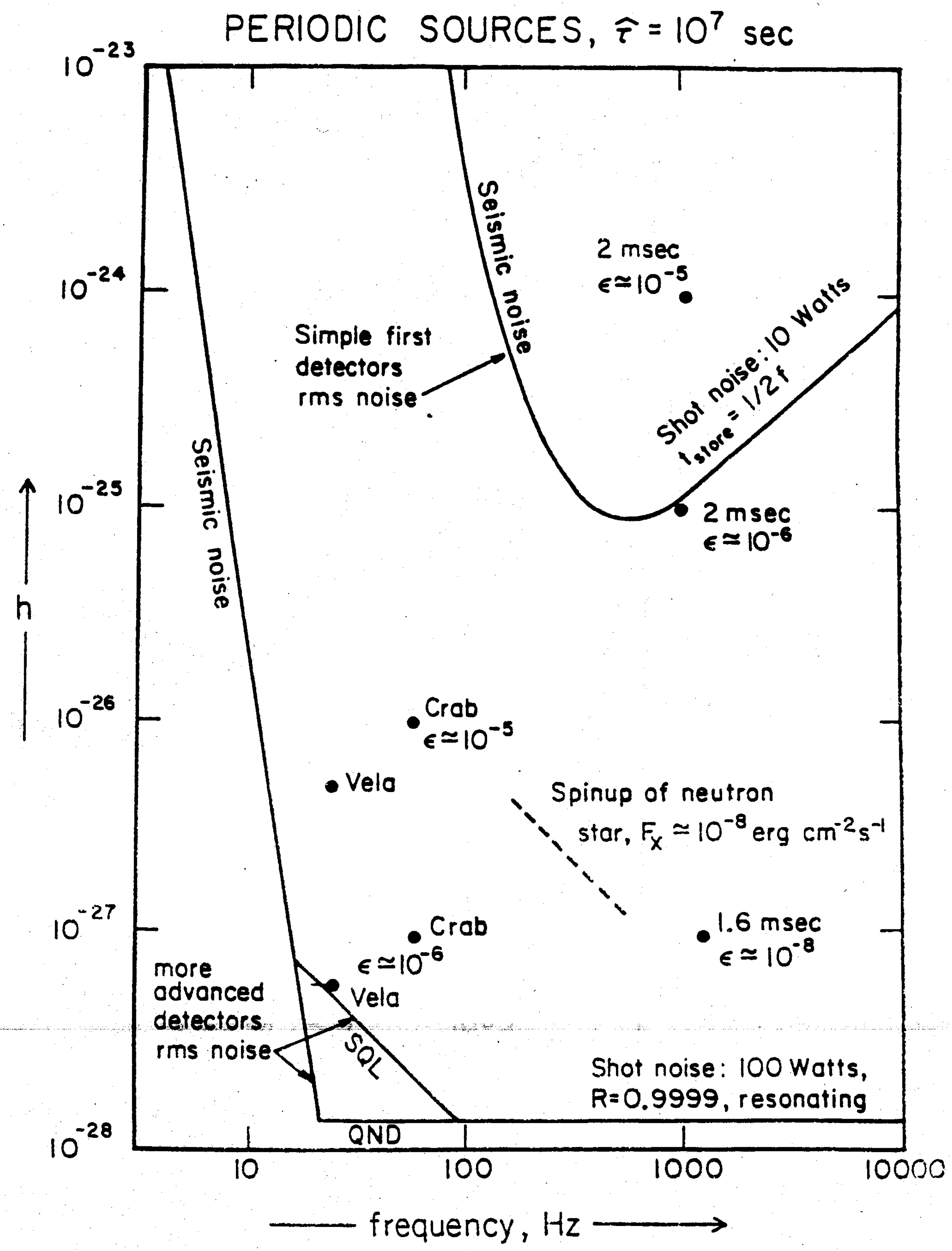


Figure 1.4. Same as Fig. 1-3, but for *periodic* sources of gravitational waves.

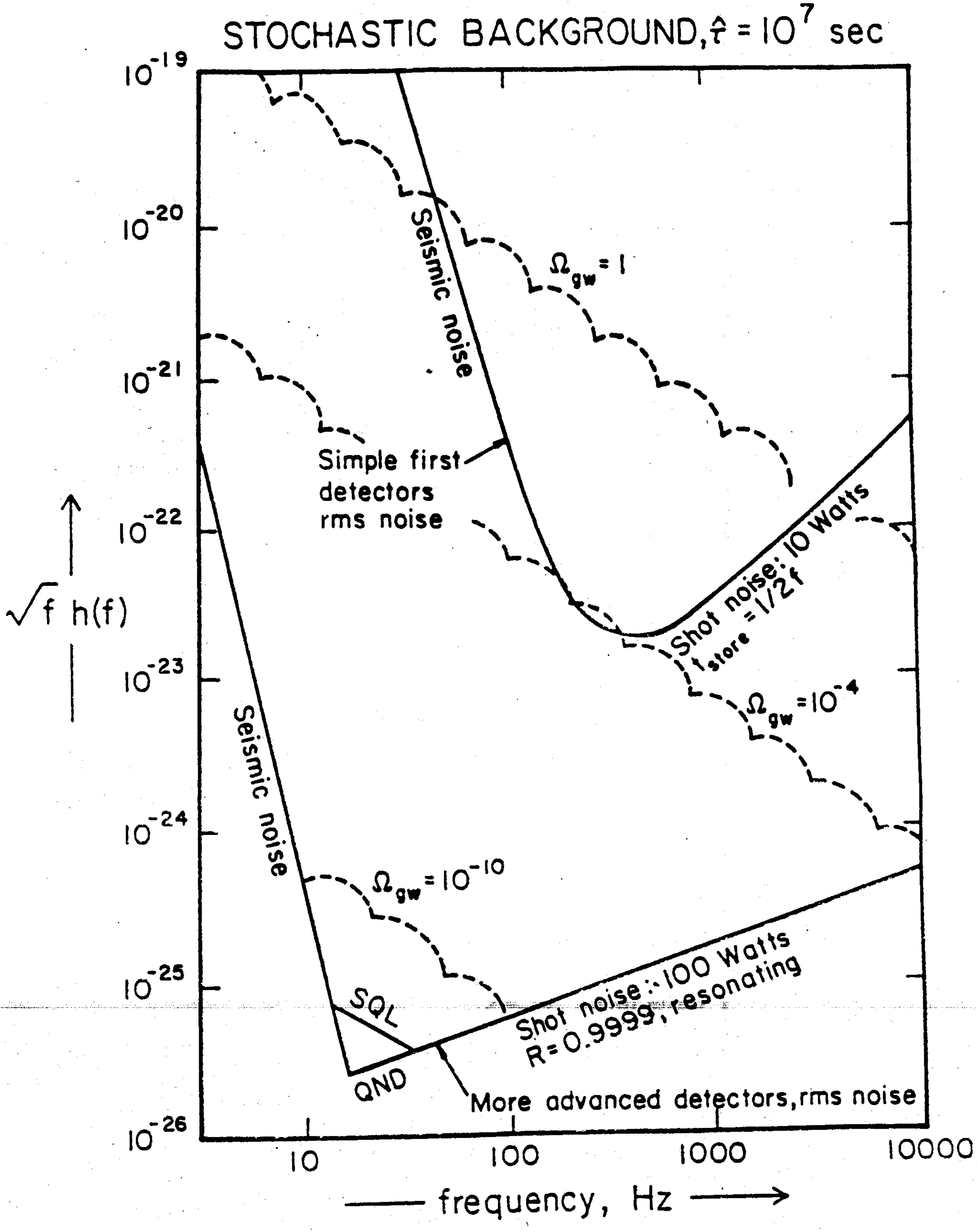


Figure 1.5. Same as Fig. 1-3, but for *stochastic background* of gravitational waves.

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.

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

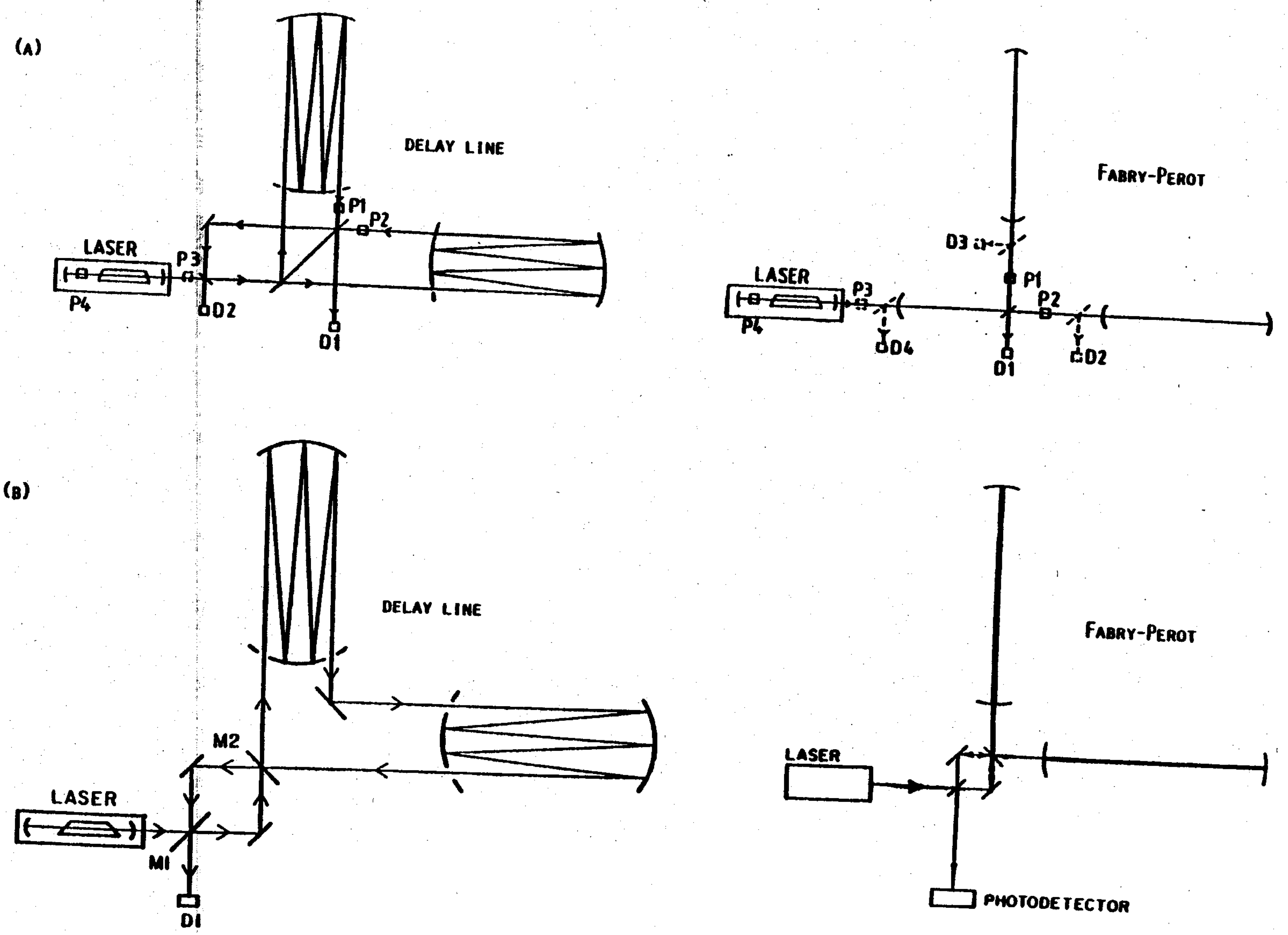


FIGURE 1.6. TWO POSSIBLE METHODS FOR ENHANCING THE SENSITIVITY OF GRAVITATIONAL WAVE RECEIVERS BUILT WITH DELAY LINES AND FABRY-PEROT INTERFEROMETERS. (A)--LIGHT RECYCLING INTERFEROMETERS. (B)--LIGHT RESONATING INTERFEROMETERS.

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 proposal

The design is based on the studies described in Appendix E and the functional requirements listed in Appendix F.

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.

Justifications for these requirements are as follows:

1. At the minimum, two facilities separated by at least 1000 km are required for an unequivocal detection of gravitational radiation bursts.

   Two widely-separated sites are essential for the elimination of the inevitable non-Gaussian, local noise which masquerades as gravitational-wave bursts. The noise is eliminated by cross-correlating receiver outputs from the two sites. Furthermore, when bursts have been discovered, two sites at least are necessary to give information about the directions of the sources.

2. Arm lengths of order 4 kilometers at each site are essential to achieving the sensitivities required for a near-certainty of successful detection. Although the probability of success is significant at the level of the "first simple detectors" of Figs. 1.3 - 1.5, a very-high-probability of success requires a sensitivity near that of the dotted line in Figure 1.3; see discussion at the end of Appendix A. Clearly, even with 4 kilometer arms there is little margin of safety. With arms of shorter length L the noise levels scale as L^{-1} for seismic noise and for other stochastic forces acting on the end masses, as L^{-1} for the standard quantum limit (SQL), as $L^{-3/4}$ for index-of-refraction fluctuations due to residual gas in the vacuum system, as $L^{-1/2}$ for photon shot noise when recycling is used on burst sources, and as L^{-1} for photon shot noise when resonating is used on periodic sources. With arms much

shorter than 4 kilometers one no longer can have strong confidence of success.

More generally, the longer the arms, the less stringent will be the demands on the receivers in order to achieve a given level of sensitivity; and thus, whatever may be the sensitivity required for success (probably, and hopefully, less than that described above), success will come more easily and sooner with longer arms. Clearly one would want the arms to be as long as possible but there are obvious constraints of cost. A rough rule that has been applied is that the length of the arms should be large enough so that further improvement of the sensitivity by a significant factor requires cost increments by a substantial factor. This implies that the costs dependent on the length should not be dominated by costs independent of the length.

3. A vacuum pipe diameter of order 48 inches is required: 1) to accommodate simultaneously the laser beams of several compact-beam receiver systems, 2) to permit the use of long-wavelength lasers, with their larger beam diameters, as they are much more efficient than shorter-wavelength lasers; and 3) to accommodate delay-line antennas, if they are the receivers of choice.
4. A vacuum level of 10^{-6} torr is required to achieve, in the face of index-of-refraction fluctuations, sensitivities near the upper solid curves of Figures 1.3 - 1.5 ("first simple detectors"); and 10^{-8} torr is required near the lower solid curves ("more advanced detectors"). The facilities will be designed to achieve 10^{-8} torr at the outset, in part due to our expectation that receiver sensitivity will advance rapidly. In addition, the acceptance tests for the facility should prove that this pressure can be attained.
5. 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 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 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.

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 the frontispiece of the proposal (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.

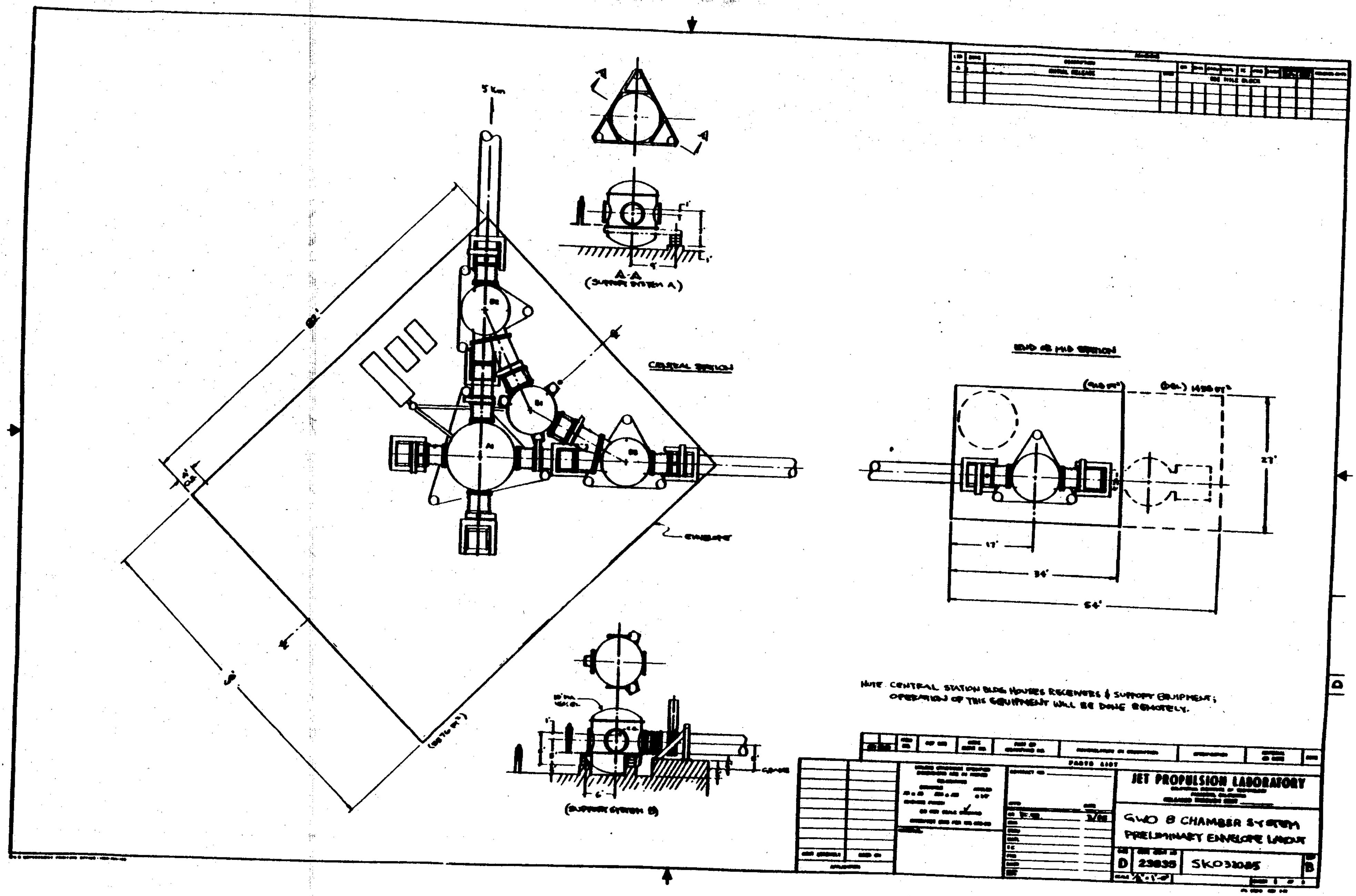


Figure 2.1(a) The corner, mid, and end stations of the LIGO shown with the configuration of instrumentation chambers that would be constructed at the begining, according to one variant of our present conceptual design.

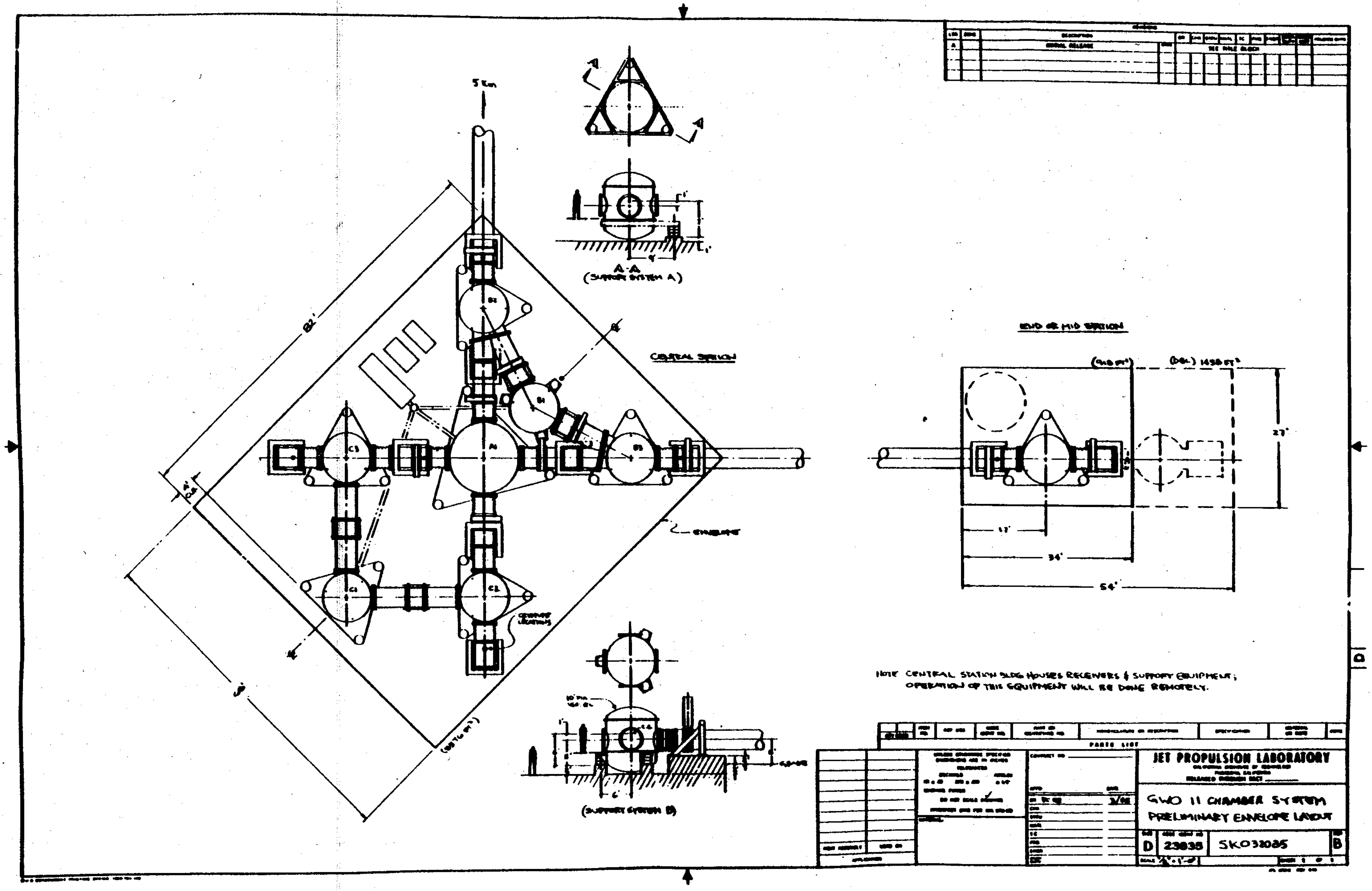


Figure 2.1(b) The corner, mid, and end stations of the LIGO shown at a later date, after the addition of three more chambers.

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 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. Appendix E.3.2 describes the vacuum system in considerable detail. The function of the vacuum system is twofold: 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 cryosorption pumps. Ion pumps are used to maintain the vacuum after initial pumpdown by the cryo 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 Edwards Air Force Base in Palmdale, 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. The specific reasons for these choices are discussed in Appendix E.3.1.

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. Cover designs are discussed in Appendix E.3.2.

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.

The estimated cost of implementing the present conceptual design (i.e. constructing the LIGO) is given in Appendix H.

3. PROPOSED DEVELOPMENT AND TESTING OF COMPONENTS FOR THE LIGO

In the previous two sections of this Proposal we have given an outline of the reasons for preparing to construct a laser interferometer gravitational wave observatory (LIGO), and the general layout and design we have arrived at for such a LIGO. In this section and the next we will describe the work on the development and testing of components and on the detailed engineering design for the LIGO, for which we are now requesting funds.

There are two important areas in which a significant amount of component development or testing is required: components for the receivers to go into the facility and components to be used in building the large vacuum systems. Most of the components to be tested will come from industry, although some will come from laboratory work at Caltech or MIT. We plan that the testing be carried out at the laboratories of JPL, Caltech, MIT, and selected industries, starting concurrently with the detailed engineering design effort so that by the end of the design phase we can be confident about the practical feasibility and cost of the whole facility.

3.1. Components for Receivers for the LIGO.

Development of special interferometers, test masses, and suspensions for interferometric gravitational wave detectors has been proceeding for several years at Caltech and MIT (see Appendix C), and will continue - for this provides the underlying technical basis for the whole project. The big step-up in scale from the laboratory prototypes to the proposed LIGO does, however, require construction and testing of certain key components built to a larger scale or operating at significantly higher power levels than in the laboratory prototypes. The major special components involved here are the large high-performance mirrors required for reflecting the light back and forth along the 4 km arms of the LIGO; and laser light sources giving higher power output and higher efficiency than those used so far in the laboratory work.

3.1.1 Mirrors and Test Facilities

Mirrors are a critical component for the receivers. The mirrors used now in the prototype receivers would be adequate for the LIGO's first generation delay line receivers and even for the most advanced Fabry-Perot configurations envisaged, except for their size. The enlargement of the mirrors is not a trivial scale change since coating uniformity, surface roughness, surface figure, the internal mechanical losses and resonant frequencies, and the thermal properties of the mirrors all have different functional dependences on the area. They also throw different challenges to the optics industry.

We propose to fund a development program in industry which has as its main focus to specify, acquire and test mirrors appropriate for at least the first generation receivers. These are likely also to be adequate for advanced Fabry-Perot designs. A secondary goal will be to begin the planning for mirrors to be used in second generation delay-line receiver designs.

a) Fabry-Perot Mirrors and Facilities to Test Them.

The availability of mirrors having very low optical losses is of great importance for the high performance interferometers planned, as already discussed earlier in this proposal. The development of special high-reflectivity mirrors for use in laser gyroscopes has produced mirrors having losses of less than 1 part in 20,000 - and possibly even better than this - and these should make particularly effective the techniques for enhancing sensitivity by recycling the light or use of resonant optical systems (see Section 1.5.2 and Appendix B). Currently, however, the laser gyroscope application has only required mirrors of diameter about 2 cm, and the mirrors used in the tests with the Caltech 40 meter system were specially made with a diameter of 4 cm. For a 4 km system with Fabry-Perot or other compact optics, the required diameter for diffraction losses of less than 10 parts per million is 15 cm (allowing some unused area near the edge of the mirror). We have been told by the manufacturers of the mirrors tested so far that they think they can make mirrors this size using existing equipment and techniques, and envisage no serious problems in doing this. However, it will be important to have some mirrors made of this size during the feasibility phase to check the losses in practice and to test for coating uniformity and errors in mirror figure which may affect mode matching in simple interferometers, and possibly degrade overall efficiency in recycling systems.

It will also be important to study operation with high laser powers and correspondingly large stored energy in a Fabry-Perot system, to test for thermal distortions and radiation damage effects. (It is known that the coatings we are using have good resistance to radiation damage, but the power levels which may be involved here can be very high).

For these purposes we plan to place contracts for development of the polishing and coating techniques for mirrors of this size, and for manufacture of trial mirrors for testing. The tests we plan to make on these mirrors will be made with the 40 meter interferometer system at Caltech, for this is the only installation with a long enough baseline and with the laser stabilizing, suspension, and mirror orientation control systems required. In order to make operation of full-size mirrors and other components in this 40 meter baseline simulate as closely as possible operation over the 4 km baseline of the LIGO we would choose radii of curvature of some of the test mirrors and lenses so that the diameter of the Gaussian beam over the 40 meters matches approximately the diameter in a 4 km system. This same installation will also be used for tests of other special large scale optical components required for the LIGO, such as low-loss beamsplitters for recycling systems, and special phase modulators. Some upgrading of vacuum tanks, vacuum pressure, and available laser power in this installation will be required for these tests. This will enable us also to make realistic tests of full-size seismic isolation and suspension systems for the LIGO - for which this installation is uniquely suited due to the isolated and completely separate foundations which support the chambers containing the test masses, and the compensated bellows system which mechanically isolates the chambers from the long beam pipes (see Appendix C.2 and Fig. C.2.2).

b) *Delay line Mirrors*

Mirrors for a first generation receiver using delay line optics would have diameters ranging between 50 to 80 cm. The mirror focal length would be of the order of the 4 km arm length. In a 4 km system the mirror sagitta for a 50 cm. diameter mirror would be about 10 microns; the mirror is virtually flat. The small sagitta does not pose a problem to mirror manufacturers, but the tolerances on figure and slope error may prove troublesome. The focal length of the mirrors must be maintained equal to better than 0.1% to allow the optical paths in the two interferometer arms to be adjusted to equality. Large wave-length surface ripples on the mirror should not cause slope errors exceeding a few microradians. Finally, the local surface roughness should not exceed 1/30 of a wave-length over the dimensions of the Gaussian spot diameters.

The thermal and mechanical properties of the mirror are also critical. The resonant frequencies of the major internal modes should lie above the gravity wave frequency and have a high Q. This condition may yet prove the most troublesome since it eliminates some of the more popular materials such as ceramic glasses as contenders for the mirrors. The thermal distortions and time constants of the mirrors especially with the high power laser beams being considered must be studied. Both active and passive mirrors are being considered.

Several mirror manufacturers (Itek/Litton, Perkin Elmer, SSG) have indicated an interest in working with us first to help specify the design of these mirrors and then to make several samples for test. Testing will have to be done interferometrically and will be carried out by the gravity research groups in the vacuum systems at MIT and Caltech. Mirror coating vendors (OCLI) do not see great difficulty in applying standard multidielectric .99 reflectivity coatings on the large mirrors.

3.1.2. High Power Laser Contracts

Laser sources for the receivers to be installed in the large baseline antennas have to meet a set of stringent requirements to meet the projected sensitivity goals for either cavity or delay line systems. The requirements are:

1. High power output in a single transverse and longitudinal mode; over 100 watts would be desirable.
2. The intrinsic amplitude and frequency noise of the laser carrier should be as small as possible even though servo systems are used to reduce both of these modulations.
3. The laser efficiency (the conversion of input power to light power) should be as high as possible. This requirement clearly has an effect on operations costs and could become a limiting factor on the number of interferometers that can be operated simultaneously in the facilities, both as it affects the

facility power budget and the laser cooling systems.

4. The laser must be reliable and able to run for long periods (months) without expensive service or replacement of parts.

The laser system used in the prototype receivers is the argon-ion laser which, in single commercially available units, is able to produce up to 5 watts in a single mode in the green. Techniques are being developed by the Orsay and Glasgow gravity wave groups to increase the power of individual argon lasers by avoiding use of lossy intracavity optical components such as Pockels cell modulators and single-mode etalons, and adding the output power of several lasers together coherently. For laboratory tests of optics and other receiver components at higher power and sensitivity, these schemes are the best short term solution. We propose to use a modest version of this arrangement, with 3 lasers, to provide the minimum laser power required for some of the tests of mirrors and other components described above. This will also give us experience with this currently practicable system which will be valuable for comparisons with other potentially more efficient laser systems which we propose to develop for use in the LIGO. It will also be a useful backup in case these other systems turn out to have high operating costs or other problems.

Recent advances in laser technology have made certain types of Nd:YAG laser a promising alternative for development for use in the LIGO, in place of argon ion lasers. We propose to initiate a cooperative program between laser manufacturers and the research groups at both MIT and Caltech to develop Nd:YAG lasers suitable for gravitational wave research.

The Nd:YAG laser system has not been used for precision laser applications but it is enormously more efficient than the Argon laser; efficiencies in CW operation of 2% have been reported in multimode systems delivering 400 watts and higher. These lasers have undergone rapid development in the past few years with the application of slab geometries and zig-zag beam paths in the gain medium. Although most of the development has been for high power in military and industrial applications, there is some research going on, in particular at Stanford University under Professor R. Byer, to develop single mode frequency stabilized Nd:YAG systems for space applications. The system being tried at Stanford incorporates the Nd:YAG gain medium in a ring resonator geometry to avoid spatial hole burning and mode competition.

The Nd:YAG laser produces 1.06 micron radiation which could be used for gravity-wave experiments; however green light, which can be generated by frequency doubling, is preferred due to the smaller mirror sizes and vacuum space required, and the better photon shot noise limit to sensitivity obtainable for a given beam power. We have contacted several Nd:YAG laser developers including General Electric, at both Schenectady and Binghampton, the major developer of the high power Nd:YAG system. Research staff and management at GE indicated that some of the requirements the gravitational radiation project imposes on the lasers would match company goals and they have encouraged us to propose a collaborative program.

Preliminary and unofficial discussions resulted in the following proposal. The gravitational research groups, using industry provided laser heads, would develop mode locked and single-mode continuous wave versions of the slab zig-zag laser. The light from a mode locked system or from a single mode CW laser could be applied to a delay line Michelson interferometer directly and, with additional frequency stabilization, to a Fabry-Perot interferometer. The frequency doubling techniques required to obtain visible light would most likely be different for the mode locked and the CW lasers. The mode locked lasers produce short intense pulses with which efficient frequency doubling can be accomplished external to the laser cavity. An intracavity doubler would be more efficient for the CW laser.

An important step, carried out primarily by the research groups, would be the development of a frequency stabilized low power CW oscillator, P<10 W, to determine the amount of power that survives in a single longitudinal mode and the difficulty of frequency stabilizing the Nd:YAG. The amount of power in a single mode depends on whether the Nd ion line is homogeneously or inhomogeneously broadened in the YAG host lattice. If this program is successful, the development of the high power (>100W) amplifiers and the high power frequency doublers could be carried out in industry. This part of the research intersects directly with industrial interests. The development of the laser heads themselves, especially the engineering required to produce diffraction limited (single radial mode) beams, is a longstanding research activity in industry in other parts of the Nd:YAG laser development program. Our present intention is to carry the preliminary research out with funds from the research grants to the groups and to develop the laser amplifiers and frequency doublers in industry with funds provided by the acceptance of this proposal.

3.2. Vacuum Subsystem Evaluations

The vacuum subsystem for the facilities is the critical element of the facility design. More than half of the capital costs for the LIGO is in the vacuum subsystem. Many large vacuum systems have been constructed and vacuum technology is not considered a high risk aspect of the facilities engineering, as is indicated by the A.D. Little and JPL studies described in Appendix E. There are, nevertheless, substantial extrapolations being made which have not been tested simultaneously in the heritage derived from vacuum systems used in particle accelerators, plasma physics experiments and space simulators. For this reason, we feel it is prudent to undertake a program of vacuum component tests. This will enable us to better understand the trade-offs between capital cost, operations cost, risk and reliability of the vacuum subsystem. It will facilitate a validation of the design before the commitment of large sums for the construction of the LIGO. As a result, we will be able to write tightly-specified fixed-price contracts for the vacuum system, and contractors will be able to bid on them with confidence that the technology exists to meet the specifications. Thus we expect this testing and design validation effort to be an important cost saver for the project.

3.2.1. Vacuum Subsystem Components Testing

During the next half year the vacuum engineer in the project office (Sec. 4.2.2 below) will develop a plan for testing components of the vacuum subsystem. The plan will include a cost risk tradeoff analysis which should determine the range of component tests required. The tests will be carried out at JPL and in industry. The following subsections of the proposal are an indication of the issues which must be addressed either by direct test or by (believable) confirmation from vendors.

3.2.2 Vacuum Tubing

Although the technology of tubing manufacture is well established, there are important technical/economic questions which deserve attention before committing to a specific tubing design. The issue is not one of whether tubing can be manufactured that will meet our vacuum specifications, this is well within standard practice, but rather how much risk we can take in saving costs and still be assured that the system will pump down to the required vacuum. The strategy adopted in the cost estimates of Appendix H is to weld, certify, preclean and rudimentary leak test each piece of tubing before installation into the system. If one could relax the procedure by taking some intelligent risks, it could result in substantial cost savings for the entire project. The evaluation of the risk does not involve only the tubing design but also the strategy adopted for dealing with leaks after the facility has been assembled. The A.D. Little vacuum system study of Appendix E.1.1 recommended aluminum tubing rolled from sheet and welded. The design incorporated periodic stiffening rings to avoid buckling and tube collapse under atmospheric pressure load. Part of the decision to recommend aluminum was derived from the success of new techniques to perform automatic heliarc welding both in plants and in the field. Subsequent studies favor stainless steel and there is at present no compelling argument to reject either material. A major issue which is beginning to emerge is the ease with which to manufacture tubing from metal ingot and be assured of minimum porosity in the base metal itself. Stainless steel, although slightly more expensive than aluminum, may be more trouble free in this regard. Whether it is to be rolled and welded or extruded in one piece is an important question which affects overall costs in a complicated way. Tubing that is rolled and welded is substantially cheaper to manufacture than extruded tubing, but it is also more likely to have leaks and therefore be more expensive to test and seal. Another consideration comes from the cost savings that may be possible if the tubing manufacture is carried out in the field. The obvious advantages of reduction in shipping costs and control of cleanliness may be offset by poorer welding reliability or difficulties in rolling the sheet stock into tubing. Another engineering factor is the ability to preclean or clean the tubing after assembly to reduce the outgassing rate without having to resort to high temperature (T > 200 C) baking after installation. Techniques for cleaning tubing have been studied in particle accelerator laboratories, but never on the scale required for the LIGO. A related issue is the benefit derived from low temperature bakeout, (T < 150C). The conceptual design calls for a low temperature bakeout as one way of achieving the outgassing flux of 10^{-12} torr liters/sec cm^2. It may be possible to precook stainless steel to achieve these fluxes if it is kept clean during assembly. The best strategy for attaining these outgassing fluxes will be studied and tested. For these reasons, as well as to be able to write proper specifications for fixed cost contracts, we plan to carry out an engineering research program with tubing manufacturers to verify cleaning procedures, test welds and weld inspection techniques. We will also test the porosity at the very low levels required of several tubing manufacturing techniques.

3.2.3. Bellows, Valves, and Pumps

a) *Metal Bellows*

Metal bellows are essential components in the vacuum facilities to allow for thermal expansion, atmospheric pressure compensation and seismic isolation at the instrumentation chambers. Small metal bellows made of brass, stainless steel, and various cupro-nickel alloys are standard laboratory items. The large bellows needed for the LIGO facilities are less common, and more experience is needed to understand their properties. The decision on the tubing material is also related to the choice of material of the bellows. If aluminum is chosen as the tubing material there may be a significant cost advantage in using aluminum bellows to avoid transition pieces between the bellows and the tubing. Aluminum bellows have only recently become available and must be carefully evaluated. Another consideration is the potential need for flanges in the bellows attachment. The ability to reliably weld bellows directly to the tubing may offer some risks, but also offers a substantial reduction in costs and could result in greater reliability of the vacuum system. The question that has to be addressed is the difficulty of successfully welding a thin bellows to a thicker tube. The project will purchase bellows of several designs and material and evaluate them and the methods of attachment.

b) *Gate Valves*

The gate valves, as has been indicated above, are troublesome components in the vacuum system design. The standard gate valves using vacuum grease and elastomer seals will work well at pressures above 10^{-6} torr. The gravitational antenna project requires several properties in valves that are not normally encountered in other facilities. The pressure in the instrumentation chambers could be as low as 10^{-8} torr and the pressure in the long arms between 10^{-6} torr to 10^{-8} torr. The valves will therefore require low vapor pressure sealing surfaces and bellows couplings for the actuators. The valves will be operated frequently in the early part of the project as there doubtless will be substantial need to frequently enter the instrumentation chambers. Throughout the work, especially during operation of multiple interferometers, it will be important to keep some experiments running while others are being installed or checked out. The long term reliability of the valves is a critical question for operational reasons alone.

The project intends to evaluate gate valves from several manufacturers. The valves will be mechanically and thermally cycled to test their ability to withstand atmospheric pressure on one side and high vacuum on the other.

c) *High-Vacuum Pumps*

The A.D. Little and JPL vacuum system studies (Appendix E) specified ion-chemisorption pumps as the baseline for the LIGO facilities. The prime reasons for this choice are their reliability and freedom from maintenance and the fact that they are mechanically quiet. The ion pumps, especially if started at pressures above 10^{-8} torr, have a reputation of causing gas bursts which may be of sufficient size to cause noise in gravitational-wave searches. Several manufacturers indicate that with specific cathode designs the gas bursts do not occur. The power spectrum of the pressure fluctuations due to these pumps must be measured to establish whether they can be used in the facilities.

The pumping strategy adopted for the conceptual design is a hybrid of ion and cryosorption pumps. The cryosorption pumps have higher pumping speeds than the ion pumps and will be used to bring the system to safe pressure so that the ion pumps can be started. The cryopumps could become the only pumps should the ion pumps prove troublesome. However, the cryopumps have closed cycle refrigerators associated with them that bring into question the vibration induced by the pumps as well as their long term reliability. The project will purchase several ion pumps which will tested in the model vacuum system. Cryo pumps will be purchased for use both at JPL for components tests and as starting pumps in the vacuum systems at Caltech and MIT.

3.2.4. Prototype Vacuum System

After initial testing and selection of components by the vacuum engineer in the project office in coordination with engineering assistance of JPL (see Secs. 3.2.1. above and 4.2 below), a small scale vacuum system of the same design and using components identical with those specified for the LIGO facilities will be assembled at MIT. This test system would be constructed of samples of the components to be used on the large antenna: sections of the tubing, bellows, a gate valve, and the candidate high vacuum pumps. The system would have 3 instrumentation chambers of smaller size than those to be used in the LIGO facilities but of the same design, so that the model system can be used as a test bed for some of the LIGO receiver components in later phases of the program. The test system would detect flaws in the design and would be made sufficiently flexible to allow substitution of components should there be difficulties with the initial choice or should ancillary tests indicate that cost savings could be made by trying other procedures or by the use of other components. The questions that a test system will help to answer include:

1. The ultimate system operating pressure.
2. The molecular constituents of the residual gas. The atomic and molecular polarizability of the gas at the laser frequencies is important in determining the magnitude of the index fluctuations that will affect the gravitational-wave measurements and that ultimately will set the vacuum specification. The expectation is that hydrogen will be the major constituent of a leak free clean system. The effect of column density fluctuations of hydrogen on the optical phase is almost an order of magnitude smaller than for nitrogen or oxygen.
3. The short period pressure fluctuations in the vacuum. The power spectrum of gas pressure fluctuations is rarely measured in vacuum chambers but is important in the gravity-wave experiments. The temporal behavior of the outgassing as a function of temperature sets requirements on the temperature excursions of the vacuum system; furthermore one of the critical parameters in the choice of the high-vacuum pumps is that they not generate gas bursts and not exhibit rapid fluctuations in pumping speed.
4. The quiescent outgassing rate of the tubing as a function of temperature and the change in this rate as a function of low temperature baking or precleaning procedures. The vacuum system design will make initial assumptions on the outgassing rate which determines the number of pumps required to establish the ultimate design pressure. This calculation is the most uncertain of the many required to design the system, and there could be real economic benefits in reducing the uncertainty by measurements.
5. The porosity characteristics of the specific tubing design. The manufacture of the tubing and its material have a strong economic impact on the vacuum system cost (Appendix H). The test vacuum system will be used to characterize the performance of the candidate tubing design.
6. The leak rate and outgassing characteristics of the gate valves. The gate valves that separate the long tubes from the instrumentation chambers are both critical and possibly questionable components of the vacuum system design. Large valves are notoriously troublesome especially as the ultimate pressure demanded gets below 10^{-7} torr. They furthermore are expensive. The test vacuum system will be used to make a functional test of the chosen gate valve.

4. THE DETAILED ENGINEERING DESIGN

4.1 Introduction and Overview

In this section we describe the detailed engineering design effort for the LIGO facilities, for which this proposal seeks funds. The aim is to establish the design in sufficient detail to arrive at optimized costs and schedules so that the proposed design may be evaluated for construction. The conceptual design of Sec.2 and its corresponding functional requirements (Appendix F), after further iteration, will be the basis for the detailed engineering design effort. This effort will be carried out by an industrial contractor under supervision of a small project office in residence at Caltech which is supported by engineering and contract monitoring personnel from JPL. The support from JPL is an effective means of applying experienced manpower to the engineering design while at the same time retaining the flexibility to adjust the amount of support before firm commitments are made to the LIGO Project. The result of the detailed engineering design effort will be detailed drawings, schedules, costs and a plan for the construction of the LIGO. Closely related to this design effort is the testing and evaluation of critical components of the vacuum and receiver subsystems described in Section 3. These evaluations are vital to validate the design of the LIGO.

We begin this section of the proposal with a description of the organization and management of the design effort. This is followed by a description of the tasks that will be accomplished, indicating the roles that are played by the various groups in the organization. This section deals primarily with the design phase of the development of the LIGO. Appendix H describes briefly how the transition would be made when the LIGO is approved for construction.

4.2 Organization and Management

4.2.1 Scientific Management

The joint Caltech/MIT Program to detect gravitational radiation was initiated in the winter of 1983. A formal Memorandum of Understanding (MOU) for this program was drafted in 1984 and appears in Appendix J of this proposal. The responsibility for the scientific direction of the Project rests with the Gravity Wave Steering Committee consisting of R. Drever, principal investigator from Caltech, R. Weiss, principal investigator from MIT, and K. Thorne, Committee Chairman, who is not a member of either experimental group. The Steering Committee has the responsibility to determine the project strategy and to establish a plan for the implementation of the LIGO functional requirements (Appendix F). The implementation of these requirements is the responsibility of the Project Manager, F. Schutz, who is also a non-voting member of the Steering Committee. One member of the Committee has been designated to work with the Project Manager on a day to day basis, serving as liaison between the Committee and the Project Office on issues related to facilities design and construction. Another member has been designated to have the responsibility to develop, coordinate, and propose plans for: experimental strategies and techniques, and conceptual designs of joint receiver elements.

The Committee meets at regular intervals, typically once a month, and is convened by telephone more frequently. The Project manager reports to the Committee monthly.

An important function of the steering committee is the coordination of the Research Groups' joint project activities.

The conceptual design effort of the past nine months has been carried out by the scientists in both groups under the guidance of the Steering Committee and the Project Manager with engineering support from JPL.

An Advisory Committee composed of members selected by the Caltech and MIT administrations will be constituted to provide oversight of the overall program. This committee will meet at least annually to review the state of the program. The members of this committee have not yet been formally chosen; however, a de facto committee consisting of G. Pettengill, Director of the MIT Center for Space Research, and E. Stone, Chairman of the Division of Physics, Mathematics and Astronomy at Caltech have been providing this oversight function for the past nine months.

4.2.2 Project Management

The LIGO Project Office is in residence at Caltech under the direction of the Project Manager. The project office will be responsible for planning, managing, and coordinating the entire engineering design effort. In addition, it will have several specific functions; see below. The project office will be the focus for channelling scientific guidance from the research groups to the design effort. To carry this function out effectively, a small core of engineering personnel with experience in dealing with industry and understanding of scientific requirements will be hired in the near future. This is being done in a careful and responsible manner since the entire project has not yet been approved. However, it is essential if we are to make credible plans and ultimately implement responsibly a project of the cost and scale of the proposed LIGO.

Among other functions performed by the project office will be the further iteration of the conceptual design prior to the engineering design; the management and oversight of the industrial contracts being let for the development and testing of receiver components to establish feasibility; and the planning and evaluation of the vacuum system components tests.

Prior to and during the engineering design the project office will be responsible for the system engineering; this is an analytic function to establish that the various subsystems being designed will actually perform together and not compromise or inhibit the performance of the receivers in the facilities.

Through its role of managing the industrial development and testing of receiver and vacuum components (Sec. 3), the project office will gain experience with some of the critical technologies in the receiver developments being made in the present prototypes. We anticipate that when the design of the first joint receivers has been completed, the Project Office will oversee and manage their construction. In the present plan, certain portions of the receiver construction work will be responsibilities of individual members of the MIT and Caltech Research Groups. The interfaces between the receivers and the facilities will be determined by the Project Office acting in conjunction with the Research Groups.

The Project Office staff will include a system engineer, a mechanical engineer, a vacuum/optics engineer, and a financial manager. The day-to-day interactions between the Project Office and the JPL support team will be conducted by this staff. The financial manager is responsible for tracking and controlling the resources allocated to the Project. Additional staff will be added if required to ensure that the Project meets its obligations to NSF, Caltech and MIT.

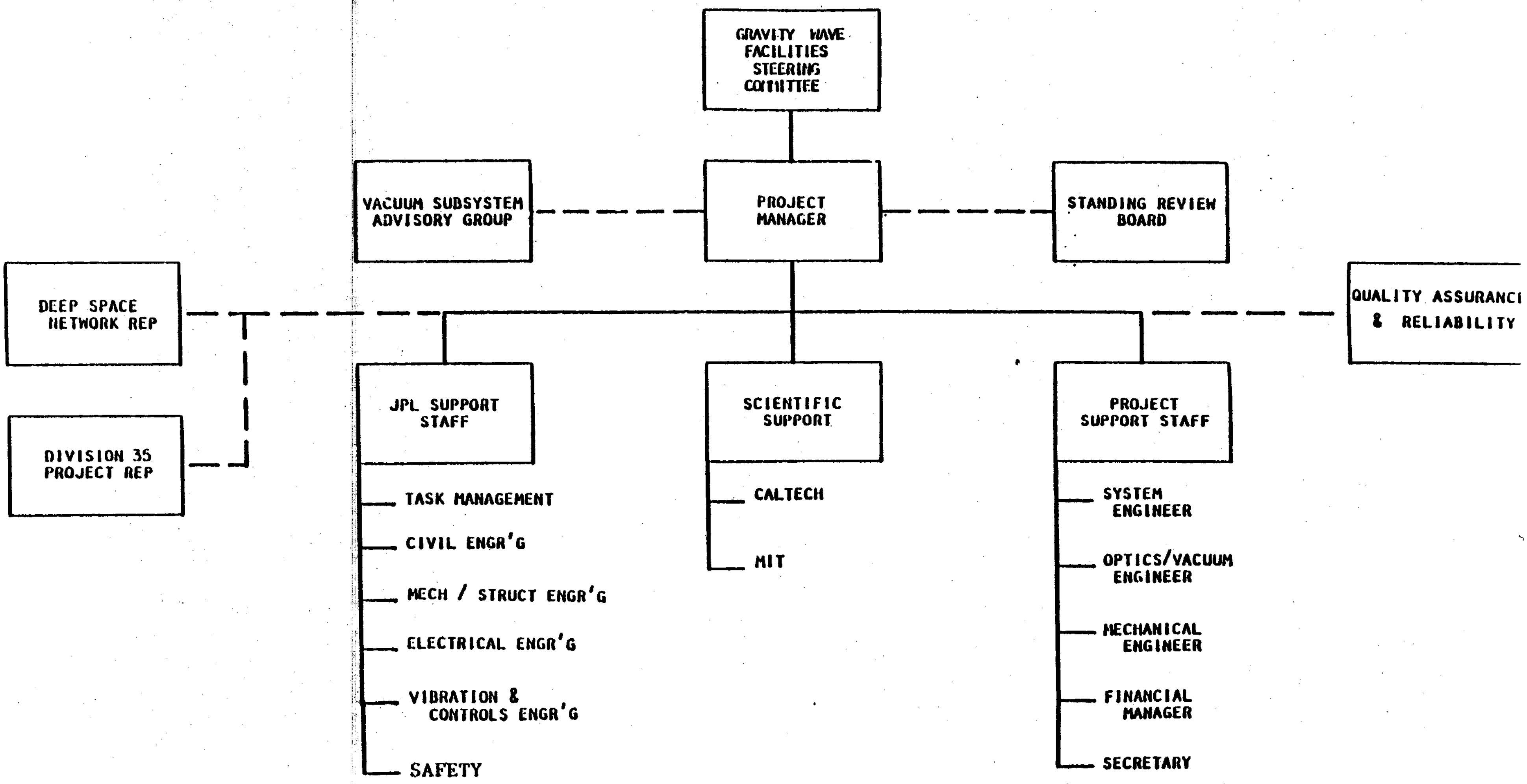
The various elements of the organization (Team) for the engineering design are shown in Fig. 4.2-1

This Team is headed by the Project Manager, who reports to the Steering Committee. The Team is composed of three groups:

1. a support activity, provided by JPL under a Caltech work order;
2. a system technical and financial management group operating as part of the Project Office; and
3. a group from each institution to provide scientific support to the Project Office.

A Standing Project Review Board will be established during the Conceptual Design Phase of the Project to advise the Project Manager of problems detected during the review process. To the maximum extent possible the Board will be drawn from technical and management personnel having experience in the technologies involved in the design. It will also include a representative appointed by Caltech and one appointed by MIT. The Board will attend all formal project reviews. It is the Board's function to comment to the Project Manager, the Steering Committee and the Caltech and MIT Administrations on the conduct of the Project. The primary charter for this Board is to provide an oversight of the conduct of the Project, both technically and managerially. A specific Board charge, outlining the scope of the review, will be prepared for each review.

Five formal reviews will be conducted between now and the completion of the engineering design. Three of these reviews will examine in detail the technical approaches used to develop cost estimates for the LIGO system construction. The other two reviews will be conducted on the Request for Proposal (RFP) issued for the detailed engineering design.



PRELIMINARY ORGANIZATION CHART
FIGURE 4.2-1

A Vacuum Subsystem Advisory Group is being established by the Project Manager to provide advice on approaches to the vacuum subsystem design. This group is composed of specialists drawn from both government and industry. It is their function to serve as a resource base for the vacuum subsystem development.

4.2.3 JPL Management and Engineering Support Group

During the conceptual design effort (Sec. 2 and Appendix E.3) the Project Office has been supported by members of the staff of the Jet Propulsion Laboratory (JPL). This support is drawn from the JPL organization responsible for the implementation of NASA's Deep Space Network antennas and supporting facilities. The group has an extensive background in the design, development, construction and operation of remotely located technical facilities.

Their responsibilities during the Engineering Design Phase will be to assist in the development of the RFP, evaluation of the proposals received, oversight of the detailed engineering design contractor selected, design analysis for the Project Office, and vacuum subsystem component tests and evaluation.

4.3 Tasks between Now and the Beginning of the Detailed Engineering Design Effort

The period between now (August 1985), and initiation of the engineering design (proposed to be November 1986), will be used to accomplish the tasks listed below with funds allocated by the NSF through the current Caltech and MIT Research Grants and with additional funds provided by the two Institutions directly.

1. A commitment to the two sites selected will be made after completion of additional investigations of their geophysical, geological, and environmental properties. We are currently in the process of negotiating a security agreement with the Air Force Systems Command for the use of the site at Edwards AFFTC. At the site in Maine, the land is privately owned. Several contacts with the landowners, the lessee's of their land, local authorities, and the State of Maine indicate that they are receptive to the construction of the other half of the LIGO in Maine. We are currently pursuing these contacts to establish definitive agreements on the acquisition of this property. The funds for this acquisition will be provided by the Institutions and not the NSF.

2. A Gravitational Wave Project Implementation Plan will be prepared and issued by the Project Office to delineate the approach to meeting the LIGO Functional Requirements. This document is a composite summary of the functions that the facilities must provide to enable us to perform gravitational wave investigations. The Project Implementation Plan will also establish policy and requirements including quality assurance and reliability, configuration management, materials and component parts application and usage, reviews,

documentation, security and safety. However, the most important aspect of the Implementation Plan is that it defines the technical and management approach that will be taken to the design and ultimately (if approved in response to a future proposal) the construction of the facilities.

3. As a part of (2) above, a management approach will be developed to monitor, control and assess the performance of the contractor(s), JPL and the Project. This will be accomplished by the following:

a. development of composite functional block diagrams of the facility at each site followed by development of subtier functional block diagrams of each subsystem;

b. preparation of a Work Breakdown Structure (WBS) that lists in hierarchical manner all facility elements having cost implications. The third iteration of the WBS, which for simplicity is only carried to the third level is shown in Figure 4.3-1. A more detailed segment of the WBS, that has elements at the sixth level, is shown in Figure 4.3-2. This latter figure is included to illustrate the detail being used in developing the design and cost data.

c. preparation of functional descriptions of each of the elements of the WBS will be done to ensure that all activities or tasks that require resources are understood and described;

d. generation of schedules describing the duration and activity of each WBS element to ensure that the constraints of individual activities are considered. A two page schedule for the period between the submission of this proposal to the end of the proposed engineering design is shown in Fig. 4.3-3 and is discussed in some detail in Appendix G. The figure shows as well the transition to construction of the facilities, which is *not the subject* of this proposal and must await a decision by the NSF after the completion of the engineering design. It nevertheless may be useful for the reader as an illustration showing the relationships and continuity of the various tasks.

e. preparation of time phased cost data essential to our ability to understand the condition of the effort at any point in time. One of the important responsibilities of the Project Office is to assess progress against plan; the time phased cost data are a vital part of this assessment.

The importance of the preparation of this set of related documents, the functional block diagrams; work breakdown structure; functional descriptions; schedules; and time phased cost estimates, must be stressed. These documents comprise a Baseline Plan against which progress can be monitored and assessed. The Plan will be updated periodically to reflect any substantive modifications. Schedules will be detailed for six months intervals and updated each three months.

4. The cost and trade-off studies underway will be continued through the completion of the detailed engineering design. The formulation of the Functional Requirements and the generation of the conceptual system design have highlighted issues with alternate engineering solutions that differ in cost and

Figure 4.3-1

3rd Level Work Breakdown Structure

1000 PROJECT MANAGEMENT

1010 PROJECT MANAGER
1020 PROJECT TRAVEL
1030 PROJECT DOCUMENTATION
1040 PROJECT REVIEWS
1050 PROJECT SAFETY
1060 PROJECT SECURITY
1070 FINANCIAL MANAGER
1080 PROJECT SUPPORT
1090 LAND ACQUISITION COSTS
1100 ENVIRONMENTAL IMPACT STATEMENTS
1200 BLANK
1300 FUNCTIONAL REQUIREMENTS

2000 SYSTEM DESIGN

2010 SYSTEM MANAGER
2020 MECHANICAL/STRUCTURAL MANAGER
2030 VACUUM/OPTICS MANAGER
2040 JPL SUPPORT
2050 SYSTEM VALIDATION
2300 FUNCTIONAL SPECIFICATIONS
2400 SYSTEM OPERATION/MAINTANCE MANUAL
2500 CONFIGURATION CONTROL

3000 VACUUM SUBSYSTEM

3010 CHAMBER ASSEMBLY, CENTRAL STATION (4)
3020 CHAMBER ASSEMBLY, MID STATION
3030 CHAMBER ASSEMBLY, END STATION
3040 CHAMBER SUPPORT ASSEMBLY
3050 VACUUM PIPE ASSEMBLY
3060 SUPPORT ASSEMBLY, VACUUM PIPE
3070 VACUUM PUMP ASSEMBLY
3080 VACUUM BAKEOUT POWER DISTRIBUTION ASSEMBLY
3300 FUNCTIONAL SPECIFICATIONS
3400 OPERATION/MAINTANCE MANUAL
3600 SPARES

4000 RECEIVER SUBSYSTEM

4010 MASS SUSPENSION ASSEMBLIES
4020 LASER ASSEMBLIES
4030 FILTER/MODULATOR ASSEMBLIES
4040 OPTICS ASSEMBLIES
4050 POCKELS CELLS
4060 DISPLAY ASSEMBLIES
4070 POWER SUPPLY ASSEMBLIES
4080 ELECTRONIC CONTROL ASSEMBLIES
4090 ANTICOINCIDENCE ASSEMBLIES
4300 FUNCTIONAL SPECIFICATIONS
4400 OPERATION/MAINTANCE MANUALS
4600 SPARES

5000 FACILITIES SUBSYSTEM

5010 SITE DEVELOPMENT
5020 CENTRAL STATION BUILDING ASSEMBLY
5030 MID STATION BUILDING ASSEMBLY
5040 END STATION BUILDING ASSEMBLY
5050 PROTECTIVE HOUSING ASSEMBLY, VACUUM PIPE
5060 POWER DISTRIBUTION ASSEMBLY
5070 LASER COOLING ASSEMBLY (.3 MW)
5080 TRAILER ASSEMBLY
5090 HOUSEKEEPING ASSEMBLY
5100 INTERCOMMUNCIATION ASSEMBLY
5110 FURNISHINGS
5120 SECURITY ASSEMBLY
5130 SEISMIC MONITOR ASSEMBLIES
5140 TRANSPORTATION VEHICLES
5150 EMERGENCY/BACKUP EQUIPMENT
5300 FUNCTIONAL SPECIFICATIONS
5400 OPERATION/MAINTANCE MANUAL
5600 SPARES

6000 DATA ANALYSIS SUBSYSTEM

6010 PRIMARY PROCESSOR
6020 STATION PROCESSORS
6030 REALTIME DATA LINKS
6300 FUNCTIONAL SPECIFICATIONS
6400 OPERATION/MAINTANCE MANUAL
6500 CONFIGURATION CONTROL

7000 SCIENTIFIC SUPPORT

7010 CALTECH SUPPORT
7020 MIT SUPPORT

8000 CONTINGENCY @ 12.5% OF TOTAL INFLATED COST

8010 FY-87
8020 FY-88
8030 FY-89
8040 FY-90
8050 FY-91

FIGURE 4.3-2

PORTION OF THE WORK BREAKDOWN STRUCTURE

3060 SUPPORT ASSEMBLY, VACUUM PIPE						$938,532 *
SUPPORTS/ANCHORS					*	$546,784
SUPPORT, SLIDING	EA	360	$1,150	$414,000		
SUPPORT, FIXED	EA	64	$1,400	$89,600		
ANCHOR, FIXED	EA	14	$1,656	$23,184		
ALIGNMENT	EA	1	$20,000	$20,000		
SUPPORT FOUNDATIONS					*	$391,748
FOUNDATION, SLIDING SUPPORT	EA	360	$650	$234,000		
FOUNDATION, FIXED SUPPORT	EA	64	$1,200	$76,800		
FOUNDATION, FIXED ANCHOR	EA	14	$2,282	$31,948		
FOUNDATION, DBL EXP JOINT	EA	60	$650	$39,000		
ALIGNMENT	EA	1	$10,000	$10,000		
3070 VACUUM PUMP ASSEMBLY						$1,501,000 *
PIPE VACUUM SUBASSEMBLY (4 KM)					*	$862,520
ROUGHING PUMP/BLWRS (600 CFM)	EA	4	$10,800	$34,560	*	
CRYOPUMPS			$22,000	$220,000	*	
CRYOPUMP, 10"	EA	10	$10,500	$105,000		
CRYOGENIC LINES, SET	EA	10	$4,000	$40,000		
ROUGHING PUMP (2 CFM)	EA	10	$4,000	$40,000		
GATE VALVE, 10"	EA	10	$8,500	$85,000		
TUBING/VALVES/FITTINGS	EA	10	$500	$5,000		
ION PUMPS						
ION PUMP, 10"	EA	64	$12,500	$512,000	*	
GATE VALVE, 10"	EA	0	$8,500	$0		
ENCLOSURE, POWER SUPPLY	EA	64	$1,000	$40,960	*	
CHAMBER VACUUM SUBASSEMBLY					*	$345,200
ROUGHING PUMP/BLWRS (300 CFM)	EA	7	$10,000	$50,400	*	
CRYOPUMPS	EA			$154,000	*	
CRYOPUMP, 10K L/S-10"	EA	7	$10,500	$73,500		
CRYO LINES, SET	EA	7	$4,000	$28,000		
ROUGHING PUMP (2 CFM)	EA	7	$4,000	$28,000		
GATE VALVE, 10"	EA	7	$8,500	$59,500		
TUBING/VALVES/FITTINGS	EA	7	$500	$3,500		
ION PUMPS				$140,800	*	
ION PUMP, 1K L/S-10"	EA	8	$12,500	$100,000		
GATE VALVE, 10"	EA	8	$8,500	$68,000		
ENCLOSURE, POWER SUPPLY	EA	8	$1,000	$8,000		
LEAK DETECTION SUBASSEMBLY					*	$90,080
HEAD, RGA	EA	86	$1,100	$75,680	*	
RESIDUAL GAS ANALYZER	EA	2	$7,200	$14,400		
MONITOR & CONTROL SUBASSEMBLY					*	$103,200
GAUGE, IONIZATION	EA	86	$1,500	$103,200	*	
PROGRAMMABLE CONTROLLER	EA	0	$400,000	$0		
NITROGEN SUPPLY SUBASSEMBLY	SY	1		$100,000	*	$100,000
CENTRAL STATION	EA	1	$20,000	$20,000		
END STATIONS	EA	2	$20,000	$40,000		
MID STATIONS	EA	2	$20,000	$40,000		

Figure 4.3-3 Proposed Project Schedule for the Completion of the Conceptual Design and the Detailed Engineering Design Phases (For a Description of Items See Appendix G)

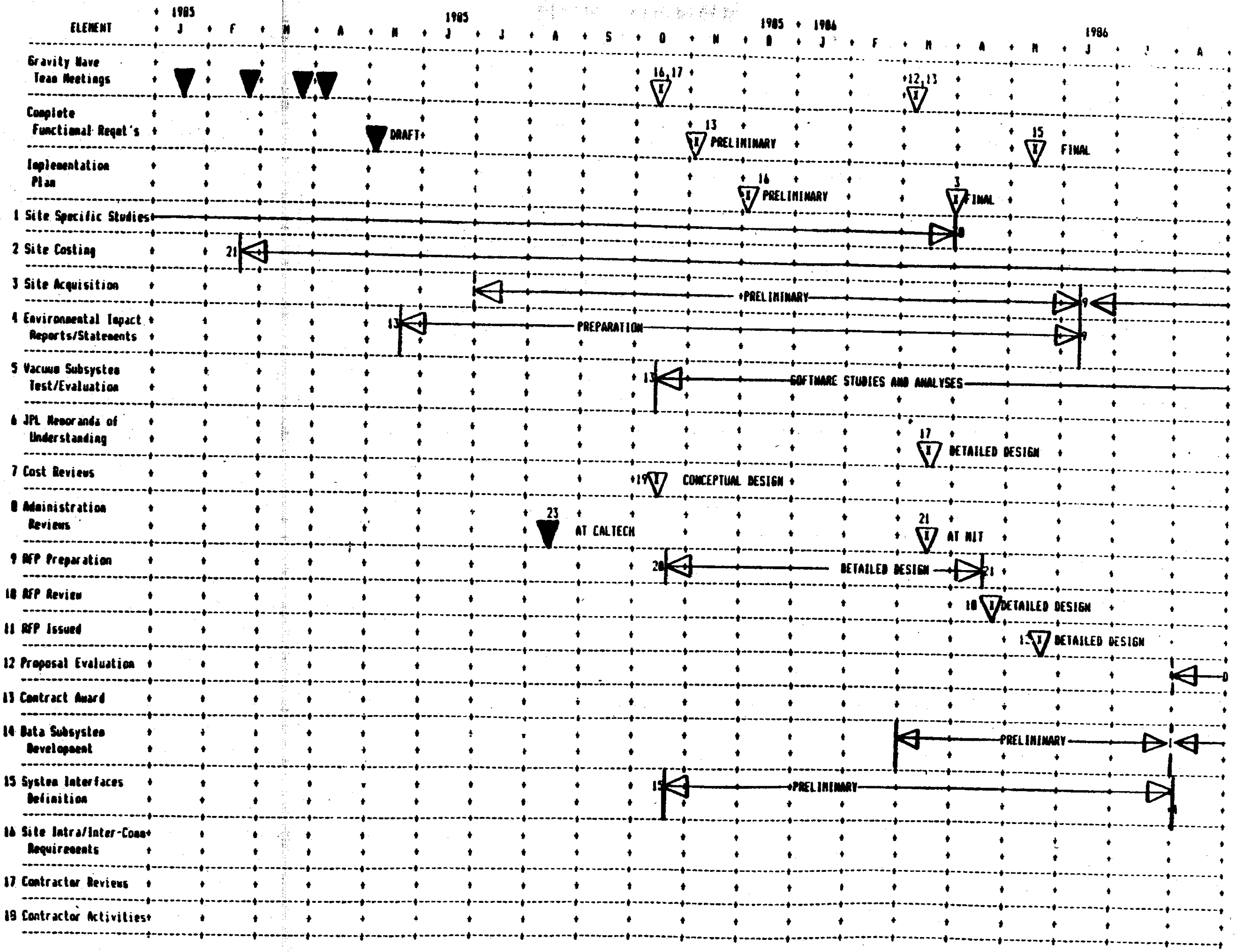
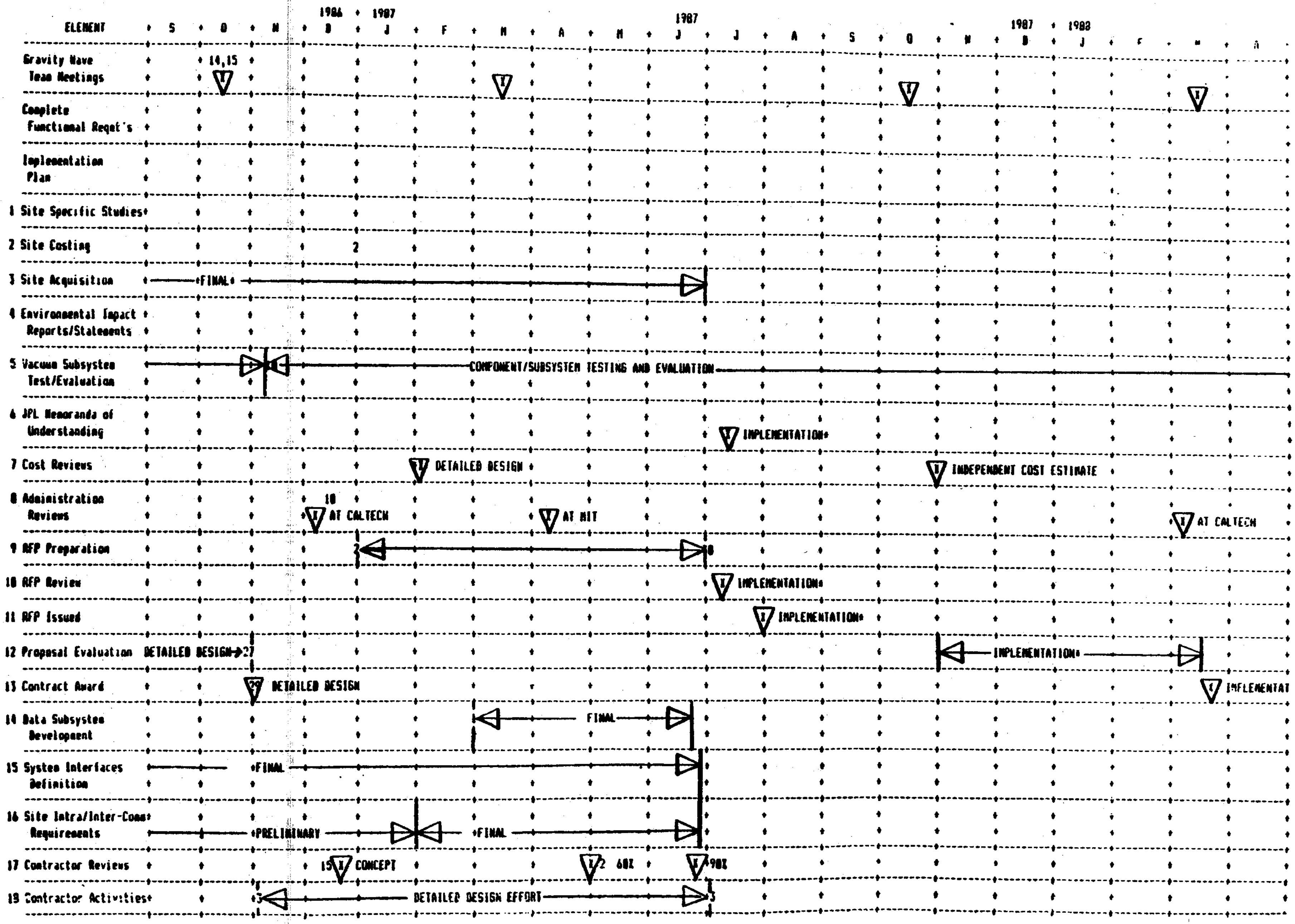


Figure 4.3-3 Continued from previous page.



* If implementation is approved by the NSF

risk. In establishing the conceptual design we have made viable choices, but not necessarily those that minimize cost. Two important examples of these decisions, since both are cost drivers, are the vacuum pipes and the protective cover designs:

The choice of vacuum pipe material, quality assurance in its manufacture, techniques for welding and validating the welding of the material to itself and to the required bellows, and ultimately the ability to locate leaks are all coupled issues which have cost implications. We will continue to explore the trade-offs that can be made to achieve an acceptable level of risk versus cost. During the preparation of the conceptual design cost estimates, we have made conservative choices, but we are not sure that alternative and less costly solutions would entail greater risks. This, in part, is the reason why the vacuum subsystem component testing and evaluation effort is important to us. We intend, when the Project is accepted for construction, to award fixed price contracts for as many elements of the system as practical. The burden of proof of feasibility will therefore be borne by the potential contractors. However, if they do not have a clear understanding of the feasibility of a specific design they will put sufficient contingency in their bids to cover uncertainty. The other extreme is that a contractor may run into an unanticipated problem, and rather than take a loss on the effort, may elect to default on his obligations. In the former case we will pay for the contractor's uncertainty, and in the latter case we will also pay because the delay of any one element will impinge on the schedule of other elements. In addition, it is important that we understand these elements as deeply as the potential contractor would since we must be able to evaluate the ultimate product.

There are many possible cover designs for above and below ground installations. The choices made to date reflect the most promising of these approaches. They have not yet been optimized in an operational sense, which must consider the techniques for assembly of the vacuum subsystem, alignment of the system, or leak detection and repair strategy.

We intend to continue studies of this sort throughout the next year. During the engineering design effort new issues will, no doubt, be raised that will require that we continue our trade-offs.

5. We will hire a Vacuum Engineer as the first technical member of the project office. The vacuum engineer, in coordination with the members of the Caltech and MIT Research Groups and the JPL support team will plan the vacuum subsystem component testing. Although the planning will have been accomplished prior to funding of this proposal, the actual testing can only begin when funds are received.

6. The RFP for the Detailed Engineering Design, will be generated and issued prior to funding availability, but after the NSF has reviewed and approved this proposal. This will enable us to maintain the momentum generated during the conceptual design effort.

4.4 Detailed Engineering Design Activities

4.4.1 Activities of the Detailed Engineering Design Contractor

With the above as a starting point, the final detailed engineering design can be carried out in a coherent manner. The industrial contractor will be asked at the outset to analyze the engineering approach we have taken in preparing a conceptual design to satisfy the Functional Requirements. From the start and throughout the conduct of the detailed engineering design contract, members of the JPL support group, who have developed experience in various elements of the conceptual design, will be resident at the contractor to act both as monitors of the contractor's progress and as interpreters of the Functional Requirements. The contractor will be asked to suggest alternate solutions where cost savings can be affected or where incompatibilities are determined to exist. These suggestions will be compared against the Functional Requirements to determine their influence. If the Functional Requirements are impacted, the Steering Committee will evaluate the change to ensure that they can be accommodated without compromising the proposed investigations.

Shortly after the award of the contract a conceptual or system design review will be held by the Project to ensure that the contractor understands the intent of the contract. Since decisions must be made quickly, the Project Manager will rely on the technical resources of the Project Office, the JPL support group, and the Research Groups (through the Steering Committee), to determine if the contractor's approach will satisfy the Functional Requirements.

This process will result in the final conceptual design. The contractor will then be directed to carry out the detailed design of this approach. The results of this activity will be detailed drawings of all elements of the vacuum and facility subsystems.

A second review, called a 60 percent or preliminary design review, will be held to analyze the detailed designs of the subsystems prior to a commitment by the Project to those designs. Project approval must be given prior to the contractor proceeding with the preparation of final detailed drawings, drawing trees, parts lists, vendor quotes, etc. In this review the elements of the design will be compared with the Functional Requirements to ensure that all requirements have been addressed by the design.

A third review, called the 90 percent or final review, will be used to examine the material defining the detailed design and associated costs. This review is to be conducted prior to completion of the contract so that the contractor can make adjustments to the final data package if required by the results of the final review. The final product is a set of detailed drawings of the system and a plan for the construction of the facilities which includes assembly work flow schedules and detailed estimates of the costs.

The Project will conduct these reviews with the support of JPL. The fact that the detailed engineering design is done in industry necessitates that rapid communication be established to make decisions. The use of resident personnel at the contractor's facility, combined with bi-weekly informal meetings with the contractor, will ensure that decisions are expedited. JPL will contrast, on a continuing basis, the contractor's design against the Functional Requirements. After each of the reviews, the contractor will be given specific authorization to proceed to the next step of his activities.

4.4.2 Vacuum Component Testing Activities

The results of the vacuum component testing and evaluation (Sec. 3) will be given to the potential design contractor as a part of the RFP data packages and during the course of the design. This information is expected to be available in the following order:

1. vacuum pipe weld techniques, including alignment requirements, pipe preparation for welding, weld schedules, and quality assurance of vacuum pipe welds;
2. vacuum pipe cleaning (internal) techniques;
3. suitability of various types of bellows;
4. validation of the approach that we are taking to the bakeout of the vacuum pipe system; and
5. large gate valve suitability and anticipated operational lifetime.

If we uncover problems during our vacuum component testing, we will modify the results of the detailed engineering design as necessary to accommodate them when the tests have been completed. In any case, these data will be carefully analyzed before being issued by the Project Office and the Research Groups at Caltech and MIT to ensure that they are valid.

4.4.3 Project Office Activities

In addition to supervising the contractor, the Project Office, with the support of JPL, will be involved in a set of specific tasks that are important to the design.

A major task is the system integration which establishes in part the interface between the scientific use of the facilities and the engineering.

The interface between the receivers and the facility-provided services must be designed and costed. This includes such items as cabling, connectors, vacuum feedthroughs, mains filtering, mounting locations and the like, which are part of the physical attributes of a laboratory. These will be documented in manuals to allow the scientific groups to design the receivers to a set of established interfaces. A major part of the systems engineering will deal with the design and costing of a data acquisition and facility control system. This system monitors the health of the facility and provides data on the apparatus environment such as seismic noise, temperature, and vacuum level. This data will become part of the received output data streams for veto and correlation in the scientific data analysis.

Another systems engineering function is the design and costing of the communication links within the sites, between sites, and between the sites and the home institutions.

The Project Office, as part of its management function, will continuously update the work breakdown structure as new information becomes available through the detailed engineering design. This will allow us to keep abreast of cost drivers and to anticipate and correct possible difficulties in the design.

Finally, the Project Office will arrange for an independent cost estimate to be carried out between the end of the final engineering design and the decision on the construction. This is a prudent step requested by the Institute administrations and desired by the NSF.

4.4.4 JPL Activities

JPL will be responsible for supervising the detailed engineering design and coordinating all contractor activities; for providing support to the Project; and for conducting an evaluation of the vacuum subsystem weld techniques, weld inspection, pipe interior cleaning, and vacuum bakeout approaches.

4.4.5 Project Milestones

The Project milestones associated with the above activities are shown in Figure 4.3-3 and are discussed in Appendix G.

5. BUDGET ESTIMATES FOR THE DETAILED ENGINEERING DESIGN PHASE

5.1 Introduction

The detailed engineering design phase of the program consists of three interrelated activities: the component development and testing activities discussed in Section 3, the detailed engineering design of the system by an industrial contractor, and the planning and management effort necessary to carry out these activities and plan for construction of the LIGO.

5.2 Budget for the Component Development and Testing

The component development and testing activities discussed in Section 3 will be funded to a maximum of $1,330,000 by the Project Office. The anticipated funding for each of these activities is:

1. Vacuum components testing and evaluation will be performed by the JPL support team under the direction of the Vacuum Engineer. It is anticipated that some of the testing will be accomplished at a contractor's facility and some will be done at a JPL facility. The results of these tests will be used in the detailed design of the vacuum subsystem and at MIT in the assembly of the model vacuum test system. The estimated budget for this activity is $300,000, of which almost $200,000 is for the acquisition of pipe, bellows, valves, pumps, etc. The components used in these tests will subsequently be used in the model system at MIT and in the expansion of the Caltech vacuum system.

2. Development of the model vacuum system for the full-scale facilities will be performed by MIT. The estimated cost of this activity is $222,000, primarily for larger vacuum chambers.

3. As outlined in Section 3, the Caltech group will perform a set of tests of optical and other components in their expanded vacuum system. The cost of this is estimated to be $258,000, primarily for larger vacuum chambers and additional argon-ion lasers to form a high-power laser bank.

4. The balance of the component costs, primarily for development of receiver subsystem components, will be contracted by the Project Office to industrial concerns having the specialized capabilities to perform the research and development activities discussed in Section 3. These expenditures are estimated to be:

a. Mirror development for the Michelson and Fabry-Perot Interferometers	$300,000.
b. Laser development for the receivers	$250,000.

5.3 Budget for the Detailed Engineering Design

The detailed engineering design will be performed by an industrial concern that has the requisite background and experience both with large vacuum systems and with the design and construction of facilities required to accommodate them. A formal Request for Proposal (RFP) will be issued and the responses evaluated to select a contractor or a contractor team to perform the detailed engineering design. The Project Office will, through Caltech, award a fixed-price contract for this design. The conceptual design and functional requirements for the facilities, as developed by the Caltech and MIT Groups, will be specified in the RFP. These conceptual design and Functional requirements will be modified by the Groups in the period preceding selection of a contractor so that the most up-to-date material will be available to the potential contractors.

The estimated cost for the detailed engineering design contract is $2,000,000. This estimate is based on the prior experience of the JPL support team and unofficial, but authoritative discussions with potential contractors for the facilities. Direct oversight of the industrial contractors will be accomplished by JPL working as the contract manager for the Project Office. Scientific oversight and guidance from the research groups will be channelled through the Project Office to JPL and the contractor.

The Project Office will also contract with a consulting firm to produce an independent assessment of the construction cost estimates made by the engineering design contractor. As indicated on the schedule of Figure 4.3-3, this independent assessment will be formally reviewed by the Project Standing Review Board.

5.4 Budget for Project Office and JPL Support Team

The estimated budget for the planning, supervision, evaluation and testing activities during the Engineering Design Phase is $1,670,000. These funds include the completion of the environmental reports on the sites, further analysis of the vacuum system design parameters, preparation of the RFP, evaluation of the potential contractor's proposals, supervision of the selected contractor's efforts, analyses of trade-off studies, award of a contract for the independent cost estimate, travel and miscellaneous expenses, and the direct benefits and indirect costs of the personnel and procurements contemplated in our proposal.

5.5 Engineering Design Budget Summary

The engineering design budget summary is shown in Table 5.5-1. A breakdown on NSF form 1030 (4-83), coupled with an explanation of the entries, is located at the end of this section.

TABLE 5.5-1

ENGINEERING DESIGN PHASE PROPOSED BUDGET

SUBSYSTEM COMPONENT TESTING ACTIVITIES		$1,330,000
VACUUM COMPONENT TESTING BY JPL	$300,000	
MODEL VACUUM DEVELOPMENT BY MIT	$222,000	
OPTICAL COMPONENT TESTING BY CALTECH	$258,000	
RECEIVER MIRROR DEVELOPMENTS	$300,000	
FABRY-PEROT APPROACH	$150,000	
MICHELSON APPROACH	$150,000	
RECEIVER LASER DEVELOPMENT	$250,000	
DETAILED ENGINEERING DESIGN CONTRACT		$2,000,000
INDEPENDENT COST ESTIMATE CONTRACT		$100,000
PROJECT OFFICE AND JPL SUPPORT TEAM		$1,489,000
PROJECT OFFICE	$681,999	
SALARIES AND BENEFITS	$382,194	
TRAVEL	$49,820	
OTHER DIRECT COSTS	$13,737	
INDIRECT COSTS	$234,749	
JPL SUPPORT TEAM	$808,501	
BURDENED LABOR	$406,250	
TRAVEL	$84,000	
CONTRACT SUPPORT	$316,751	
INDIRECT COSTS ON CONTRACTS		$81,000
PROPOSED COST OF DETAILED ENGINEERING DESIGN		$5,000,000

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:

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

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

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

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:

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

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

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

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

where

L = (armlength) = 4 km, $\lambdabar$ = (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,

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

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

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

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

$$\mu \equiv \frac{M_1M_2}{M_1+M_2} = \begin{pmatrix}\text{reduced}\\ \text{mass}\end{pmatrix}, \quad M \equiv M_1 + M_2 = \begin{pmatrix}\text{total}\\ \text{mass}\end{pmatrix},$$

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

$$h(f) \simeq (6\times10^{-19}/\sqrt{\mathrm{Hz}})(1\,\mathrm{Hz}/f)^{3/2}\,\Omega_{gw}{}^{1/2}\,.$$

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[15] 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 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 $\Omega_{gw} \sim (\delta\rho/\rho)_{\text{galaxy seeds}} \sim 10^{-4}$ to 10^{-6}. 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

$$\eta P_0 = 100\,\text{Watts}\,,\quad R = 0.9999\,,\quad \hat{\tau} = 10^7\,\text{sec}\,,\quad L = 4\,\text{km}\,,\quad \bar{\lambda} = 0.1\,\mu\text{m}.$$

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

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

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 $1000 M_{\odot}/(1+Z)$, 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 $\sim 10^{-3}$ 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 $\gtrsim 3\times10^{-10}$ 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

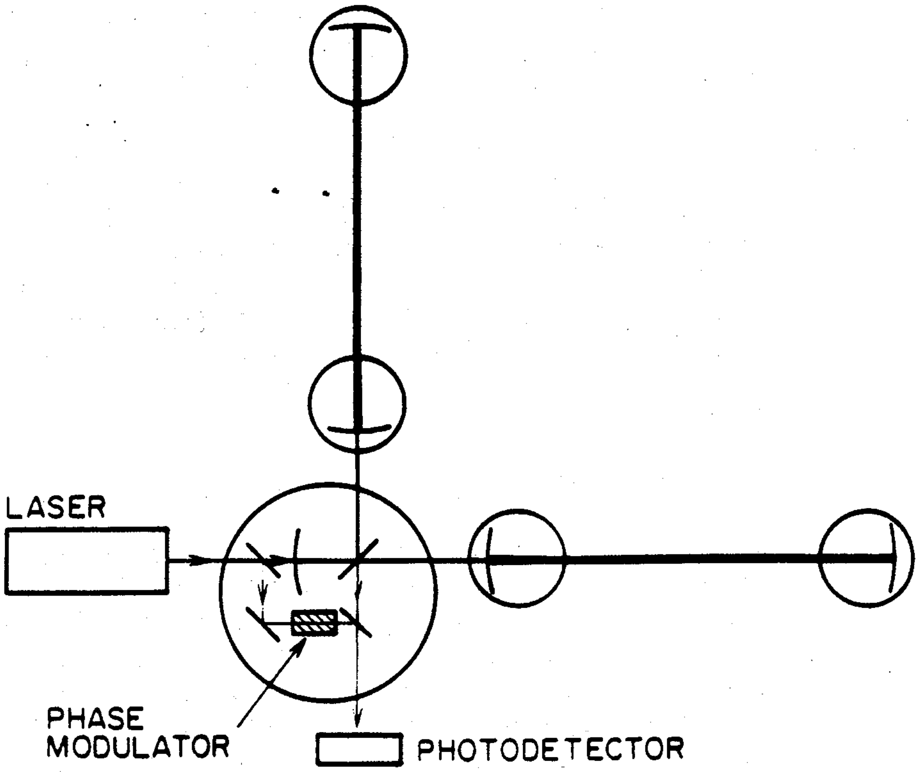


Figure B.1 A practical method of recycling light within a Fabry-Perot cavity in which the Pockels cell modulator is placed outside the cavities to reduce losses.

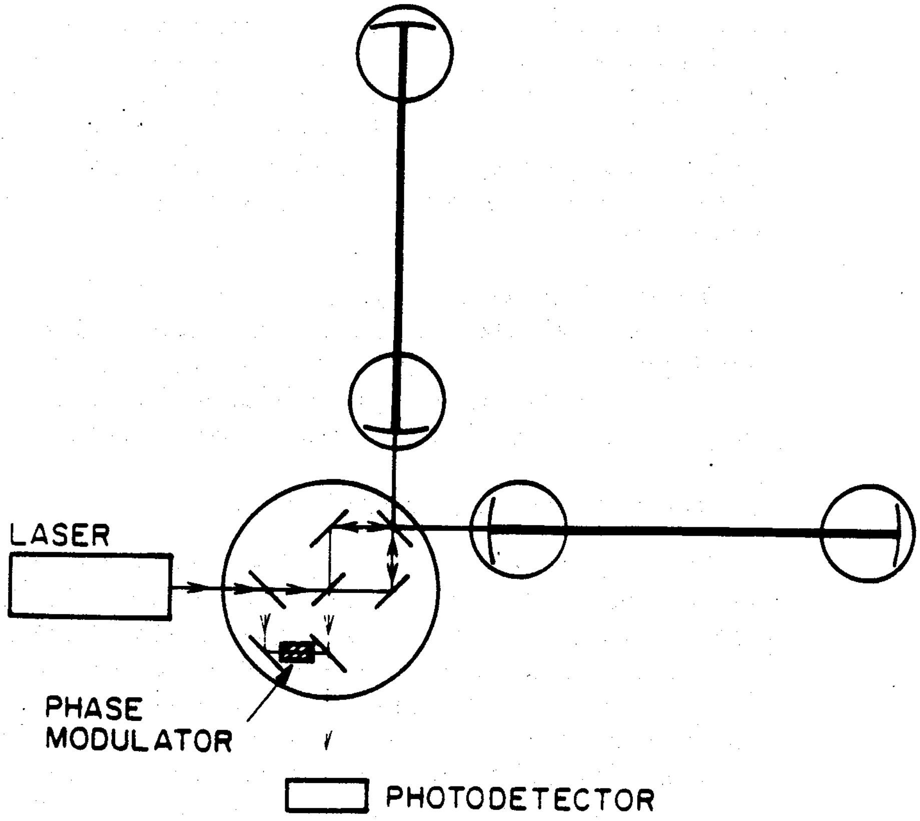


Figure B.2 A low-loss method for enhancing the sensitivity of a Fabry-Perot antenna for periodic signals.

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, 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

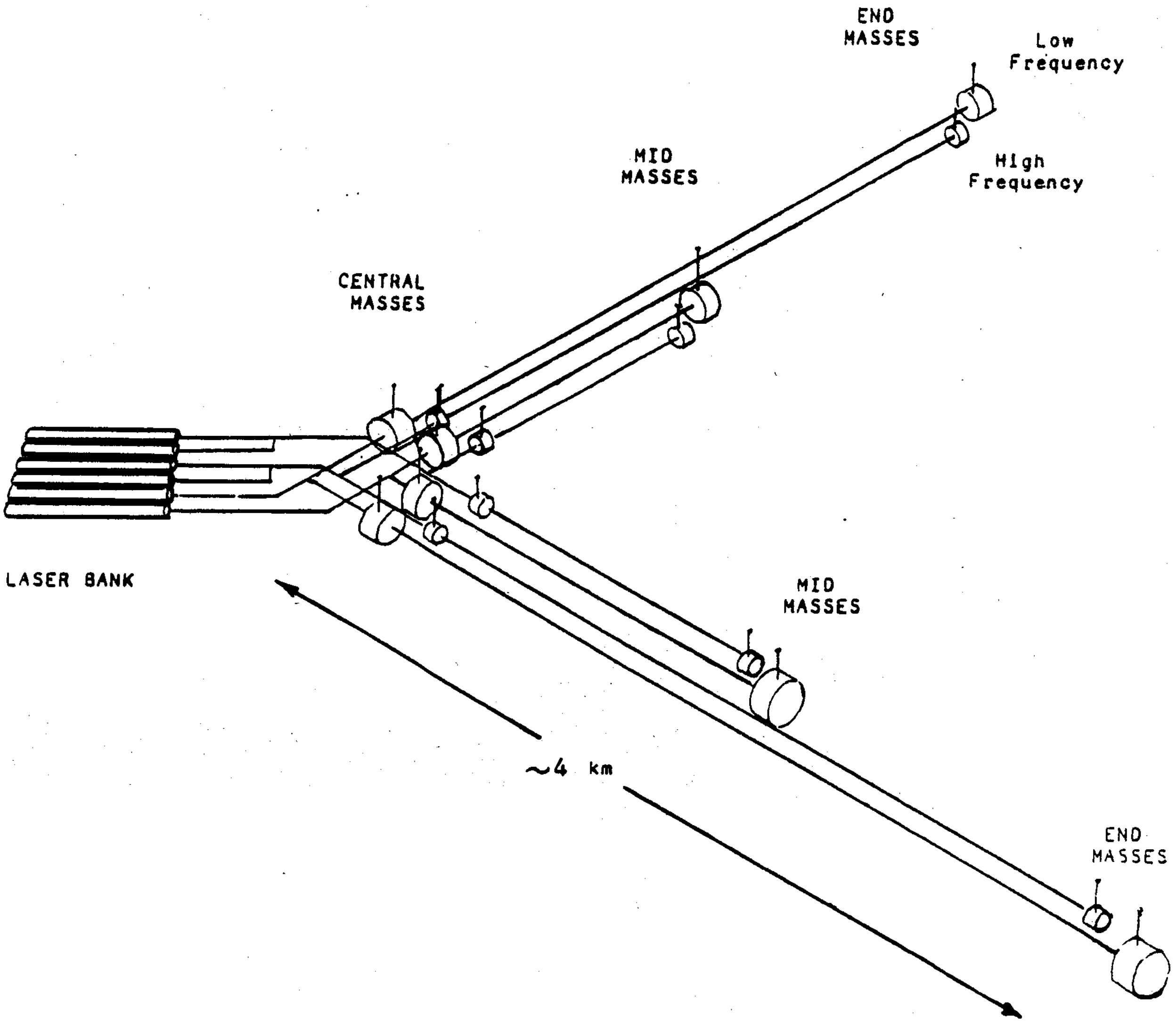


Figure B.3 Example of a possible type of multiple interferometer system. Initially only some of the masses might be installed. Further masses—and possibly more than those shown here, to facilitate periodic searches—might be added later. (Note diagram is highly schematic and not to scale: light beams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

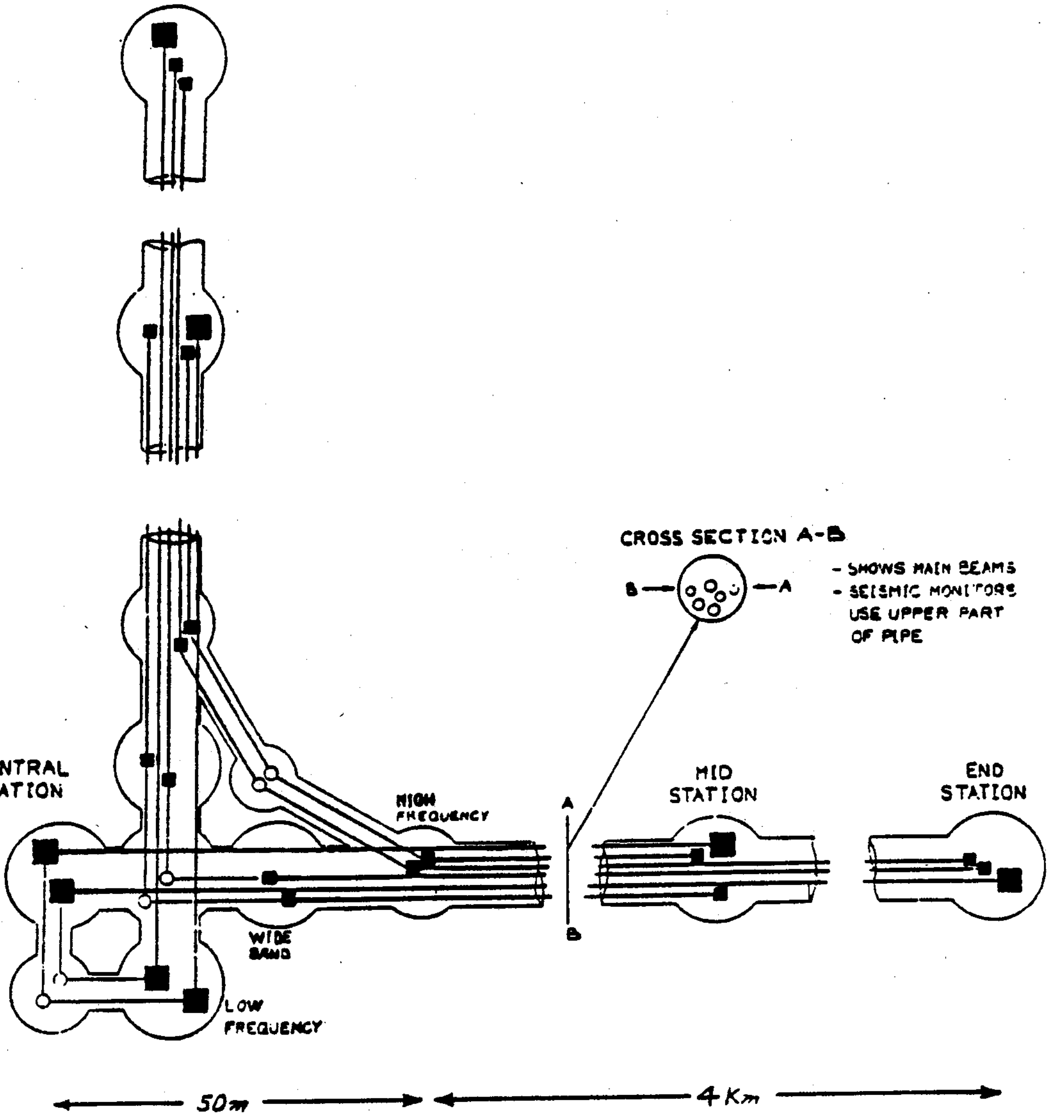


Figure B.4 An example of how large diameter (>1 m) pipe can be exploited to operate many interferometers simultaneously. Depicted here are three seperated detectors, optimized for low frequency (< 100 Hz), high frequency (> 1kHz), and wideband operation. Each detector consists of four interferometers 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

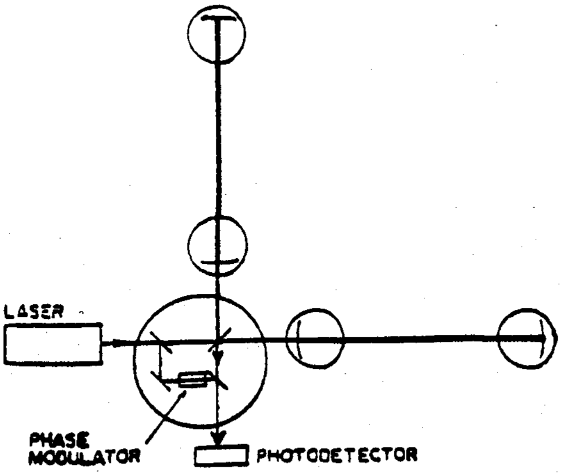
The experimental work we foresee for the LIGO might be regarded as having two partially overlapping phases: the first phase being the exploratory search phase leading to the unambiguous detection of gravitational radiation from one, or more, types of source; and the second being the detailed study and 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.

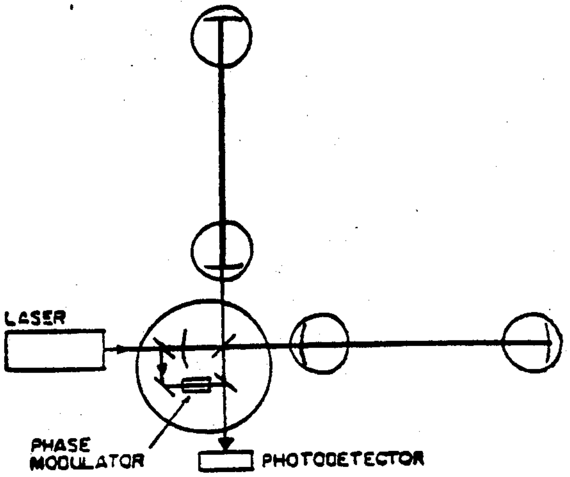
Our present expectations about gravitational wave sources and anticipated detector performance, summarized in Section 1 of this Proposal, indicate that the probability of discovery of gravity-wave signals is likely to depend strongly on the sensitivity of the search performed. And it may be noted here 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.

(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.

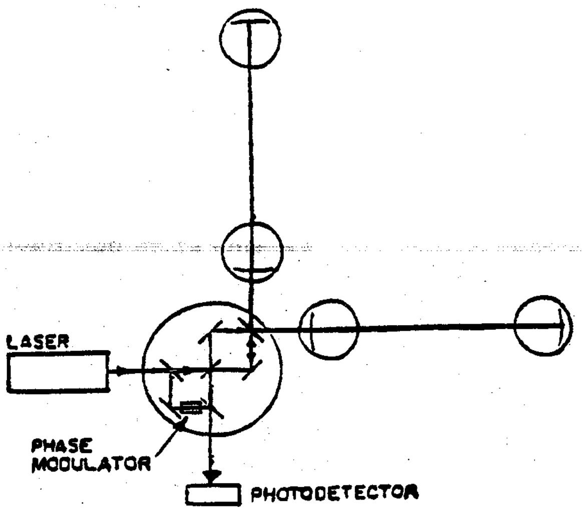


Figure B.5 Gravitational wave detectors designed for different types of experiments, but arranged to have many components in common. (Diagrams are schematic and show principal features only.)

(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.

APPENDIX C
PROTOTYPE RECEIVER RESEARCH AT MIT AND CALTECH

C.1 The MIT Prototype Receiver

C.1.1 Description

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 interferometer is shown in Fig. C.1.1. The interferometer mirrors are attached to masses suspended on pendula with periods of 2 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 frequency band. The interferometer is operated in a vacuum of 10^{-6} torr, 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 reemerges through the same hole by which it entered. The multipass geometry, formed by spherical mirrors, is called a Herriot delay line. The number of beam transits is determined by the mirror radii and their separation. When properly aligned, the optical path length in the arms is first order sensitive to mirror displacements along the optic axis and second order sensitive to all other motions. After leaving the delay line the light passes through electro-optic phase modulators, (Pockel's cells) one in each arm, and is then recombined. Both the symmetric and the antisymmetric outputs are measured on photodetectors.

To determine the fringe motion a 5.3 MHz phase modulation is impressed on the light beams by the electro-optic modulators. When the interferometer is at a symmetry point of a fringe, the photodetector output contains 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 operation. 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. 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

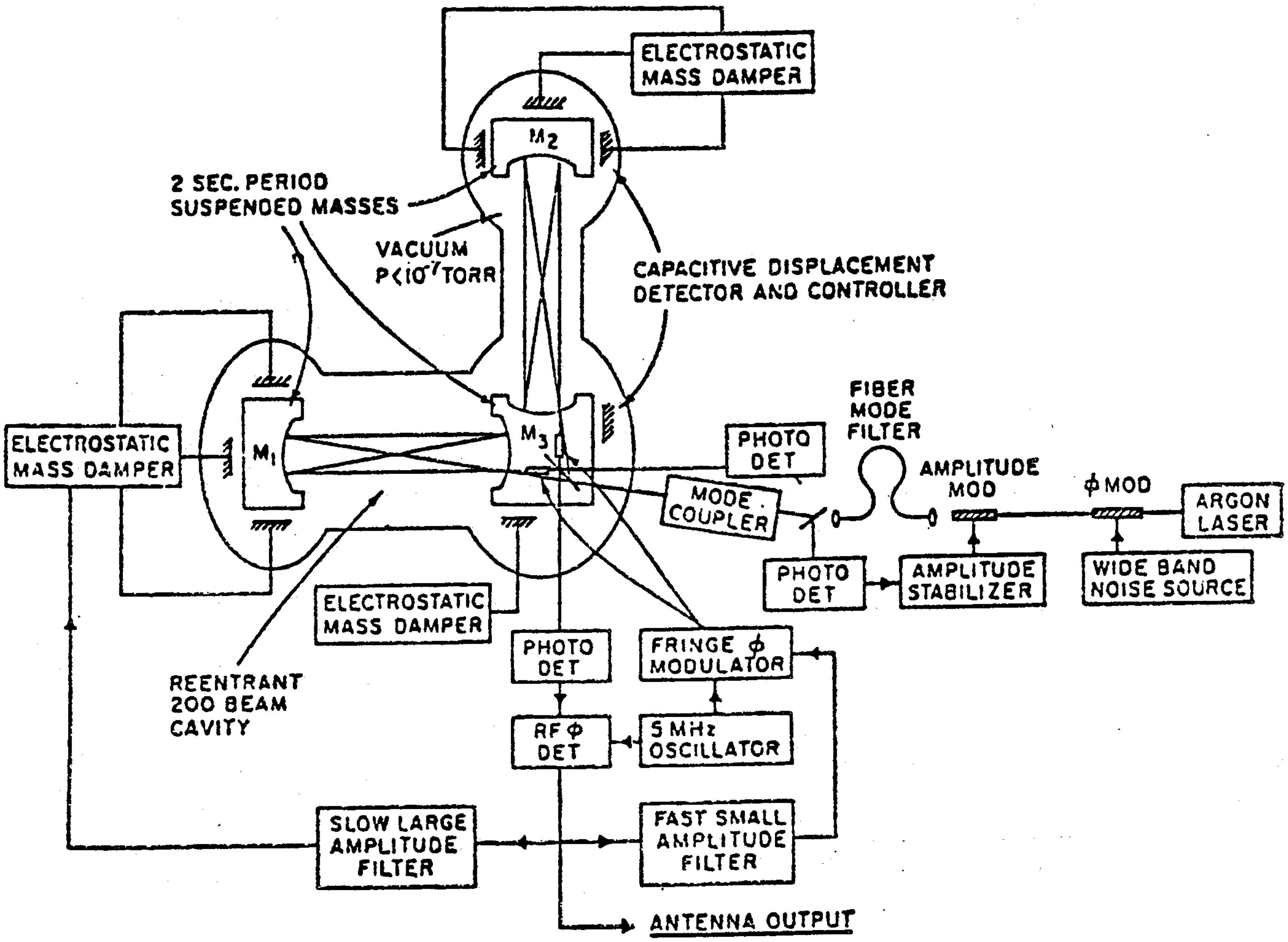


Figure C.1.1. A schematic of the MIT delay line interferometer gravity antenna prototype.

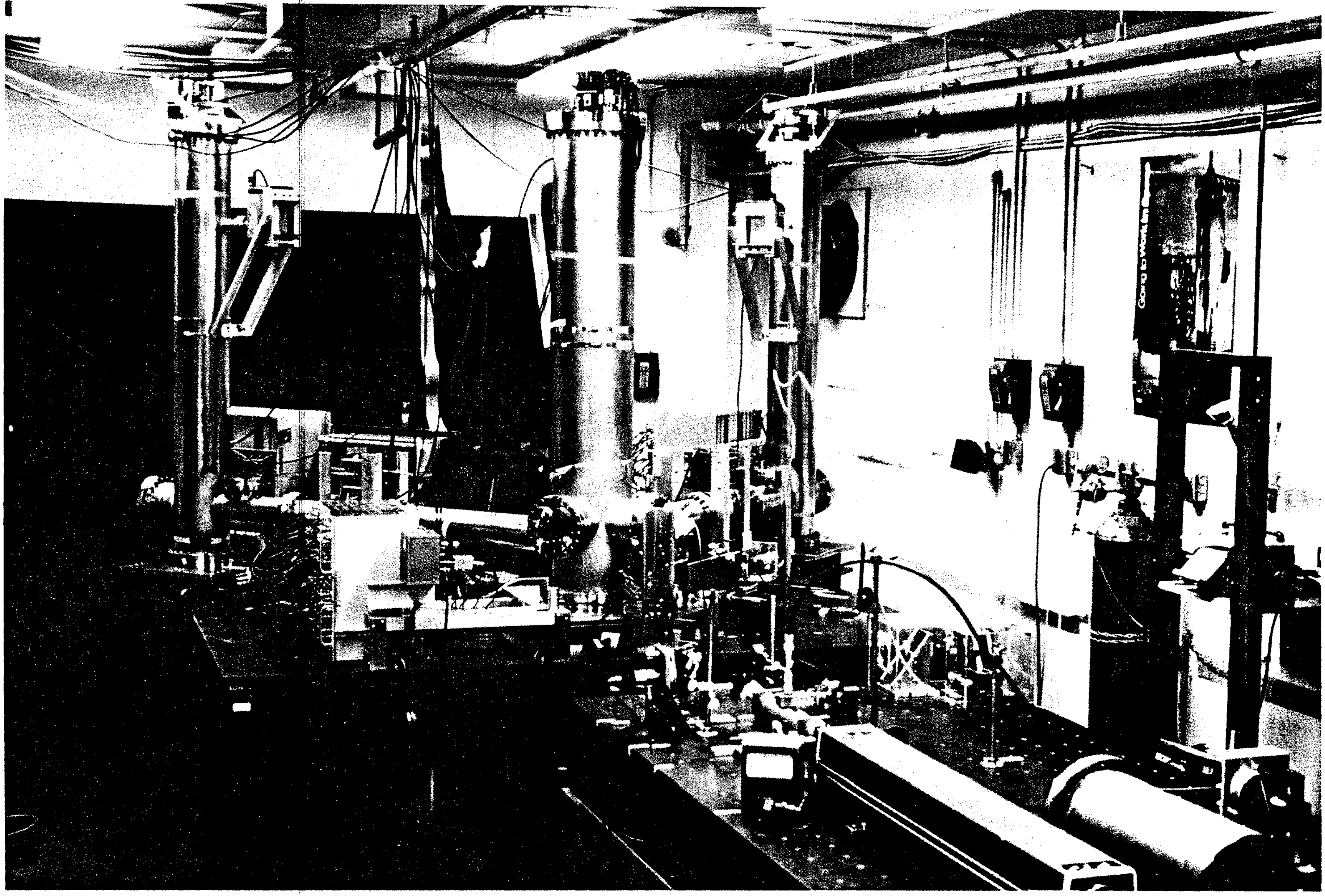


Figure C.1.2 The MIT Prototype Antenna

amplitude fluctuations. It furthermore 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.

The light source is a 1/2 Watt argon ion laser operating in a single mode at 5145 Angstroms. 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 wide band Gaussian or periodic random noise. The 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 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. More importantly, it reduces 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. The residual amplitude noise produced by the fiber can be removed by an amplitude stabilization servo. At present, however, this does not appear necessary.

C.1.2 Present State of the Prototype – June 1985

The main goal of our efforts in the past year has been to bring the M.I.T. prototype antenna to the stage where we could make a serious search for gravitational radiation with the apparatus. We successfully operated the interferometer almost every night for a period of ten days and took sufficient data so that our two graduate students, Dan Dewey, and Jeff Livas will be able to graduate this fall or winter, once the analysis of the data is complete. The improvements to the apparatus covered four areas: mechanical improvements, electronics, optics, and data systems.

Mechanical Improvements.

A major effort of the year was to improve the acoustic and seismic isolation of the interferometer by redesigning the suspension of the mirrors. The original suspension of each mirror was a 1/4 inch aluminum rod attached to an x-y-z-theta stage which was mounted directly on top of a three foot tall vacuum tube. This was found to give inadequate vibration isolation at frequencies below 2 kHz. A new suspension system using a single 0.015 inch tungsten wire to support each mass was constructed. The new stages included improved translation mounts which incorporated elastomer vibration isolators. This gave an improvement in vibration isolation of 10 to 100 in the range 100 to 1000 Hz. A log-log plot of the mass motion versus frequency comparing the original spectrum with a rod suspension and the new wire pendulum is shown in Fig. C.1.3. Direct measurement of the acoustic and seismic isolation of the suspensions appears to indicate that at current sensitivity levels the remaining low frequency noise is not transmitted to the instrument through the suspensions.

Electronics.

It was necessary to make significant modifications to some of the mass damping servos since the torsion time constant of the wire pendulum, 90 seconds, was so different from its pendulation period of 2 seconds, and the dynamic range of the torsional motion was much larger than had been anticipated in the original design of the electronics. Although the servos would stay locked for long periods of time, it was not always easy to achieve lock if the vibration from a large truck or train set a mass swinging out of control. The high vibrational noise environment of the laboratory during the day makes it mandatory to run the apparatus at night in its present state. When the laboratory comes back into operation in the fall (at present there is a large scale remodeling being done) the improvement in the servo system and the use of the air mounted table on which the apparatus is mounted will have high priority. Although neither of these steps should have an effect on the noise performance they will make the apparatus easier to live with.

The phase modulation of the laser light was changed from white noise to digital modulation with a pseudo-random sequence. This was done because the white noise was exciting Pockels cell resonances which in turn generated excess amplitude noise at rf frequencies. The digital modulation only drives the crystal at specific frequencies which can be tuned to avoid the resonances.

Optics.

A new Spectra Physics 2020 Argon Ion laser was installed this year to replace our aging Spectra Physics 165 Argon Ion laser. The new laser had to be modified since it had poorer noise performance than the older model at rf frequencies. It was slightly better than the old laser at low frequencies. We were able to make the laser perform at the shot noise limit above 3 MHz by adding a magnetic field control and by filtering the filament power supply. We were unable to use the full power of the laser due due an unforeseen problem; at powers greater than 250 mW the phase modulating Pockels cell sustained optical damage and dispersed the beam. In order to gain clearance for ease of alignment, the beam inside the crystal has been focused more tightly, than is necessary, resulting in beam intensities higher than 10^3 watts/cm^2. This will be corrected by making the beam diameter inside the crystal larger using different focusing lenses. Other changes were made to the internal optics of the interferometer. A small

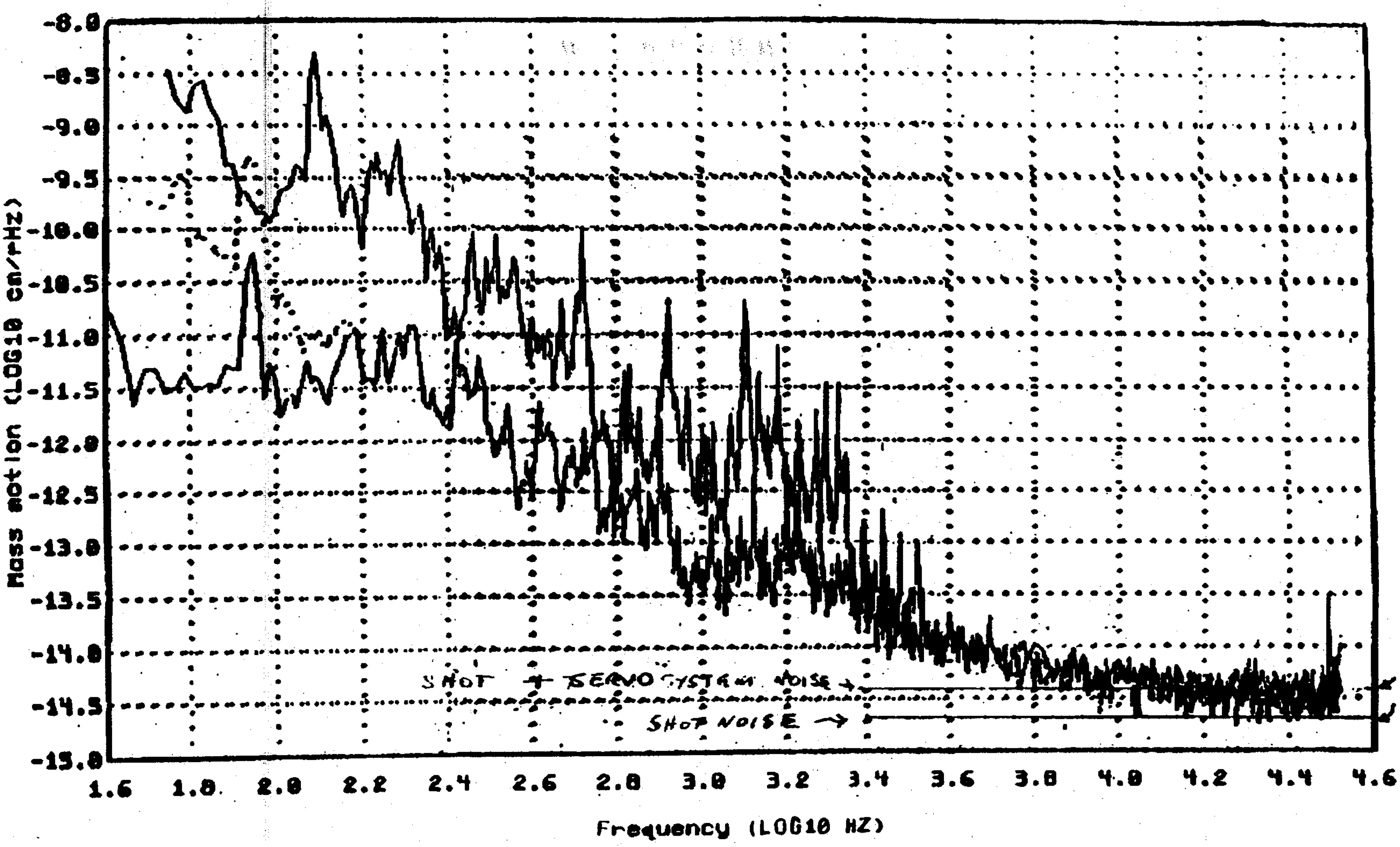


Figure C.1.3 Noise spectra from the MIT instrument showing the amplitude spectral density of displacement noise. To convert to amplitude spectral density of strain one must divide by the length of the antenna arms, 1.5×10^2 cm. Upper noise curve is with old suspensions. Line drawn shows the theoretical noise limit due to shot noise of the light. The power modulated by the interferometer was 26mW using 56 passes of the beam in each arm. Data taken during runs May/June 1985.

iris was added to the entrance/exit hole of each delay line mirror and the alignment was done more carefully. In combination, these two measures reduced the amount of scattered light in the interferometer significantly. Lossy optical elements were identified and will be replaced to improve the overall optical throughput, which is now 12%. Currently, all our experiments are performed with an etalon in the laser cavity so that the laser only oscillates at a single frequency. The etalon costs about a factor 2 to 3 in the output power of the Argon laser but is needed to avoid the amplitude noise of mode competition which has components at RF frequencies. In part to increase the output power of the argon laser but more importantly to test the concept for use in Nd:YAG systems we carried out a quick experiment to determine if mode locked laser light could be used in the prototype. The results appear very encouraging but not yet definitive.

We have begun research on high power fiber optics. The EOTEC company has manufactured a 10 micron diameter single mode fused quartz fiber for us that is now being tested for its power carrying capability and optical properties.

Data System and Run.

During the past year we built a data taking system useful for a search for gravitational radiation that allowed us to take data at sampling rates up to 100kHz to magnetic disk and up to 20kHz to disk or magnetic tape. The data were taken with two A/D's: a slow A/D, multiplexed to sample 64 channels, which was used to take data from slow servos such as the mass dampers, and a fast A/D which sampled the output of the interferometer and could be multiplexed to 8 channnels if desired. A fair amount of software development was required to make all of this work.

Approximately 900 minutes of data were taken over a period of 6 nights in a search for pulsed and periodic sources of gravitational radiation. The data taking had to be done at nights and on weekends because of the laboratory's proximity to a busy city street. The A/D triggers for the data taking were derived from a rubidium atomic clock with stability of a part in 10^{11}. This will ensure phase stability in a search for periodic sources of radiation. The clock was also synchronized to WWV to allow us to make a search for pulses in coincidence with the Stanford bar group, which was also taking data while we were on the air.

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 are ground to a curvature radius of 62-meters and 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 evacuated to 2×10^{-3} torr. (see Figure C.2.2). Pipe flanges are joined with metal seals; by adding pumps the detector can operate at much lower pressure if performance becomes limited by effects of residual gas.

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 mirrors has sidebands due to the modulation, but the sidebands are stripped off the light which is stored in the narrow bandwidth (200 Hz) cavities. The phases of the stored and reflected pieces of light incident on the photodetector are compared,

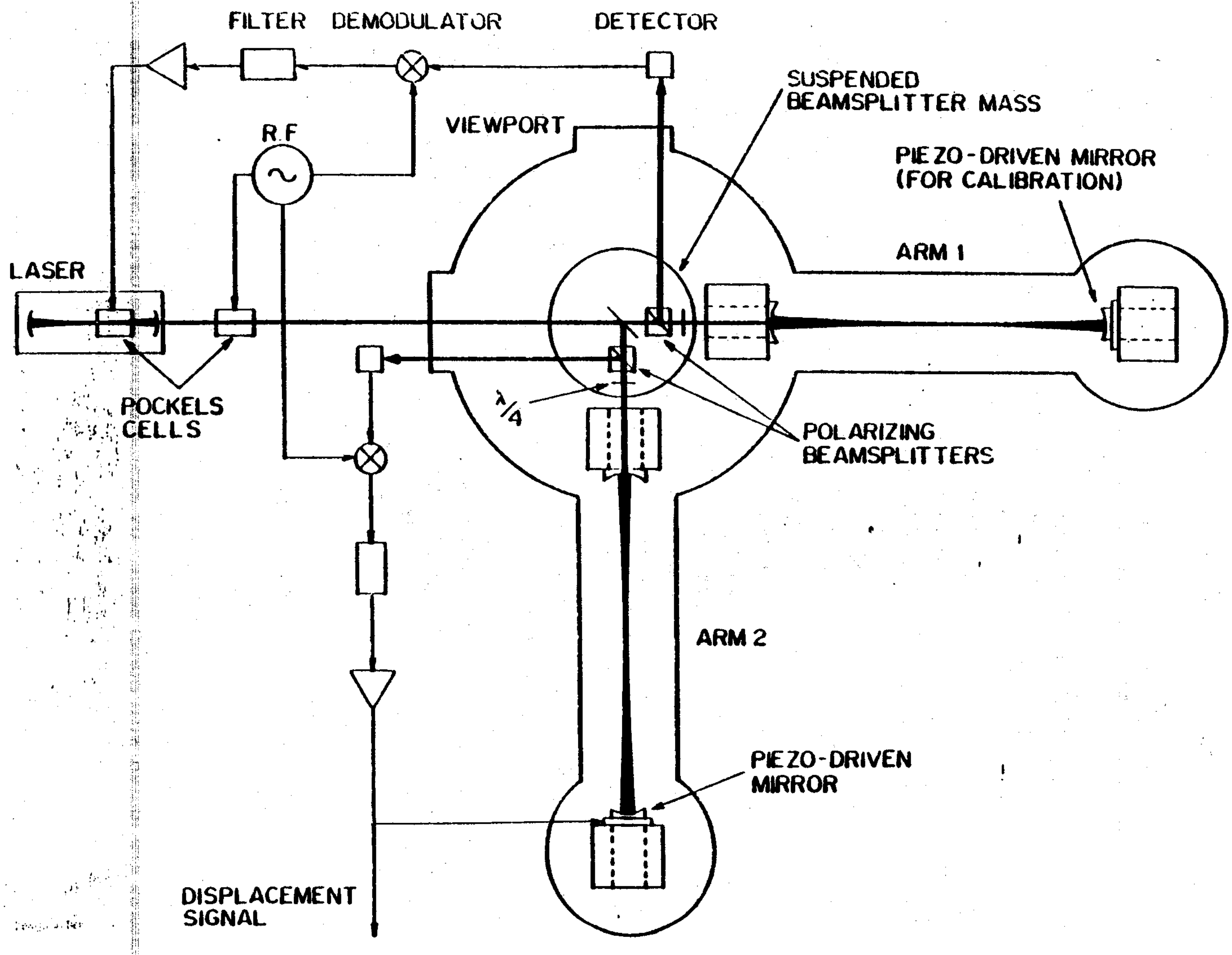
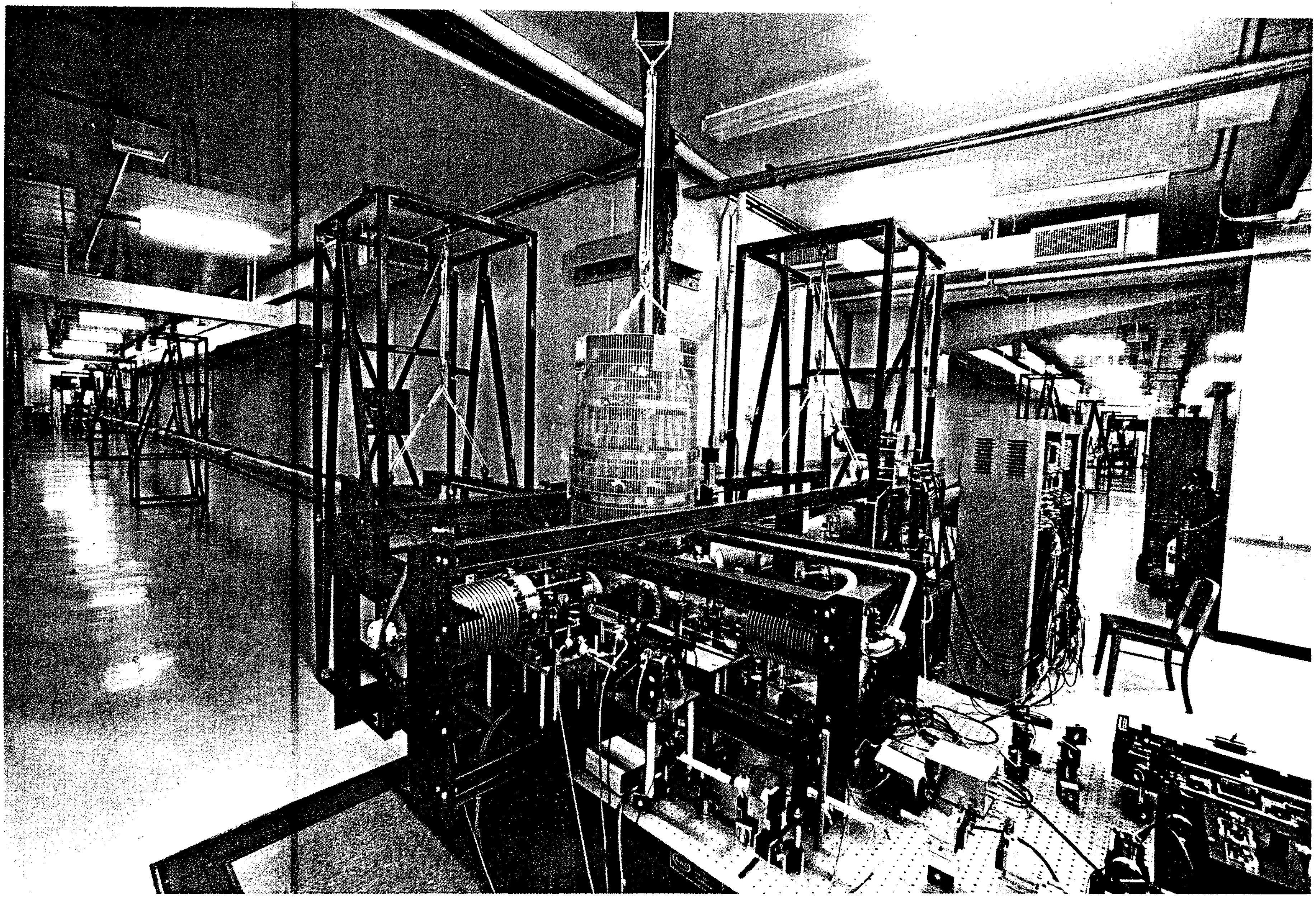


Figure C.2.1. Schematic diagram of the Caltech 40 meter prototype. The interferometer uses five suspended masses inside the vacuum chamber-- four to carry the mirrors which define the ends of the two arms and one to carry the beamsplitter and associated optics. Radio-frequency phase modulation is used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



and the difference signal controls the frequency of the laser and lengths of the cavities to maintain resonance.

Low-frequency control of the orientation and longitudinal position of the masses is provided by multi-wire suspensions. Mass orientation is monitored by 40-meter long optical levers which use the cavity mirrors to reflect beams from low-power He-Ne lasers onto position-sensitive photodiodes. The signals from these photodiodes are attenuated at frequencies below 30 Hz and fed back to coil-and-magnet transducers which exert forces near the suspension points, fixing the angular degrees of freedom of the masses to within a microradian. Longitudinal motion is measured at all frequencies by separate ground-referred devices mounted below each test mass which synchronously detect the shadow of the test masses in the illumination field of modulated LED's; feedback signals to maintain optical resonance are applied to piezoelectric stacks which push and pull on the cluster of suspension wires, controlling the longitudinal position of the test masses.

Several stages of seismic 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 2.5 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 = 4×10^{-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-Hz$^{-.5}$ and in strain-Hz$^{-.5}$. Also shown is the theoretical performance, limited

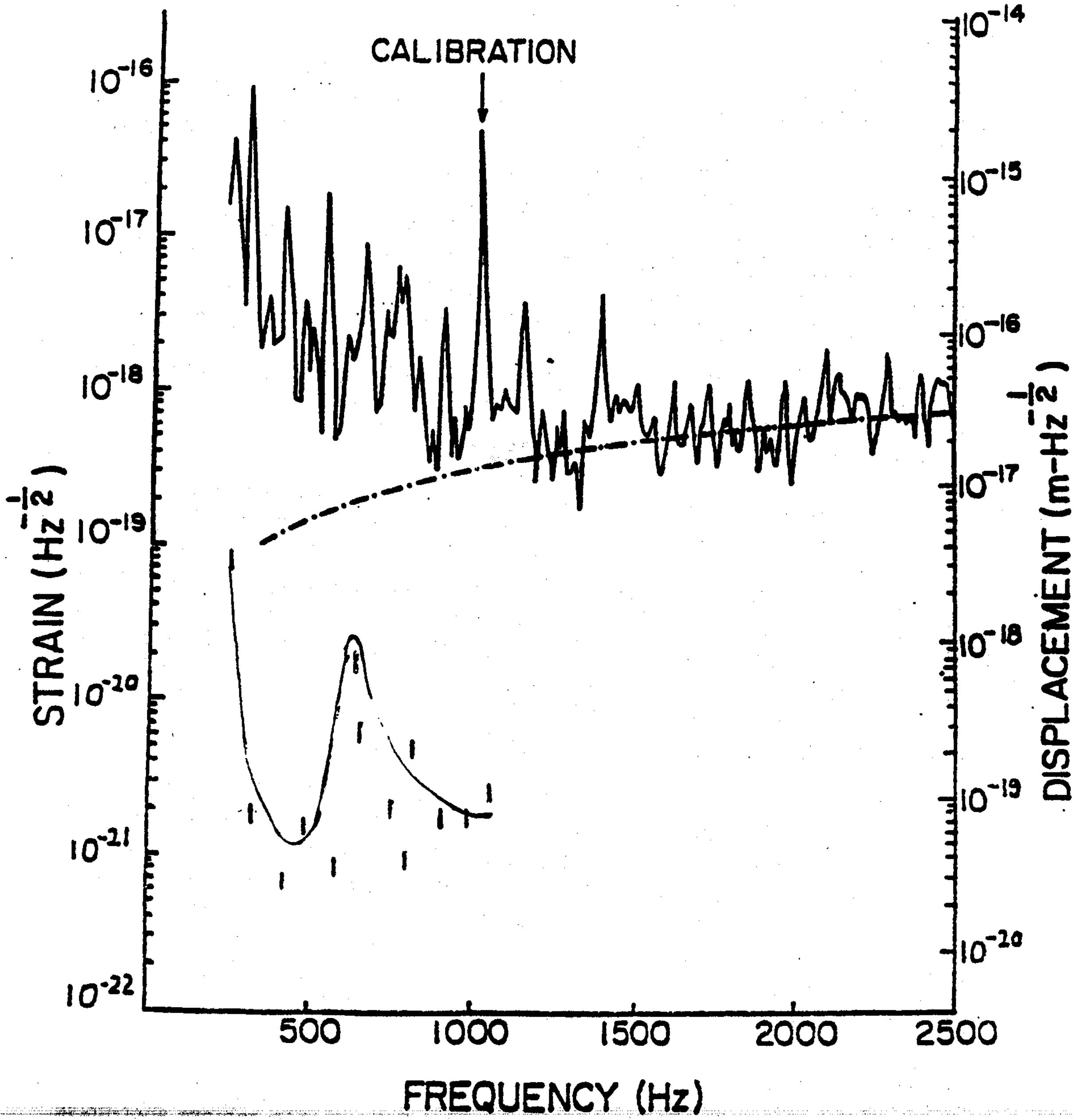


Figure C.2.3. Noise spectrum of the Caltech prototype antenna, calibrated in strain (Hz $^{-.5}$) and displacement (m-Hz$^{-.5}$). The upper curve is the measured noise. The portion of the spectrum below 250 Hz was not well calibrated in this measurement and has been deleted. Many of the peaks below 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.

only by photon shot noise. The shot noise calculation, based on 1 mW of light power incident on each photodiode and 50% quantum efficiency, was checked by an independent calibration of the system response. The observed noise is within a factor of two of shot noise at frequencies above 800 Hz. Near 1 kHz the displacement sensitivity is $2 \times 10^{-17} m/\sqrt{Hz}$, and the strain sensitivity is $5 \times 10^{-19}/\sqrt{Hz}$.

Improvements Underway

In the region of the spectrum limited by shot noise, the sensitivity is expected to increase with the square root of the laser power. Preliminary trials with higher power have yielded a reduction of the high-frequency noise below the level shown in Figure C.2.3. A new laser capable of five watts of single-frequency output (more than a factor of 100 greater than the power used in the spectrum of Fig. C.2.3) is scheduled to arrive in the Fall of 1985, and will be installed in the prototype after modification to accommodate active frequency stabilization. The efficiency of the optical chain external to the cavities has been improved recently, and further increases in effective light power are achievable by increasing the visibility of the two optical fringes. Fringe visibility can be increased by installing input mirrors of slightly higher transmission or by optically combining the two arms. The result of higher laser power and improved fringe visibility expected in early 1986 will be reduction of the shot-noise component of displacement noise to $5 \times 10^{-19} m/\sqrt{Hz}$, a factor of two better than required for the mid-1987 sensitivity milestone tabulated in appendix I. The corresponding strain sensitivity is $1 \times 10^{-20}/\sqrt{Hz}$, more sensitive than any existing gravitational wave detector.

Efforts underway are intended to identify and eliminate the sources of low frequency noise in excess of shot noise. Below 100 Hz performance is possibly limited by seismic noise, and between 100 Hz and 1 kHz fluctuation in the geometry of the laser beam is believed to be an important noise source. Optical fibers will soon be installed to reduce geometry fluctuations, in the same manner as fibers were first used successfully at MIT and Garching. Additionally, an automatic cavity alignment sensing and control system has just been built. The system senses the optical phase of the resonant light across the wavefront, and extracts signals to control orientation of the masses. Early tests are encouraging: the alignment is maintained to higher accuracy and with less drift compared to the 40-meter optical levers. In addition to controlling the masses, the signals can also be used to actively steer the laser beam, reducing fluctuations beyond the reduction afforded by the fiber.

Noise sources which are not presently limiting performance, such as seismic motion at 1 kHz and laser intensity fluctuation, are under continuing investigation. These hidden noise sources are uncovered by artificially enhancing them--for example by shaking the vacuum tanks or by modulating the laser intensity--to a level strong enough to appear as noise added to the interferometer displacement signal. The enhanced motion is compared to the naturally occurring motion, indicating the headroom available above the hidden noise sources. The ability to identify noise sources before they limit performance has proven useful for planning improvements to the Caltech prototype.

Specifically, a test of seismic isolation recently 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. These results are preliminary as of this writing (August, 1985) and are currently being checked. The seismic shaking test implies that the isolation now in place will suffice until large reductions are achieved in other noise drivers, especially shot noise. (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 in Fig. C.2.3.)

As well as separating unimportant from important noise sources, measurements of this sort aid in predicting the performance of larger detectors. 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}. In terms of milestones, the data of Fig. C.2.3 demonstrate that the seismically induced noise specification for the end of 1986 has already been surpassed. 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.

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 strain spectral sensitivity 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. Their current research on the 30 meter system is focused on understanding the rise in the noise below 500 Hz.

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.

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

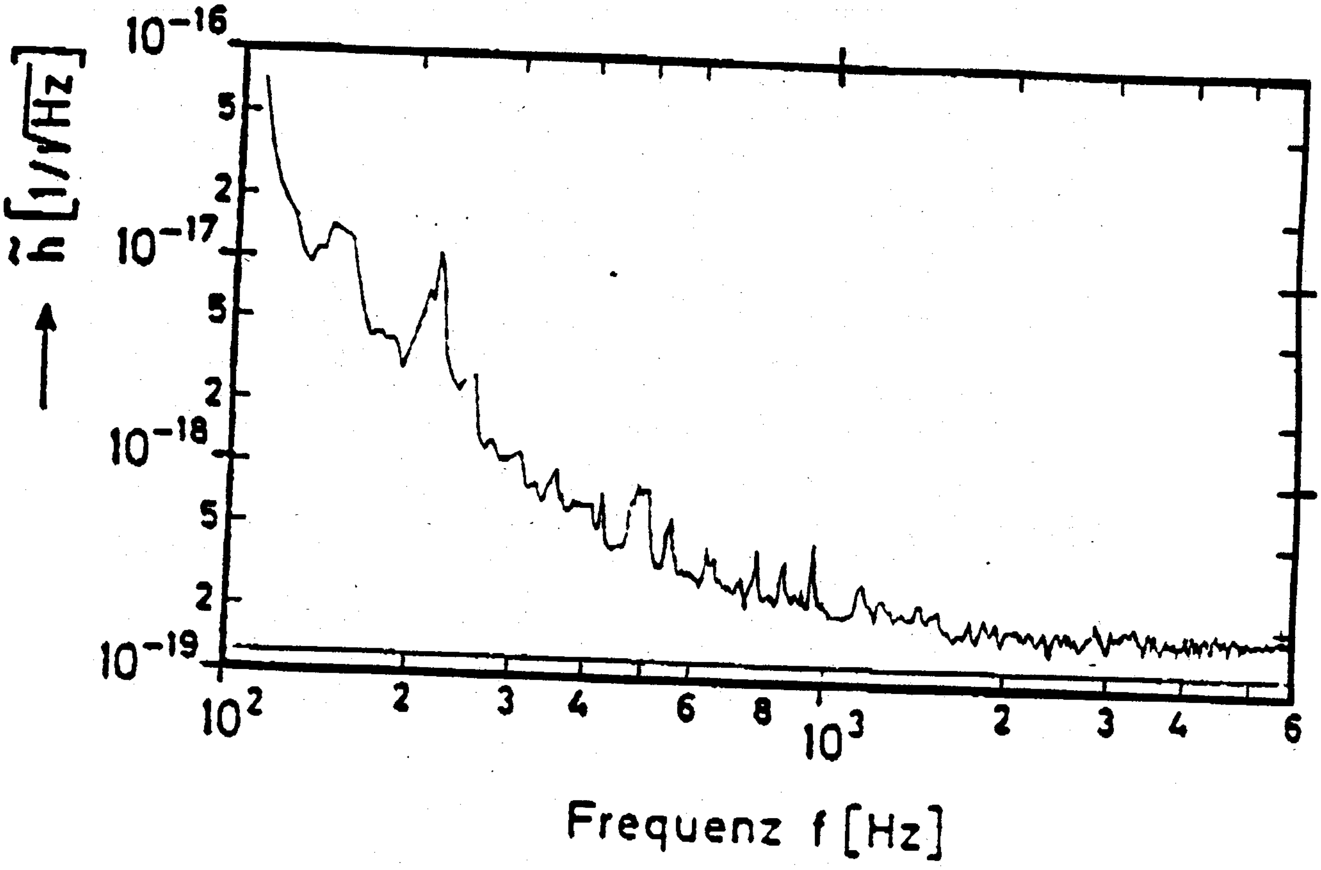


Figure D.1.1 Amplitude spectral density of strain of the 30 meter prototype at the Max Planck Institute.

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.

Commercially available mirrors with relatively large losses are currently used in this interferometer, but until recently the sensitivity achieved[29] (Figure D.2-1) has been better than that of any other Fabry-Perot system, and is essentially at the photon shot noise limit for the mirrors and the light power used at all frequencies between 500 Hz and 10 kHz. It has currently been overtaken by the Caltech 40-m interferometer, however, with the installation of mirrors having losses lower by two orders of magnitude in the latter instrument.

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.

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

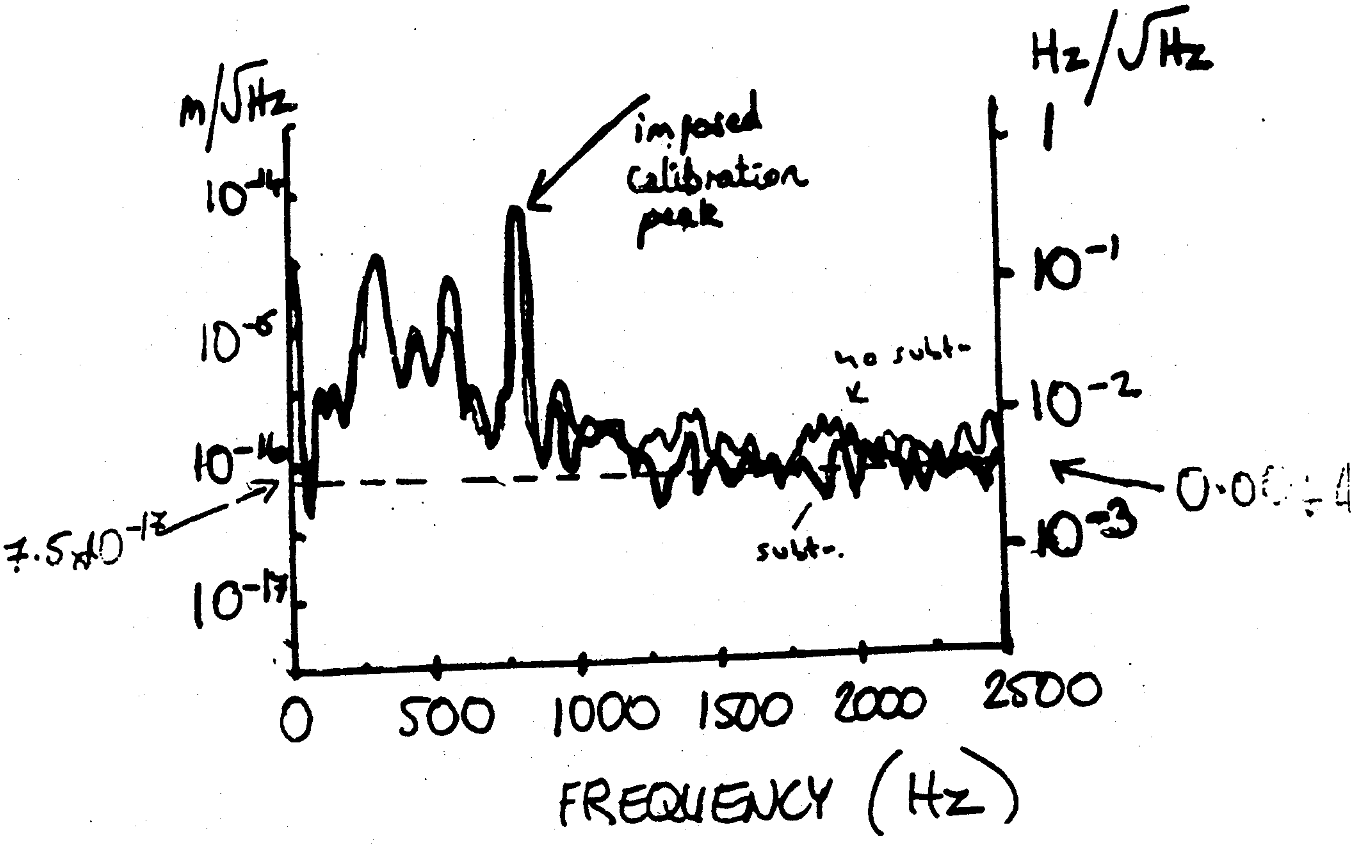


Figure D.1-2. Spectrum of noise in the 10-meter Glasgow Fabry-Perot detector, demonstrating shot-noise limited sensitivity with 5 mW of laser light on each photodiode, and cavity finesse of 200. The left-hand calibration indicates equivalent displacement noise of the test masses, and the right-hand calibration shows the antecedent frequency noise in the highly stabilized laser.

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 (contained in Appendix F) 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 required.

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 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.

E.3.1 Site Surveys

JPL, using much of the material generated during the MIT Study, made on site assessments of the potential locations for the LIGO to a set of criteria established by the Research Groups. These criteria included the following:

(1) Accessibility

Travel time to site; Availability of local housing and facilities; Ease of local travel to site; Location with respect to air service.

(2) Construction Suitability

Rail receiving; On-site facilities; Nearest access road; Distance to major power lines; Road construction or relocation requirements; Local labor rates (from National Construction Cost Estimator); Borrow and waste areas; Subsurface conditions; Topographical conditions.

(3) Environmental Suitability

Flood; Climatic conditions; Subsurface conditions; Water supply; Seismicity; Acoustic noise.

(4) Acquisition Requirements

Ease; Surrounding area development potential; Environmental impact report requirements; Mining operations; Existing site security; Facility expansion capability.

Approximately 30 sites were investigated and, based on the criteria listed above, the following sites were determined to be prime candidates for large scale system implementation:

(1) Western Sites:

Edwards Air Force Flight Test Center, California**
Goldstone Tracking Station, Ft. Irwin, California*
White Sands Missile Test Center, California
Fort Bliss, New Mexico
Idaho National Engineering Laboratories, Idaho*

(2) Eastern Sites:

Fort Stewart, Georgia
Eglin Air Force Base, Florida
Easton, Massachusetts
Cherryfield, Maine**
Saponac, Maine

The sites marked with a double asterisk were selected by the Gravity Wave Steering Committee to be the prime East and West coast sites. The sites marked with a single asterisk are backup sites, which would be considered further in the event a prime site was unavailable. Detailed documentation of the site analysis performed by JPL was submitted to the Steering Committee for reference in making their selection of prime and backup sites for the facilities. It should be noted that the Idaho National Engineering Laboratory site is a backup for both the Western and Eastern sites since it is over 1000 kilometers from both of the prime sites.

Figures E1 and E2 show the antenna facilities laid out at the two prime sites, Edwards Air Force Base in Palmdale, California; and Columbia, Maine. The relative orientations of the LIGO legs at the two sites are chosen to give the maximum probability of equally sized strain amplitudes when averaged over a random distribution of sources on the sky. The optimum relative orientation is the obvious one where one "L" is the projection onto the other in 3 dimensions, since the earth does not shield gravitational radiation.

Figure E3 shows the distribution of detector responses to a random sample of sources when the two sites have different relative orientations. The orientation angle is the rotation of one antenna relative to the other about the line joining the two antennas, subject to the constraint that both antennas lie locally in a horizontal plane.

Seismic and acoustic spectra have been taken at the two prime sites, Figure E4, as well as at other possible sites. Also shown in this figure are the seismic noise spectra in the present prototype laboratories at MIT and Caltech and the spectra from the quietest known surface location in the US at Lajitas, Texas. None of the proposed sites lie on known active faults.

Specific properties of the two prime sites make the facilities different in the following ways. Edwards Air Force Base is the site of the JPL Rocket Test Facility. This facility has the infrastructure of a well-equipped laboratory: machine shops, laboratory space, garages, electronics rooms, offices, sleeping quarters and a cafeteria. The antenna is placed close to this facility so that there is no need to construct support buildings at this site. To minimize costs and achieve maximum flexibility, the gravitational wave facilities will be placed above grade, Figs. E5 and 1.1, but covered to eliminate wind loading and the temptation to shoot at it, as well as to provide some measure of thermal control. The proposed location of the LIGO facility at Edwards is near a dry lake which occasionally has shallow floods, and the soil nearby is strongly alkaline and corrosive.

The Columbia, Maine site is in the native blueberry barrens of northeastern Maine. The site is actively farmed with peak activity for 3 weeks in August. For most of the year it is almost unpopulated. The barrens lie on a mesa 280 feet above sea level formed of fine glacial till. There is no history of flooding in part because of the altitude and the excellent drainage in the soil. The soil is slightly acidic. The state of Maine has strong restrictions on the disturbances permitted to the environment, and we have been advised to make the facilities as unintrusive (invisible) as possible. The favored construction strategy in Maine (Fig. E6a, E6b) is to bury the system in a culvert. Although there is ample power and well water at the Maine site, it is otherwise undeveloped. The conceptual design includes support trailers and the acquisition of a building in Cherryfield for offices and quarters.

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

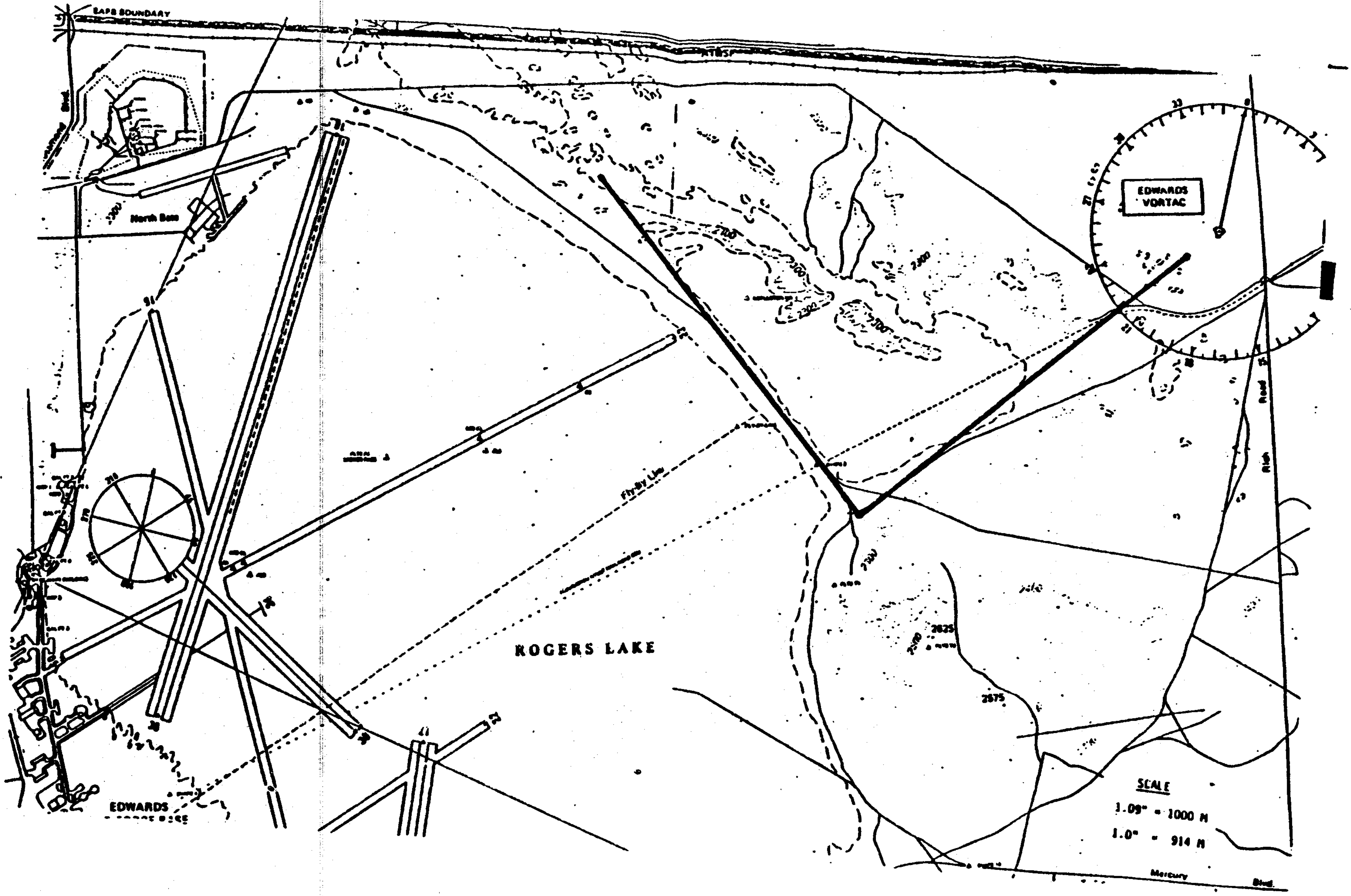
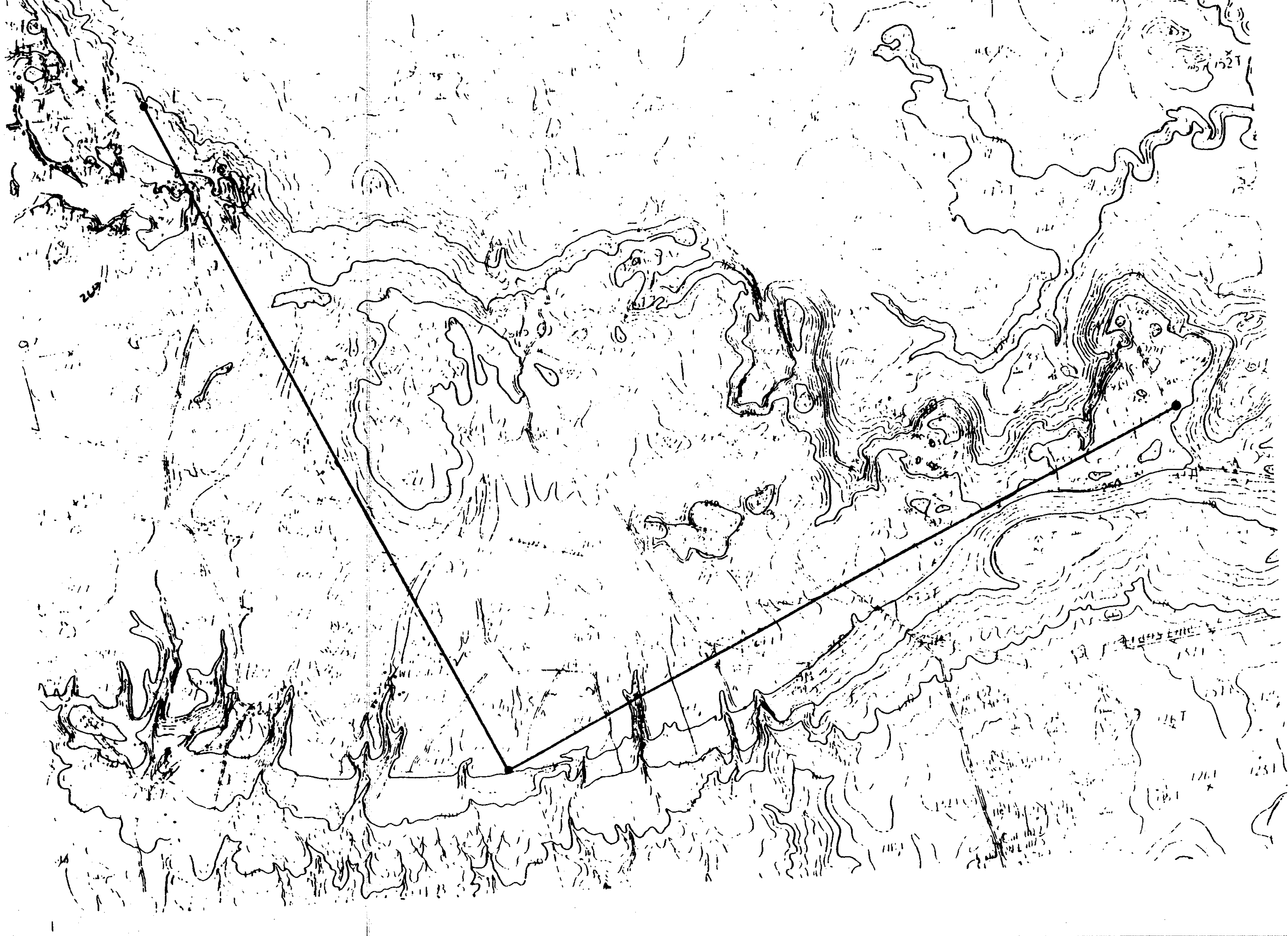


Figure E.2 Optimal Orientation of LIGO at Cherryfield / Columbia Falls, Maine.



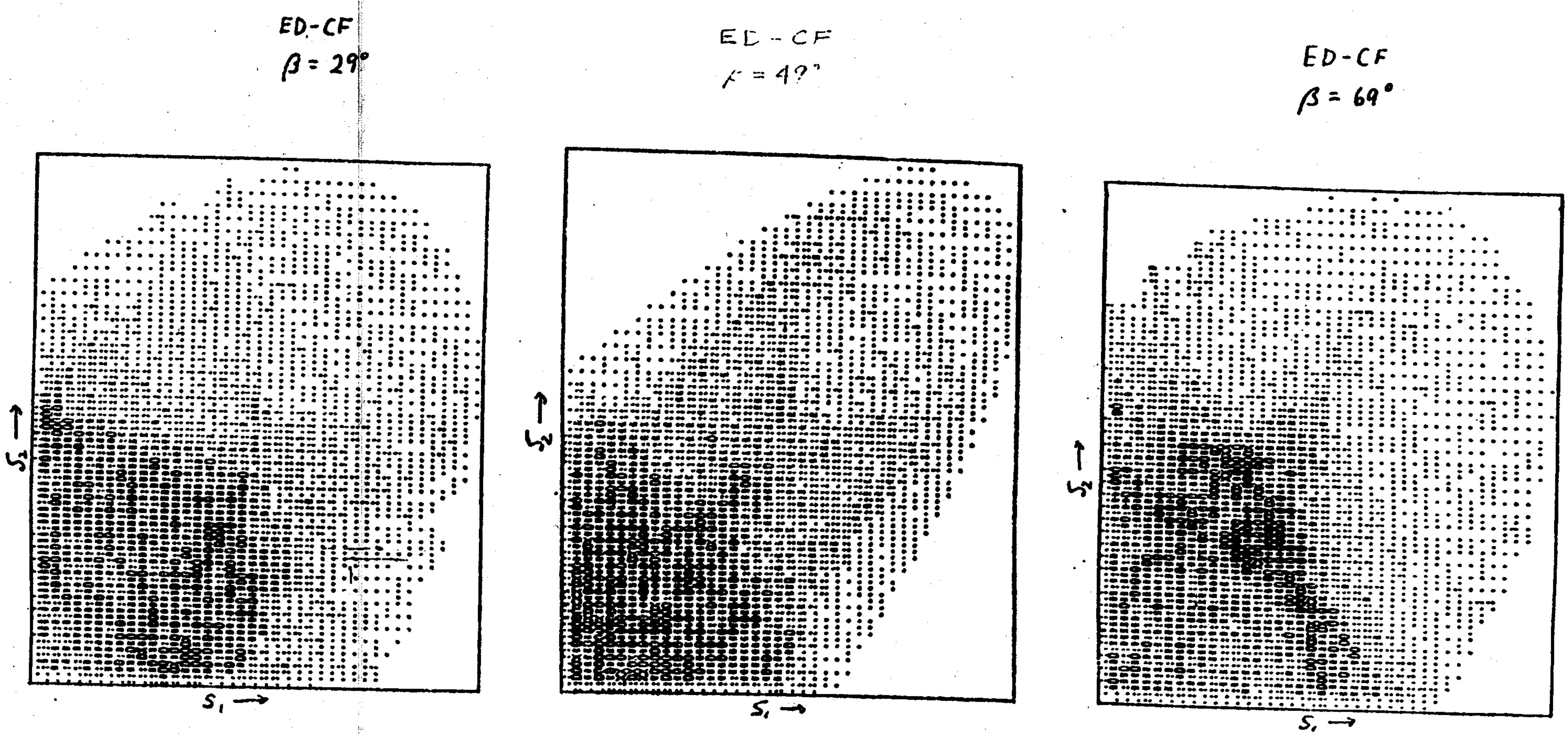


Figure E.3 Distribution of measured strain amplitudes from equal strength sources having random polarizations distributed randomly over the sky. S1 is the strain amplitude at one antenna while S2 is the strain amplitude at the other. Beta is the angle between one leg of the antenna at Edwards AFB and north. The antenna at Columbia, Maine is held at a fixed orientation. The legend is:

blank under 5 . 5-14 .. 15-24 .: 25-34
:: 35-44 :* 45-54 ** 55-64 *0 65-74
00 75-84 0* 85-94 ** more than 95

Beta = 49^{o} is the optimum orientation, as indicated by the higher density of points along the diagonal at large amplitude.

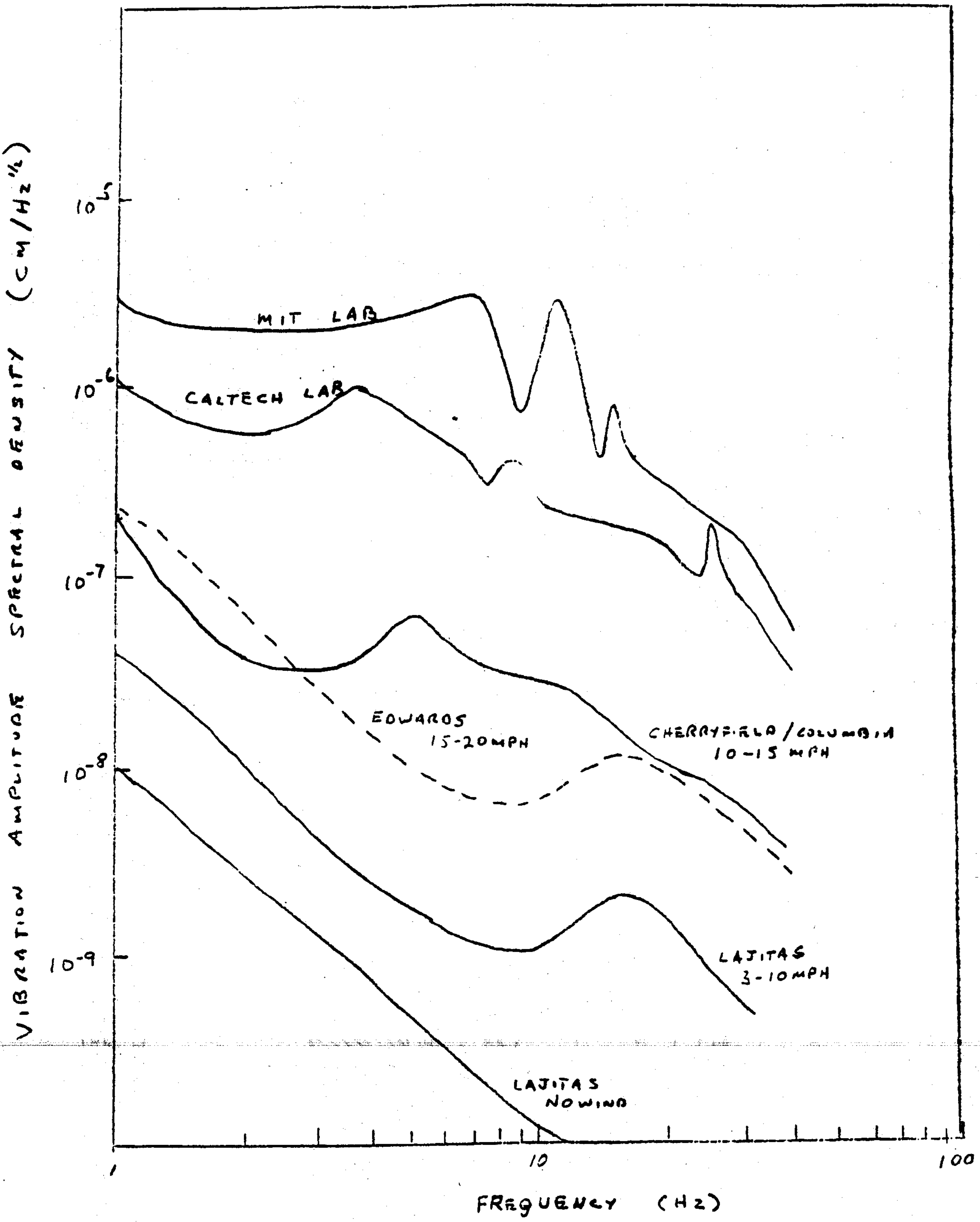


Figure E.4 Range of Seismicities as Indicated by Spectra Sampled at Five Representative Locations

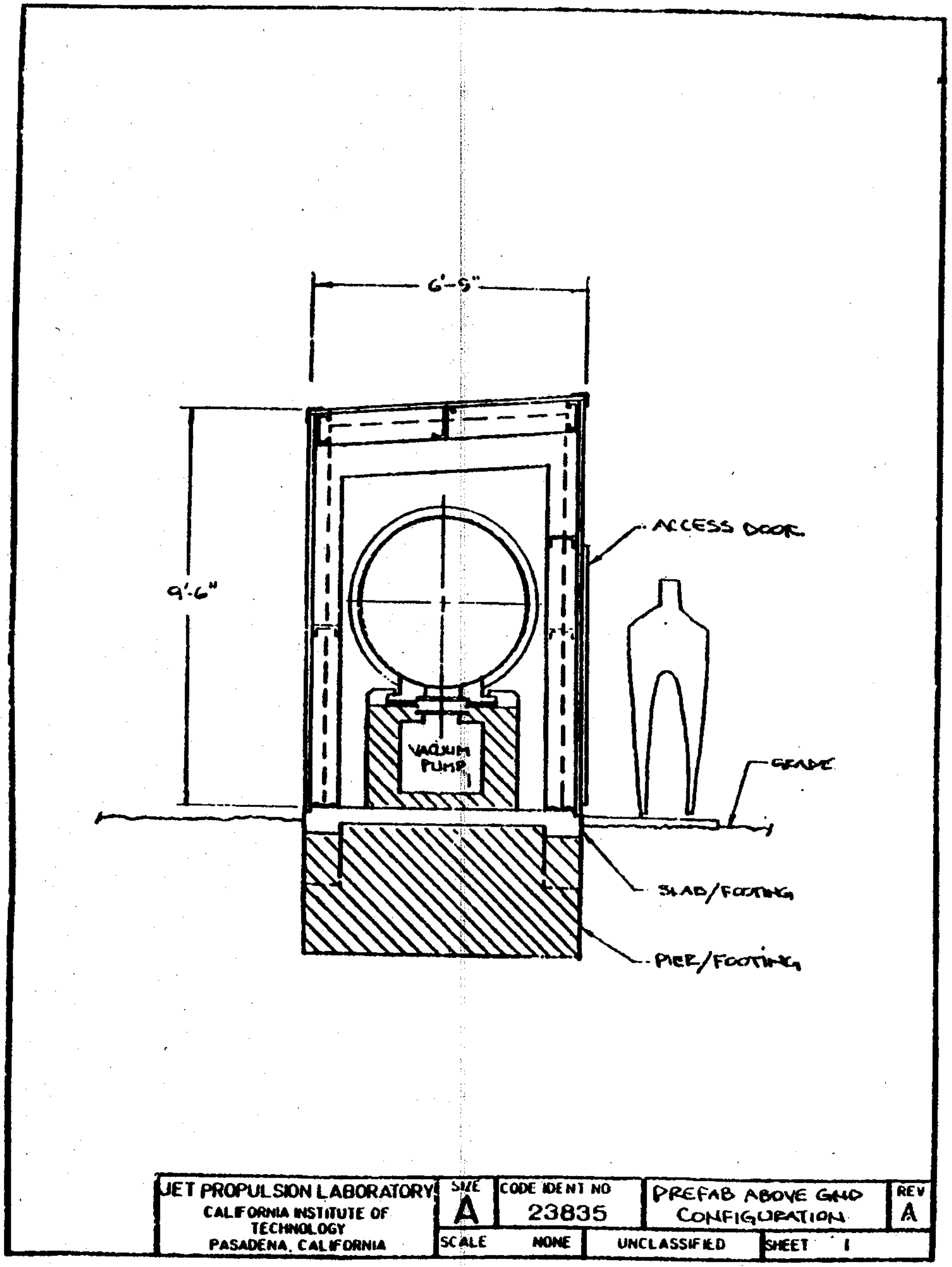


FIGURE E5

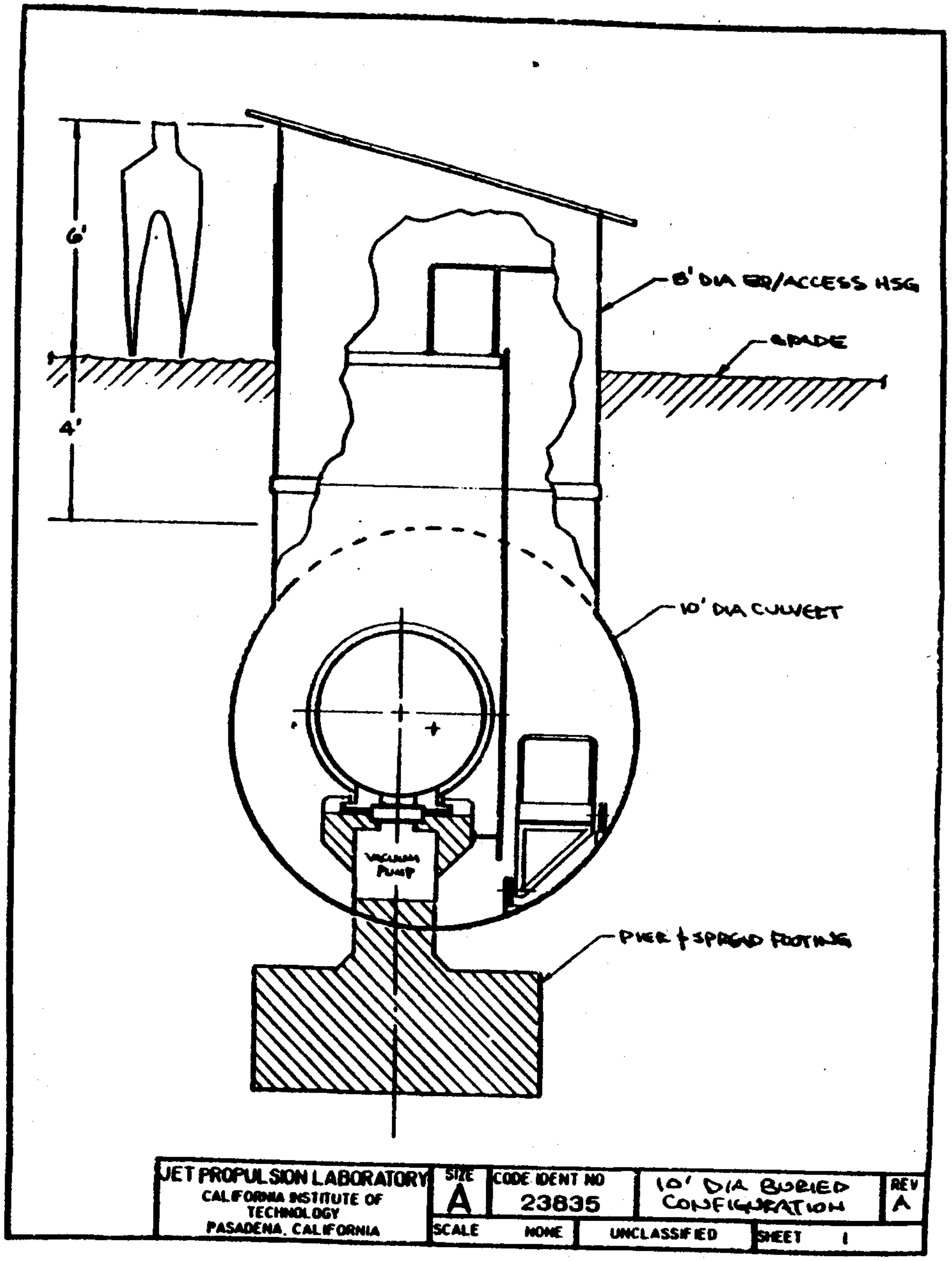
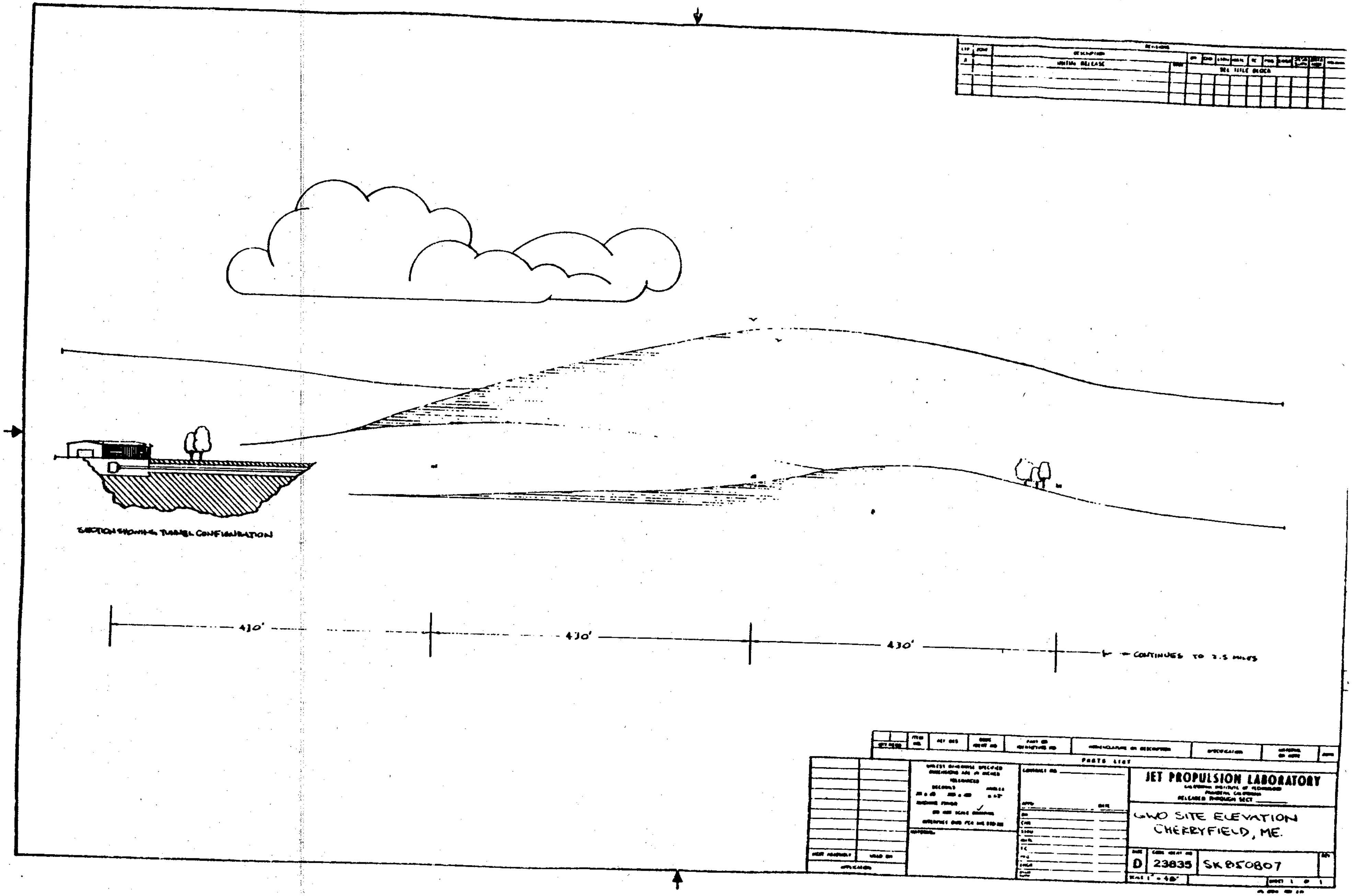


FIGURE E6a


SECTION SHOWING TUNNEL CONFIGURATION
430'
430'
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CONTINUES TO 2.5 MILES
PARTS LIST
JET PROPULSION LABORATORY
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CHERRYFIELD, ME.
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23835
SK850807

Figure E.6(b)

At both sites the design lifetime of the facilities is to be a minimum of 20 years.

E.3.2 Vacuum Subsystem Design

On the basis of material collected by JPL and submitted to the Research Groups for consideration, stainless steel will be used for the vacuum tubing rather than aluminum. This decision was based on the opinions of a number of large vacuum system users and designers interviewed by the JPL team. The consensus is that there is no cost advantage of aluminum over stainless steel to outweigh the large base of experience with stainless steel in vacuum systems. It seems a prudent policy not to make the vacuum system a separate experiment in and of itself.

The primary requirement is to maintain a low enough gas pressure so that statistical fluctuations in the residual gas column density about equilibrium do not compromise the receiver sensitivity. The strain noise amplitude spectral density due to this effect is given by

$$h(f) = \frac{2\alpha\rho^{1/2}}{[nv_{th}(\pi\lambda)^{1/2}]^{1/2}L^{3/4}} ,$$

where f is the gravity wave frequency, ρ the average particle density, α the molecular polarization at λ, the light wavelength, v_{th} the molecular speed at the vacuum wall temperature, and L is the arm length. n is the number of beams passing in the interferometer arm; for compact geometries such as a Fabry-Perot or tagged-beam delay line $n = 1$. Minimum diameter Gaussian beams of width $(\lambda L/2\pi)^{1/2}$ have been assumed.

Using green light, a strain sensitivity of $h(f)\sim 10^{-22}/\sqrt{\text{Hz}}$ (the sensitivity level of the "simple first detectors" in Figs. 1.3 - 1.5) will require that the average pressure be less than 5×10^{-5} torr of N_2 in a 4 km system using a single beam or 3×10^{-4} torr in a distributed delay system with 30 beams. The sensitivities of the "more advanced detectors" of Figs. 1.3 - 1.5 correspond to $h(f)\sim 3\times 10^{-25}/\sqrt{\text{Hz}}$ and will require pressures of less than 5×10^{-10} torr of N_2 or 9×10^{-9} torr of H_2 for compact optical systems. The potential high sensitivity of the receivers will make ultra high vacuum demands on the system, although the requirements are eased by the fact that the residual gas in a clean baked stainless steel system without leaks is predominantly H_2. The vacuum system must be bakable to 150 degrees C and be able to have enough pumping capacity to hold a pressure less than 10^{-8} torr of H_2 against an anticipated outgassing flux of 10^{-12} torr liters/sec cm^2.

The high vacuum requirements also extend to the instrumentation chambers. Several of the stochastic forces on the antenna masses depend on the residual gas pressure. Acoustic isolation requires evacuation to a pressure such that the mean free path is larger than the size of the suspended masses. Acoustic isolation does not drive the vacuum requirements. The reduction of the "radiometer" effect due to thermal gradients on the mirrors because of heating by high power laser beams and the reduction of the broadband thermal noise due to impacts of the residual gas molecules with the suspended components require pressures of 10^{-4} to 10^{-8} torr depending on the receiver sensitivity. Deposition of oil or other condensible substances on mirror surfaces must be avoided.

The vacuum system proposed for further study is constructed of 304 L stainless steel. According to current plans, the tubing in the arms has a 1/4 inch wall and a diameter of 4 ft stiffened against collapse by either welded rings or rolled beads every 5 ft. Stainless steel expansion bellows welded directly to the tubes are placed every 400 ft. Pump ports are mounted every 400 ft. A layout of the vacuum system is shown in Figure E7. The long tubes will be isolated from the instrumentation chambers by 48 inch diameter gate valves so that access can be made to apparatus without bringing the entire system to atmospheric pressure.

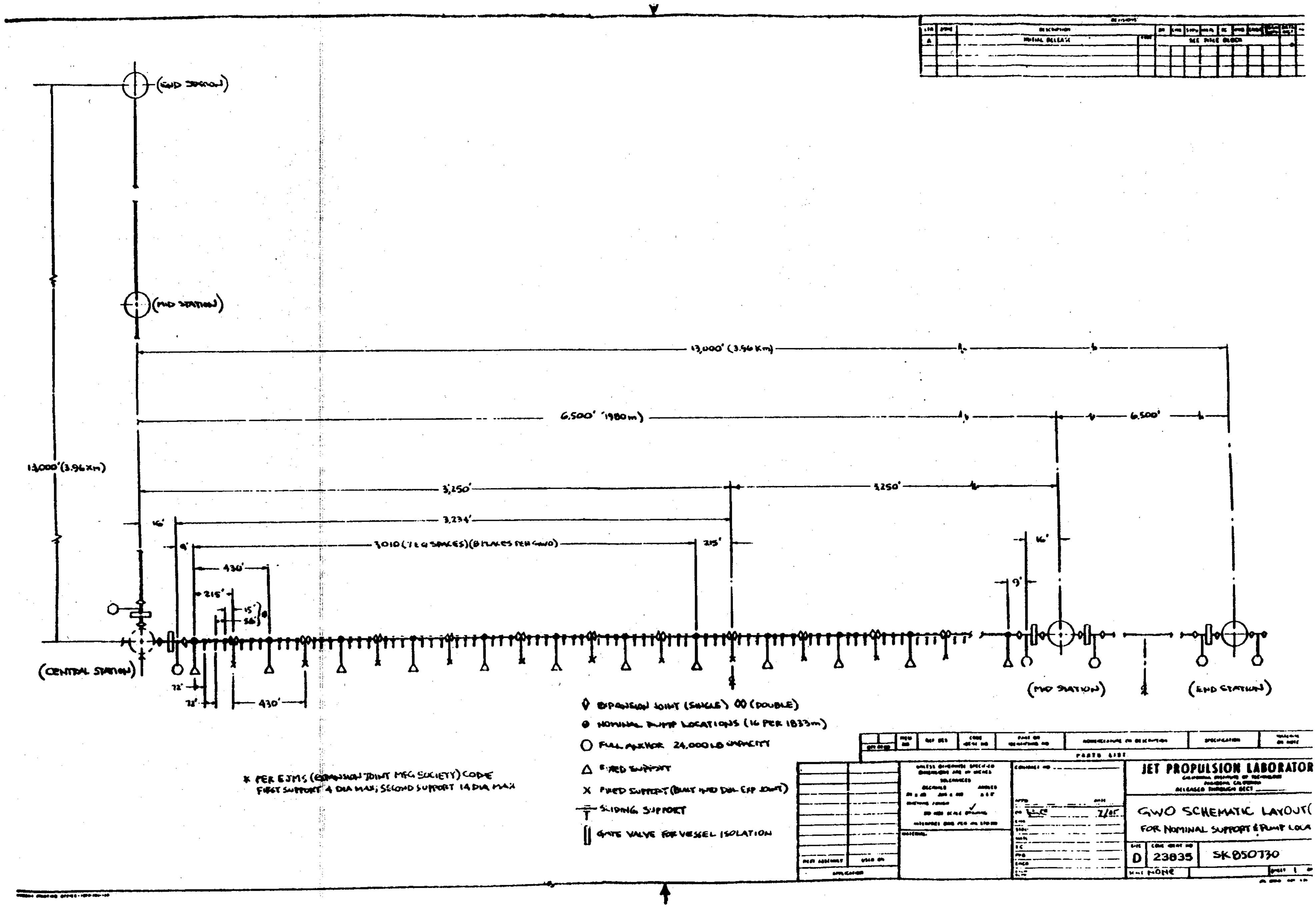
The tubes are supported every 70 ft. on rolling supports and at each pump there is a fixed support which clamps the system to the ground. The alignment of the tubes will be maintained at ±2 cm over the 4 km length. Scatter suppression baffles are placed in the tubing at intervals of 400 ft.

The tubes and bellows are wrapped with 2" thick insulation for bakeout at 150 degrees C. The tubes themselves will be used as resistance heaters. The bakeout will be done with auxiliary generators to reduce the costs of the permanent power installations as bakeout of the entire system will occur infrequently. Should the system be brought to atmospheric pressure once having been baked, it will be back filled with boil-off nitrogen from liquid nitrogen brought in by tank truck.

The tubing will most likely be rolled from plate and welded in the field. Cleaning and leak testing facilities for individual tube sections would be set up at the site. One strategy for construction is to use the central station for tubing manufacture and then transport tubing under controlled conditions to be machine welded to the rest of the system. The construction strategy would permit multiple shifts for assembly and leak hunting.

A proposed strategy for leak monitoring and isolation once the LIGO has been constructed is to leave a sealed dead space between the tubing and the insulation which can be filled with a trace gas, such as helium, by remote control. Each 40 ft section would be isolated. In addition ion gauges and residual gas analyzer heads would be placed every 400 ft.to monitor the pressure and gas composition, thereby giving further information about the location of leaks in case any develop in the course of time.

The proposed vacuum pumping system is a hybrid of ion-chemisorption pumps and cryosorption pumps backed by mechanical roughing pumps. In quiescent operation, the system is maintained by 1000 liter/sec ion pumps, 64 of which are distributed evenly along the arms. Ion pumps are free of


(END STATION)
(MID STATION)
(CENTRAL STATION)
13,000' (3.96 Km)
13,000' (3.96 Km)
6,500' (1980 m)
6,500'
3,250'
3250'
3,234'
3010 (7 E Q SPACES) (8 PLACES PER GWO)
215'
16'
9'
430'
215'
15'
56'
72'
72'
430'
16'
9'
(MID STATION)
(END STATION)
EXPANSION JOINT (SINGLE) 00 (DOUBLE)
NOMINAL PUMP LOCATIONS (16 PER 1833m)
FULL ANCHOR 24,000 LB CAPACITY
FIXED SUPPORT
FIXED SUPPORT (BUILT INTO DBL EXP JOINT)
SLIDING SUPPORT
GATE VALVE FOR VESSEL ISOLATION
* PER EJMS (EXPANSION JOINT MFG SOCIETY) CODE
FIRST SUPPORT 4 DIA MAX; SECOND SUPPORT 14 DIA MAX
PARTS LIST
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FOR NOMINAL SUPPORT & PUMP LOCA
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23835
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NONE
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INITIAL RELEASE
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A

Figure E.7

mechanical noise and do not require extensive maintenance; however, to retain their lifetime and to avoid gas bursts that could originate in the pumps, they must be started at pressures below 10^{-6} torr. 10000 liter/sec cryosorption pumps placed after every 10th ion pump are used for initial pump down and bakeout. The cryo pumps generate mechanical noise and, if left on permanently, would cause a substantial problem during operation as they require frequent maintenance. The cryo pumps are to be separately valved off the system. Figure E8 shows a plot of the number of pumps required in a 4 kilometer section of 48" tubing as a function of the ratio of the average pressure to the outgassing flux.

The conceptual design of the LIGO's initial configuration specifies 8 instrumentation chambers at each site, with three more to be added in the initial upgrade. All are cylindrical structures of stainless steel using dished heads as ends. The requirement is that the tanks can be easily opened for access to the apparatus. All optical and electrical leads are brought through the bottom. The entire cylinder can be lifted off with a crane for major apparatus alterations. The top shells are demountable for quick access which should not involve disconnecting the vacuum plumbing to the main light tubes. Each tank will be separately pumped with its own ion and cryo pumps. The tanks will also have the capability of being baked.

Tanks in the mid and end stations are specified to be 10 ft in diameter and 10 ft high. Each of these can be isolated from the main vacuum system by 48" gate valves. The tanks are placed on rudimentary vibration isolation systems to decouple them from high frequency ground motion; this is the first stage of many involved in seismic isolation of the receiver components. The tanks at end points are compensated for atmospheric pressure induced torques and forces by bellows tied at one end to ground anchors.

E.3.3 Construction Strategy

The conceptual design specifies a cover for the long evacuated tubes. The JPL study has analyzed several cover designs for both above and below ground construction. The design presented is considered the most economical approach at each site. In a buried configuration (Fig. E6a), the tubes are placed in galvanized cylindrical corrugated culverts of either 12 or 10 foot diameter. The culvert has silos for ventilation and access every 600 feet. Instrumentation cables and most likely the power cables will be placed in preformed trays built into the culvert. A transport vehicle designed to operate in the culvert could be used both for tube installation and subsequent access to pumps and tubes during operations. During construction the culvert would be installed by open trench and backfill operations, and the tubing manufactured in the central station building would be transported down the culvert for welding and leak hunting. An operational virtue of the culvert is that the alignment and assembly of the antenna could be carried on in all seasons and weather and the cleanliness of the vacuum system is maintained during the construction. (A further consideration is that the construction could be phased more easily, the buildings

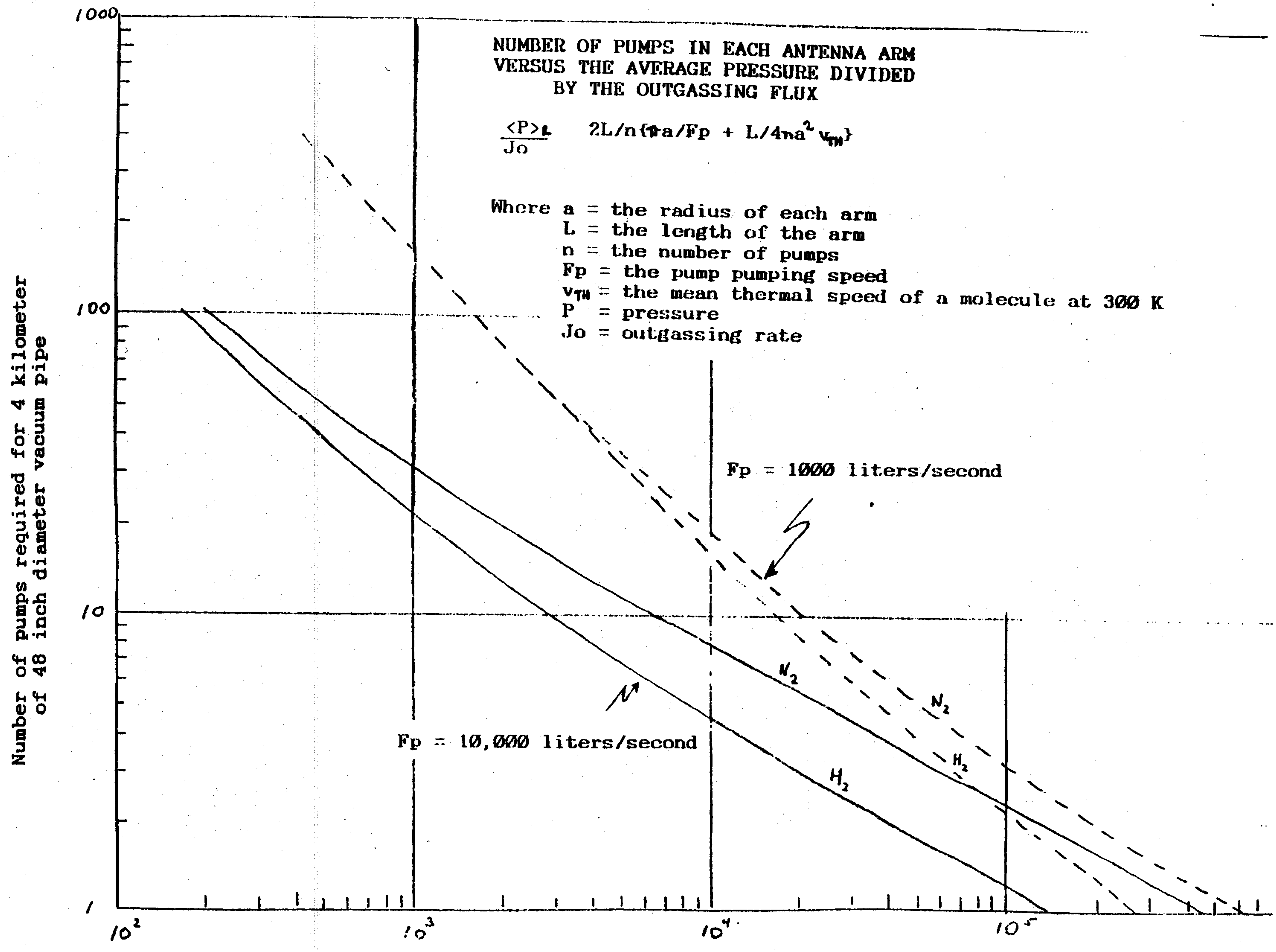
NUMBER OF PUMPS IN EACH ANTENNA ARM VERSUS THE AVERAGE PRESSURE DIVIDED BY THE OUTGASSING FLUX
$\frac{\langle P \rangle}{J_o}$ $2L/n\{\pi a/F_p + L/4\pi a^2 v_{TH}\}$
Where a = the radius of each arm
L = the length of the arm
n = the number of pumps
Fp = the pump pumping speed
v_{TH} = the mean thermal speed of a molecule at 300 K
P = pressure
Jo = outgassing rate
Fp = 1000 liters/second
Fp = 10,000 liters/second
N_2
H_2
N_2
H_2
1000
100
10
1
10^2
10^3
10^4
10^5
Number of pumps required for 4 kilometer of 48 inch diameter vacuum pipe
<P> / Jo (Torr-liters/sec square centimeter)

Figure E.8

and culvert could be installed in one funding cycle with the vacuum system installation being carried in the second.)

The vacuum tube is supported every 70 feet on adjustable supports to allow alignment to ±2 cm. Shallow piles support the tube in the culvert. The piles are placed before installation of the culvert which is precut to accept the piles and then sealed around them.

In the present conception of an above ground installation, Fig. E5, the tubing will be placed above grade and Construction will be carried out in the open. The tube support and anchors are much the same as described for below ground construction, except that they should be sufficiently high so that the tubing and insulation will remain above grade in the worst case. As with below ground construction, the central station would be used for tubing manufacture. The tubing may be placed along the antenna arms by a conveyor running on sills. The sills will later become the anchor points for a cover to be placed after welding, alignment and initial leak hunting. Access to the tubes after initial construction will be made by removing small sections of the cover. The space between cover and tube could be temperature controlled to provide temperature stability.

E.3.4 Buildings

All buildings in the conceptual design are prefabricated structures. The buildings surrounding the instrument stations are steel "Butler" buildings placed on concrete foundations. In both below and above grade construction, the pads that hold the instrumentation tanks are anchored either to bedrock or sufficiently buried casements so as to reduce the effect of differential expansion of the antenna arms due to surface temperature gradients. Access to the lower dished heads of the instrumentation stations will be below grade. The buildings housing the end and mid stations are 1000 sq. ft. while the central station is 5500 sq. ft. Each instrumentation station building will be equipped with a bridge crane. The buildings are air conditioned and efforts are to be made not to raise the acoustic or vibrational noise in the buildings and on the pads more than 3db above the naturally occurring background at the sites in the 10 to 10000 Hz band. The buildings will be equipped with clean benches and some work area, but in order to keep the buildings "quiet", it is not intended that they also serve as general laboratory space or staging areas.

The other buildings at the facilities depend on the site. At Columbia-Cherryfield trailers will be used to house all equipment including maintenance facilities, a small machine shop, electronics stores and construction, instrumentation and data analysis hardware. A house will be purchased in the town to accommodate personnel. At Edwards Air Force Base, no additional buildings are required.

E.3.5 Power and Cooling

Power is available at both the prime and the backup sites. The demands of the facilities will require a substation and connection to high voltage lines. Excluding the power required for bakeout, the average power demands of the facilities are about 2 MW. The assumptions concerning the type and quantity of lasers that will be used at the facilities are critical in determining the total power budget. 100 watts of single frequency optical power derived from Argon Ion lasers of present day designs would require at least 300 kW of electrical power and cooling capacity. (At present prices this alone would correspond to a recurring operating cost of 150 thousand dollars per year). The assumption made in the conceptual design is that newer laser designs, in particular the Nd:YAG system, will be available which have 10 to 100 times higher efficiency. The laser cooling capacity specified is 0.3 MW. Laser cooling will be done using closed cycle cooling systems with proportional temperature control. The cost of the laser cooling system as a function of the dissipated power is shown in Figure E9.

E.3.6 Instrumentation

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

The conceptual design specifies an instrumentation system designed round "Camac" crates with both analog and fiber optic digital ports which will monitor the health of the facility and generate data for storage to be correlated with receiver signals. A list of the signals to be monitored is given in the functional requirements for the LIGO (Appendix F). A standardized and documented instrumentation system is considered a necessity.

The conceptual design includes specifications for the number of standardized panels and interconnection wiring and optical fiber links between the stations. A users handbook will be prepared that documents the operation of the facility. This document will include information such as programs, wiring connections, and the properties of facility-provided sensors. A broadband communications link between the two sites, possibly using satellites, is being considered.

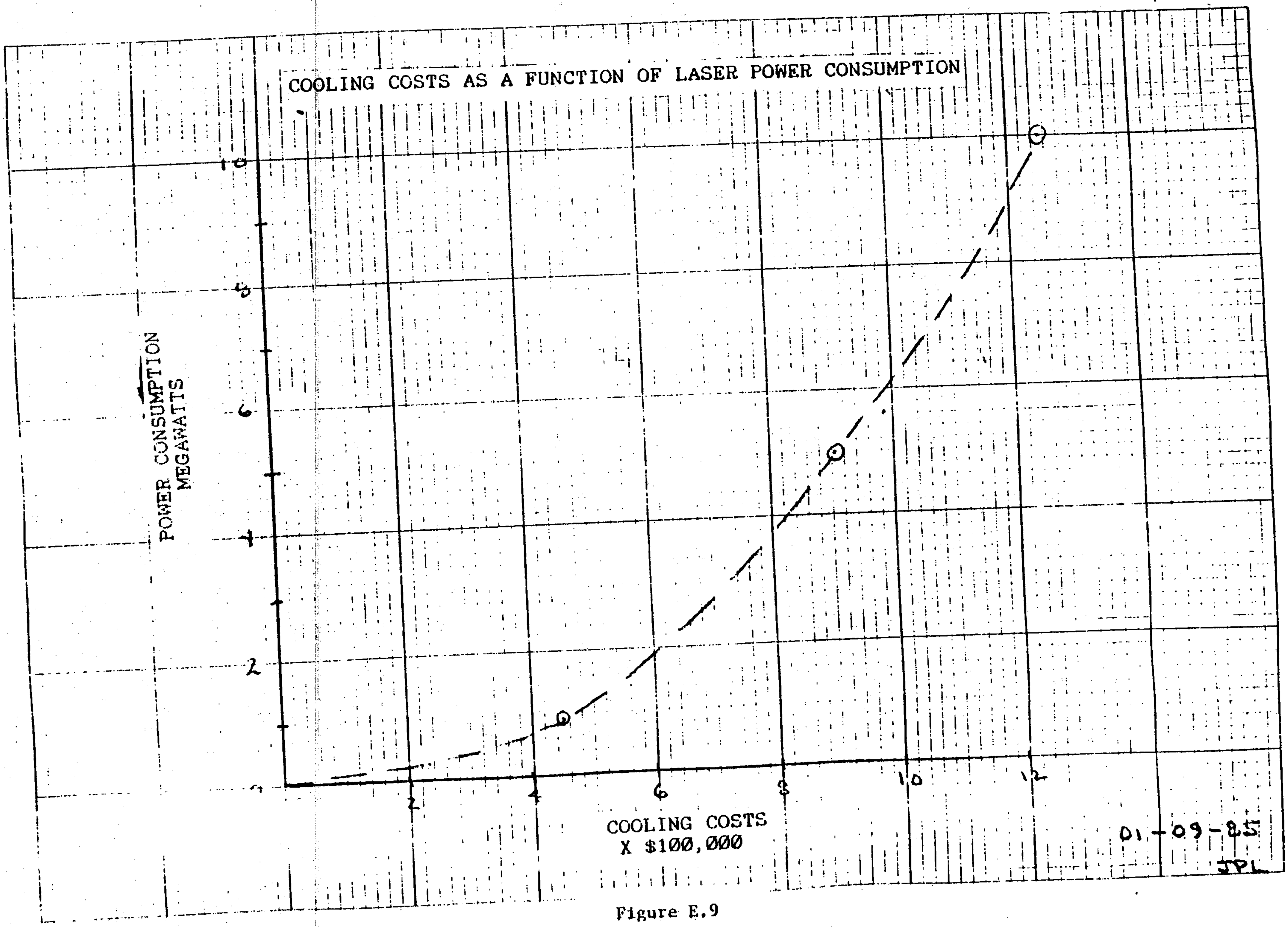
COOLING COSTS AS A FUNCTION OF LASER POWER CONSUMPTION
POWER CONSUMPTION MEGAWATTS
10
8
6
4
2
COOLING COSTS X $100,000
2
4
6
8
10
12
01-09-85
JPL

Figure E.9

APPENDIX F
FUNCTIONAL REQUIREMENTS FOR THE LIGO

This appendix is the present, as-yet-not-complete version of the functional requirements document for the LIGO. When completed, this document will be a key input for the detailed engineering design effort for which this proposal seeks funds.

F.1 Overview

The functional requirements outlined below describe the vacuum system and related facilities needed to house a variety of gravitational wave receivers to be developed and built over the next 20 years.

Similar vacuum systems will be built at two sites. (See Figure 1.1) Each system will have two 4 km long vacuum pipes extending at right angles from a central station. Each arm will have two smaller stations, one at the end of the arm away from the central station, and one near the middle of the arm. Each station will contain one or more vacuum chambers housing receiver elements. The functional requirements for the vacuum system given below specify the configuration of the vacuum system including the chambers, pipes, valves, pumping system and gauging requirements. The facilities also include buildings for the stations, tunnels or covers for the pipes, associated work areas, and utilities. An automated housekeeping data subsystem for monitoring and controlling the operations of the facilities will also be supplied.

1.1 The design lifetime of the facilities is to be twenty (20) years. No materials shall be used in the major structural elements which would preclude achievement of this lifetime.

F.2 Sites

2.1 The two facilities will be located at Columbia, Maine and at Edwards Air Force Base, California, as shown on the attached maps. (See Figs. E2 and E3.)

2.2 At the Columbia site, the central station will be located at latitude ________, longitude ________ with one arm along a line ____degrees east of true north and the other along a line ______degrees east of north. The arms will be 4 km long with mid stations ___km from the central station along each arm. Environmental constraints demand that the vacuum pipes must be below ground level in a culvert or tunnel. The tunnel must be large enough to allow access to any part of the vacuum pipe for repairs.

2.3 At the Edwards site, the central station will be located at latitude ________, longitude ________ with one arm along a line ____degrees east of true north and the other along a line ______degrees east of north. The arms will be 4 km long with mid stations ___km from the central station along each arm. At this site the vacuum pipe could be above ground level. If so, it shall be fitted with a cover to protect it from wind, rain, and vandalism. The cover must be removable to allow access for repairs to the vacuum system.

2.4 At both sites, the arm lengths, measured from the geometrical center of the chambers must be equal to within 3 cm. The same tolerance applies to the distances from the central station to the mid-stations.

2.5 Prior to construction at any site, a seismic and acoustic survey shall be conducted using instruments similar to those described in item 5.3. This survey will produce a spectrum which represents the pre-existing noise spectrum (late night during calm weather), in the frequency band between 1 Hz and 10 kHz. The sum of all the additional vibration or acoustic power due to installed equipment shall not exceed the level of this measured spectrum. As part of the noise reduction strategy, all rotating machinery shall be mounted on standard passive vibration isolation mounts.

F.3 Vacuum Subsystem

The vacuum system will consist of a set of instrumentation chambers and the vacuum pipes connecting them, the complement of pumps to achieve and maintain the vacuum, associated valves and gauges for vacuum monitoring and leak checking, means for baking the above mentioned parts, and a nitrogen supply and manifold for backfilling the system.

3.1 PIPES: The vacuum pipe will be forty-eight inches in diameter. It will be welded from individual sections with bellows spaced along the pipe to allow for thermal expansion during baking.

a. All of the tubing used in the construction of the vacuum pipe shall be from one mill run having the characteristics defined by Document ______ Each section of vacuum pipe shall be individually leak tested prior to installation. The maximum leak rate for a 40 foot long section of pipe is _______ .

b. After installation each section of the vacuum pipe will be leak tested. The welds shall be certified leak free at a level of ________

c. Internal light baffling shall be included in the pipes to reduce scattered light. These baffles are to be installed at intervals of _____meters and shall be tilted at an angle between 10 and 30 degrees to avoid back reflections. The baffles shall extend 3 cm into the pipes.

d. The deviation of any arm of the vacuum pipe from a straight line shall not exceed +/- 3 centimeters.

3.2 CHAMBERS: All chambers shall have the following characteristics:

a. Each chamber shall have the form of a right circular cylinder with dished (outward) heads for both the base and top. Each chamber shall be constructed to that the top head may be removed without disturbing the main body and base. (See the new figure to be drawn.) Additionally, it must be possible to remove the top and main body as a unit from the base. Connection to the primary 48" vacuum pipes is to be made entirely through the main cylindrical portion of the chamber. Provision for quick connection between the pipes and the chamber is required.

b. All electrical, fiber optic, and vacuum pump connections to the chamber are to be made through the base of that chamber.

c. Each chamber shall be pumped down by a combination of ion, cryo and mechanical roughing pumps, although only ion pumps will be used during operations. Provision shall be made for isolating the other pumps from the chambers mechanically and acoustically so that receiver operations can be initiated during the final pumpdown.

d. Equipment installed in the chambers is to be mechanically coupled at the base section of the chamber. To facilitate these connections 3 tie-down points are to be provided. These tie-down points are to be located directly above one of the mechanical connections between the base and the pad on which it is mounted. The tie-down points are to be oriented in azimuth to prevent interference between suspension members and the optical paths of the interferometers. To allow work in the chamber, a removable floor shall be installed in the base. Additionally, a ladder is to be provided to allow access to the inside of the chamber with the top removed.

e. It must be possible to obtain access to a chamber in under sixty minutes

f. The central (fourteen foot) chamber must have six 48" ports, two of which will be used for personnel access to the chamber and the other four will be used to connect to the vacuum pipes. Additionally it must have 8 12", 20 9", and 44 6" visual or blanked off ports to permit visual or mechanical access to the interior of the chamber. Provisions for the connection of vacuum pumps to the chambers must also be provided. Electrical access to each of the chambers shall be through four 24 inch removable and twenty 2-3/4 inch removable blank panels distributed equally about the base of the chambers. The 10 foot chambers must have a proportional number of ports. An optical quality access port for injecting the laser signal into the chamber shall also be provided. Access to the interior of the fourteen foot vertex chamber shall be through the two 48" diameter access hatches and through the top, which shall be removable through the use of a winch. The fourteen foot chamber must be able to function properly with contents weighing up to ten tonnes. The ten foot chambers must function properly with contents weighing up to five tonnes.

3.3 GATE VALVES: Gate valves shall be provided to isolate all chambers from the remainder of the vacuum system as shown in Figure 1. All isolation valves shall be capable of maintaining a vacuum of 10^{-8} on either side while the system on the other side is at ambient atmospheric pressure. The valves may use viton seals for the main gate seal only; all other seals must be all metal. Viton seals must be outgassed prior to installation of the valves in the system. All valves should be operable remotely through the housekeeping data system, with provision for manual operation if necessary.

3.4 VACUUM LEVEL: The working pressure in the vacuum system should meet the following specification as measured by suitably calibrated residual gas analyzers and ion gauges (~~see 3.7~~)

3.5 A bakeout system for the vacuum pipes is required. The bakeout system should be capable of raising the temperature of the pipe in one arm to 150 C in a period of one day. Since bakeout of the pipes is expected to be an infrequent occurrence, the use of portable gas fired generators is acceptable for powering the heaters. Use of the pipes themselves as the heating elements is allowed.

Provision shall be made for baking out each chamber each time it is pumped down.

3.6 PUMPDOWN TIMES:

a. chambers - first time, then subsequently. The pumpdown time of individual chambers shall not exceed 8 hours with a gas load from the experimental apparatus in the chambers of 10^{-3} torr-liters/sec. This value implies that all equipment that is to be placed in an operating chamber shall be cleaned prior to installation.

b. pipes - ~~first time, then subsequently~~ after initial pumpdown

3.7 CONSTRAINTS ON PUMPING SYSTEM:

a. Mechanical pumps adequately trapped to prevent backstreaming
b. Only ion pumps in normal high vac operation
c. Cryopumps allowed during pumpdown

3.8 GAUGES: Ion gauges and controllers shall be installed to measure the pressure in any chamber or pipe to an accuracy of 20 percent. Ion gauges shall be located at each of the cryo and ion pumps used in the system as well as wherever else we want them. All ion gauge outputs will be monitored by the housekeeping data subsystem, which will also monitor the current from all operational ion pumps as a check on the perfomance of everything (see section 5). Separate gauges shall be provided to monitor the pressure during pumpdown from atmospheric pressure to the pressure where ion gauges may be safely turned on. Residual gas analyzer (RGA) heads shall be installed on each of the chambers and elsewhere to assist in leak-hunting, and to verify compliance with the pressure specification in 3.4.

3.9 BACKFILL:

a. Liquid Nitrogen storage shall be provided external to all buildings housing vacuum chambers. This must be sufficient to supply liquid nitrogen for cold trap coolant for the chamber pumps for a period of XX weeks, and gas to fill the vacuum chambers in the building XX times

b. Heaters shall be supplied so that sufficient nitrogen gas can be created from the liquid to fill any chamber in XX minutes. Further heater capacity to boil off liquid nitrogen shall be supplied so that the entire vacuum system (pipes and chambers) can be filled in XX hours. To fill the main pipes, a separate tanker truck of liquid nitrogen will be ordered.

3.10 LEAK DETECTION: A scheme must be implemented which will allow us to isolate leaks to individual 100 foot sections of the pipe once the vacuum system has been installed. A suggested technique is to install bags around the pipe, underneath the insulation. These bags should be able to be filled with He gas by a manifold accessible from outside the tunnel or above ground enclosure. Whatever system is installed must be able to withstand a bakeout temperature of 150 degrees C.

F.4 Facilities Subsystem

The specifications for the facilities include the buildings to house the vacuum chambers, additional workspace in trailers, furnishings, utilities, and roads.

4.1 CENTRAL STATION BUILDING: The central station for each facility (shown in Figures 1 & 2) shall be designed to contain:

a. One fourteen foot chamber and six ten foot chambers at the vertex of the antenna arms interconnected as shown in Figure 2.1(b).
1 [illegible] arranged [illegible]

b. Work space of not less than 500 square feet in close proximity to the chambers.

c. A crane capable of lifting all or any individual portions of a chamber individually.

d. Sufficient space shall be provided to allow each chamber midsection and cover or cover dome to be separated from its base and stored during periods when the chamber is being refitted. This implies that all seven chambers in the central station may be open simultaneously. Additionally, protective devices must be included to protect delicate flanges of the covers or chamber sides during the period of time that they are open.

e. External vibration isolation systems must be installed on all chambers and each of the chambers must be isolated from the other chambers in the central station. Furthermore, the vertex chamber isolation system must be operational regardless of the state of any other chamber or any other vacuum system. The vertical and horizontal isolation systems shall have fundamental resonances less than 2.0 Hertz and the transmissibility shall be less than 10^{-1} at 10 Hertz and less than 10^{-2} at 100 Hertz. Each isolation system shall be equipped with a means of being rigidly clamped in the same location and orientation as the system has when functioning as an isolator. An isolator for a fourteen foot tank shall function as specified under any load between the weight of the empty tank and that weight plus 10 ton. Isolators for 10 foot tanks should function as specified at weights between the empty weight and that weight plus 5 tons.

f. A 6 foot Class 100 clean bench shall be installed at the central station to provide for the storage and assembly of optical and other delicate instrumentation.

g. Sufficient space, as indicated in Figure 1, shall be provided to install lasers and associated optics on an optical bench; separate facilities shall be provided for the main (fourteen foot) or vertex chamber and the satellite chambers. The operation of the vertex chamber shall be undisturbed regardless of the state of the satellite chambers. In addition, sufficient space shall be provided to allow installation of a 12 foot long, 2 foot diameter mode cleaning cavity.

4.2 END/MID STATIONS Each of the end and mid stations shall contain:

a. One ~~fourteen~~ ten foot diameter chamber in each of the mid stations with identical specifications to the central station chamber.

b. One ten foot diameter chambers in each of the end stations with identical specifications to the central station chambers.

c. Work space of not less than 500 square feet in close proximity to the chambers.

d. A crane capable of lifting all or any portion of a chamber individually.

e. Sufficient space shall be provided to allow the mid section or the top of each chamber to be separated from its base and stored during periods when the chamber is being fitted.

f. A 4 foot Class 100 clean bench shall be installed at each station to provide for the storage and assembly of optical and other delicate instrumentation.

4.3 GENERAL BUILDING SPECS: All buildings containing vacuum chambers shall have:

a. A security fence around the building. The gates in this fence shall be monitored to provide an indication that they are either open or closed. Both vehicle and personnel access gates shall be provided. The vehicle access gate shall have a minimum width of fourteen feet.

b. Air conditioning to maintain the facilities at a temperature 70±2 degrees F.

c. Humidity control to maintain the facilities at fifty 50 ±1 percent.

d. Sanitary facilities.

e. Independently switched incandescent and fluorescent lighting. Emergency lighting systems shall be provided in all buildings and in the tunnel containing the vacuum pipe at Columbia.

f. A potable water supply shall be supplied to mid, end and central station buildings. The pressure in this supply shall be 75 psi. The quantity of water stored shall be _____liters minimum. The flow rate shall be _____liter per second minimum. Each end, mid and central station shall contain failities to accommodate emergency showers and eye washes.

4.4 HEADQUARTERS: Each of the two sites shall have space for offices, shops, storage, etc. which may consist of 50 × 10 foot trailers, no closer than 1 km to any of the instrument stations. This space shall also include:

a. A garage for storage of three vehicles.

b. Machine and electronics shop facilities of 1000 square feet. (Depending upon the facilities already available at the individual sites.)

c. 1000 square feet minimum, for data acquisition, storage, reduction, and analysis.

d. A kitchen and dining area to serve 15 people.

e. Electrical power substation.

4.5 SHOP EQUIPMENT: The following equipment shall be installed at the Columbia shop:

a. One milling machine, Model_____

b. One lathe, Model_____

c. One drill press, Model_____

d. One grinding wheel, Model_____

e. Two mechanical work benches

f. Two electronic work benches

g. Ten 6 foot high, 30 inch wide and 24 inch deep storage cabinets shall be provided to store electronic and mechanical parts.

h. One twelve cubic foot refrigerator for film, etc. storage.

i. Two four-wheel drive vehicles.

j. One pick-up truck with a removable 2 tonne hoist.

4.6 EQUIPMENT FOR EDWARDS: The facility at Edwards shall be supplied with same equipment as listed in item 4.5, with the exception of items a. through d.

4.7 LAB SUPPLIES: The Project Office shall establish an account for the purchase of general purpose scientific equipment for each facility (for oscilloscopes, power supplies, test equipment, etc.). This account shall have a minimum of $XXX,000 for each site. This money will be spent by the MIT and Caltech groups under guidelines set up by the dreaded Steering Committee.

4.8 Compressed air at 75 psi nominal shall be supplied in the Headquarters shop. The amount of moisture and oil contained in this air shall be limited to 0.001 per cent.

4.9 COVER FOR VACUUM SYSTEM: At the Columbia site the vacuum system shall be installed in a protective steel culvert of circular cross section. The culvert shall have a diameter of 12 feet. The top of the culvert shall be 4 feet or more below grade. All fittings and seals must be able to withstand the elevated temperature which will be attained during bakeout of the vacuum system.

4.10 ACCESS TO TUNNEL: At the Columbia site, there shall be access to the tunnel containing the vacuum pipes at each of the cryo and ion pump installations; these access ports will be located between 400 and 800 feet apart. All access hatches shall be monitored electronically from the central station through a key interlock system to provide positive determination of the state of the hatches.

4.11 CART: For a buried system a cart shall be developed to readily transport heavy or bulky items (tool boxes, pump parts, etc.) between access hatches and the work area.

4.12 WATER LEAKS: Below ground facilities shall not admit ground water at a rate greater than 2×10^{-2} liters/hour-meter. Additionally, any below ground installation shall be provided with sump pumps, well points, or French drains so that the water level in the tunnel cannot exceed one inch.

4.13 VENTILATION Adequate ventilation must be provided in the tunnel to allow a crew to enter for inspection of the vacuum system and to perform repairs.

4.14 COVER FOR ABOVE GROUND VACUUM SYSTEM: At the Edwards site, the vacuum system will be installed above grade, protected by a corrugated steel shell. This cover will be just large enough to contain the vacuum pipe and its supports. The cover must be installed in such a way that a portion of the pipe may be exposed quickly, to allow inspection and repairs. All fittings and seals must be able to withstand the elevated temperatures which will be attained during bakeout of the system.

4.15 MAINS POWER: The power used for all receiver applications shall be isolated from the power used to drive the vacuum pumps or any other equipment that will couple noise onto the power lines. All line voltages shall be regulated to +/- 10 percent. Input Electrical power required by the facilities shall be:

a. 440 volts, 3 phase, ac at _____amps.

b. 230 volts, 1 phase, ac at _____amps.

c. 115 volts, 1 phase, ac at _____amps. All power supply voltages in remote (away from the central station) locations shall be connected through ground fault interrupters.

4.16 POWER FAILURE: In the event of a power failure the following actions need to be taken with respect to system operation:

a. Backup operating power shall be applied to emergency systems as follows:

b. To all alignment lasers and their associated electronics.

c. The precision clock must be tested to insure that it is still in synchronism with the clock at the other site.

d. All computers or peripherals not on the emergency power system should be capable of a graceful shutdown.

e. There should be a delay of ten minutes between the failure of a laser power supply and the shutdown of the laser cooling system. Additionally, this should be a feature of the normal operation of the laser cooling system as indicated in section 6, Facilities.

f. The auxiliary power system shall be required to be operational for a minimum of three hours after the primary power is removed.

4.17 LASER COOLING SYSTEM: A cooling assembly shall be provided at the central station to dissipate the heat generated during laser operation with a minimum cooling capacity of 300 kilowatts. This system should provide a flow of XX gallons per minute of microfiltered, de-ionized water at a temperature of 75 +/- 1 degrees F. The pressure of the cooling water should be adjustable between 20 and 80 PSI. Safety shutoff of laser power shall be accomplished on loss of cooling water. Provisions shall also be made to prevent the reapplication of cooling water to the lasers prior to a proper startup sequence. The laser cooling plumbing must be free of iron and other corrodible materials.

4.18 FIRE: Adequate fire control must be provided in all operating areas.

4.19 COMMUNICATIONS: Ten telephone lines shall be provided at each facility. Three of these lines will be reserved for the housekeeping data computer. Two lines will be connected only at the support trailers. The remaining five lines will have extensions at each of the main stations (mid, end, and central) as well as at the support trailers. A voice intercom system will link all the chamber buildings and the frequently used support buildings.

4.20 ROADS: All roads shall be capable of handling trucks with a maximum weight of twenty six ton.

4.21 INSTRUMENTATION WIRING: Cable troughs shall be provided along each arm of the vacuum subsystem to interconnect the elements of the facilities. These troughs shall have the following characteristics:

a. Fiber optics and regular cables shall be installed in separate troughs.

b. Incoming and outgoing signals shall be in separate troughs, where out is defined as being generated from the central station.

c. Trough sizes shall be as defined by standard telephone company cable installations.

d. Provision shall be made for sealing the troughs to prevent entry of insects or rodents.

F.5 Housekeeping Data Subsystem

The housekeeping data subsystem is a computer controlled network whose purpose is to monitor the status of the facilities, record a variety of system conditions and signals which may be important to the operation of the receivers, and to provide an alarm/control system for the vacuum system and other related systems. Separate data acquisition systems for the receivers will be provided by the Caltech and MIT groups. One role of the housekeeping data subsystem is to provide standard interfaces for the receiver data systems so that they can access the housekeeping signals when necessary.

5.1 The following parameters are to be monitored by the housekeeping data subsystem:

a. Temperature at ____evenly separated points in each tunnel.

b. Temperature in each station containing chambers.

c. Pressure in the pipes at ____points.

d. Pressure in each of the chambers using as many as ____separate sensors.

e. Seismic motion from thirteen seismometers.

f. Servo loop signals from __________ n?

g. Status of all access hatches or entrances to the facilities.

h. Bellows strain.

i. Positions of all pneumatically operated valves.

j. Ventilation assembly operation in any portion of the facilities.

k. Acoustic noise signals from ____sensors.

l. Power line noise from ____different sources.

m. Alarms for security, cooling, power to various critical equipment, etc.

n. Manual data entry of operations performed that effect the data records.

o. Recording of all emergency alarms.

In addition, a number of inputs of all sorts should be provided as spares which will let us patch in all the things that we forgot.

5.2 ALARMS: Each facility will be equipped with safety alarms as follows:

a. Main power system failure.

b. Kickin of the backup power system.

c. Failure of the laser cooling assembly.

d. Vacuum loss in any portion of the system.

e. Failure of any critical pump.

f. Failure of any pneumatic valve to operate properly.

g. Failure of any ventilation system to operate.

5.3. Seismic motion at each chamber shall be monitored in all six degrees of freedom. This monitoring shall include all frequencies from 1 Hertz to 10 kiloHertz. The analog outputs from each of the three seismometers shall be digitized to 16 bits. The noise in the seismometers shall be less than or equal to

$$x(f) = 10^{-7} \times 1/f^2(\mathrm{Hz}) \quad \mathrm{cm}/\sqrt{\mathrm{Hz}}$$

This is applicable between 1 and 300 Hertz. The instrument noise shall be below 10^{-12} cm/root Hertz between 300 Hz and 10 kHz. The transfer function of each of the chambers, while mounted on its support structure, shall be characterized for each different mass used. Measurements shall be made during system operation at each of the chambers to provide a permanent record of any disturbances. In addition, airborne acoustic sound shall be monitored from 20 Hertz to 10 kiloHertz at a sensitivity of 10×10^{-4} dynes/cm^2 to measure the ambient spectrum (during quiet periods at a signal to noise ratio of 20 *db*). The measurement system shall have sufficient dynamic range so as not to saturate at a signal level due to that caused by footsteps or a normal speaking voice within one meter of the instruments.

5.4 Data collection is to be done by accumulating and processing signals at nodes along the vacuum pipes and linking the nodes to a central housekeeping computer via fiber optic links. The housekeeping computer will log all data, produce "strip charts", bar charts and other diagnostic aids, and generate alarms if an out of tolerance condition is detected.

5.5 The housekeeping data acquisition hardware shall include the following:

a. the central housekeeping computer equipped with a 1 Gbyte mass storage device, two terminals at the central station, one terminal at each of the other stations, three auto-answer modems connected to phone lines for off-site monitoring of the data, standardized interfaces for linking to receiver data acquisition systems,

b. controllers for the nodes along the pipes with modules for monitoring transducers and controlling pumps, etc. These should use standard components such as camac crates and modules. Each node should be equipped with an interface to a roving computer terminal for diagnostic purposes.

c. Primary timing standard to provide an accuracy for data logging of 10 microseconds. Additionally, the ability to correlate timing between sites to 10 microseconds shall be provided. A separate clock synchronized to the primary timing signal shall be supplied as a backup to the primary standard at each facility. The timing information will also be supplied to the individual receiver data acquisition systems.

5.6 The software for the housekeeping data system shall provide the following features:

a. collection and storage of the signals listed in 5.2

b. maintain calibration records for each ion gauge and each ion pump used for pressure measurement

c. monitor pump performance, flag imminent failure of any pump, schedule regeneration of cryopumps based on operating history, and have the capacity to automatically regenerate cryopumps.

d. respond to emergencies by sounding local alarm and by phoning a succession of people until it receives a response. auto call

e. provide easy to use graphics capability for displaying data.

5.7 A realtime data link between the two facilities shall be developed. This link shall have the following characteristics:

5.8 A data record library shall be maintained in each institution to store master data records. All data records shall be stored in a protected environment to preclude loss due to fire or theft. A master listing of all data records shall be maintained in local, to each site, memory which can be accessed by remote computers.

5.9 All software directly related to facility operation shall be under change control after it is released and has been performance validated.

APPENDIX G
MILESTONES IN THE LIGO PROJECT

G.1 Introduction

This appendix describes in some detail the LIGO project milestones, which are shown in Figure 4.3-3. It is suggested that Figure 4.3-3 be consulted from time to time while reading this section.

The project milestones are for the period between submission of this proposal and the award of a contract, if approved by NSF, for construction of the system. These milestones are shown to provide the reviewer with a reference for the events of importance to the program. In addition, some milestones critical to the construction of the LIGO are also shown to establish the schedule relationship to other activities taking place during the conceptual and detailed engineering design phases. However, the planning and management activities that make for a well run program necessitate that certain activities be carried out in advance of an approval of construction so that the effort can be initiated without delay and/or unnecessary expense.

G.2 Gravity Wave Team Meetings

This activity lists the joint meetings of the Caltech and MIT Research Groups. These meetings are scheduled periodically to provide a communication path among members of the Team. The earlier meetings, January to May, 1985, were used to arrive at the present version of the conceptual design of the LIGO (Sec. 2 and Appendix E) and a draft of the Functional Requirements (Appendix F). Future meetings will be used to review progress in the prototypes and plan for the detailed engineering design and construction.

G.3 Functional Requirements Completion

The Functional Requirements (Appendix F) contain the composite list of all of the requirements essential to the successful system development and operation. Overall system, subsystem, assembly and subassembly specifications will be derived from these requirements. When completed, the Functional Requirements serve as the governing document for all system implementation decisions. The Functional Requirements, after final approval, are to be placed under a change control process administered by the Gravity Wave Steering Committee. Completion of the Functional Requirements is a major milestone.

G.4 Project Office Activities

The Project Office activities are summarized as follows:

1. *Site Specific Studies*. Further studies, including biological, geophysical, geological, and archaeological, of the two prime selected sites to insure that they remain viable. The results of these studies will be used as a basis for preparation of the site environmental impact assessments. Completion

of this activity is a major Project milestone.

2. *Costing of Selected Sites*. This activity involves an assessment of the impact of specific sites on the overall construction cost. Since each site, by virtue of its unique geophysical properties, has some impact on the construction approach used, it must be carefully analyzed to ascertain the affect on cost.

3. *Site Acquisition Activities*. This effort involves the process used to reach agreements on the acquisition of the sites. The Project will enter into agreements that allow it to proceed with studies to determine the acceptability of a specific site for a LIGO facility. In some cases "use" agreements will be entered into with government agencies for the free use of government held property. All of these agreements will be based on the fact that this is a proposed activity, and will not be binding on either party if the Project does not proceed within a specific time period. In some cases land held by either MIT or Caltech will be used at no cost to the government until construction is approved by NSF.

4. *Environmental Impact Reports*. Environmental impact statements, studies or reports will be required at the sites under consideration. Some of these activities have already been conducted (a biotic study at Edwards, an archaeological study at the Maine site will be conducted in the near future), while others are in the planning stage. Accomplishment of this milestone is vital to the Project since construction cannot proceed until the reports are approved by the governmental agencies involved. Failure to go ahead with this activity as scheduled would set the Project back by a period equal to the delay past the scheduled date. The cost of the Project cannot be established with accuracy until the sites are selected and the environmental considerations or conditions governing the approval of a specific site are met.

5. *Vacuum Subsystem Test/Evaluation*. The vacuum subsystem is the most expensive element to be designed; and an early evaluation, through testing of selected components (Sec. 3), is felt to be a cost effective activity. These activities will be initiated through paper studies starting sufficiently far in advance of the actual physical studies, discussed in Section 3, to allow them to be carried out in an orderly, cost effective manner.

6. *JPL Memorandum of Understanding*. These milestones are related to an agreement with the management of the Jet Propulsion Laboratory on the level of support that will be made available to the Gravity Wave Project. There will be two agreements, one for the Engineering Design and a second for the Construction, when it is approved by the NSF.

7. *Formal Cost Reviews* Formal cost reviews will be conducted periodically to insure that the Project has not overlooked any substantial elements of cost. The Project Standing Review Board will be charged to examine the method of collecting the elements of cost against the specific system designs. This Board is chartered by the Steering Committee and consists of members who, in general, do not have administrative or management involvement in

the Project. The Board reports its findings to the Administrations of the two Institutes, the Gravity Wave Steering Committee and the Project. Two reviews will provide oversight of the cost estimates prepared during the conceptual and detailed engineering design phases of the effort. A third will be held to review the independent assessment of the construction cost. Two others will be held to review the RFPs before their release.

8. *Administration Proposal Review.* Periodic reviews of the Project are made by the administrations of MIT and Caltech in accordance with the Memorandum of Understanding discussed earlier; a copy of the MOU is contained in Appendix J. These reviews are scheduled to occur at approximately six month intervals. The meeting schedule may be adjusted to accommodate the specific needs of the program and the administrations.

9. *Prepare Requests (RFP) for Procurement*

   a. Detailed Engineering Design. This period will be used to formulate a RFP for the detailed engineering design. The results of the subsequent contract will be a set of detailed design drawings, a preliminary plan for the construction of the facilities, and a more accurate estimate of the facilities cost. The RFP will be based on the conceptual design as modified by investigations and studies conducted between now and the RFP review.

   b. Construction. This period will be used to prepare a RFP for the construction of the system. This RFP must be in preparation prior to the approval of the NSF to proceed, since otherwise a gap in the program would occur. Processing of the RFP through release would not take place until after the NSF makes a decision on construction.

10. *Formal Requests for Procurement Review.* The RFP's will be formally reviewed by the Project Standing Review Board to ascertain that they incorporate the pertinent Functional Requirements and are concise in terms of objectives, constraints, and methods of proposal evaluation.

11. *Issue Requests for Procurement.* These events are critical to the schedule for preceding with the detailed design and the construction of the system; they represent major milestones for the Project. It is the culmination of a number of activities that conclude with a formal review of the RFP's.

12. *Proposal Evaluation.* This is the period set aside for the proposal evaluation process and includes any time required to obtain additional data from the prospective engineering design or implementation contractor(s) prior to contract awards. It also includes the time required to fact find and negotiate contracts.

13. *Contract Awards.* Contract awards are major milestones for the Project.

14. *Data Handling Subsystem Development.* This milestone involves the process of identifying and specifying elements that comprise the data handling subsystem and its interfaces with the rest of the system. This is being undertaken at this early stage because of the necessity of ensuring that the data subsystem can supply the data on facility operations and environmental conditions, which are required to facilitate the reduction and analysis of the gravity-wave data acquired by the receivers.

15. *Establish Facility/Receiver and Data Subsystem Interfaces*. Establishing interfaces between the facility and the receiver and data subsystems takes a very high priority in the later portion of the engineering design phase since it is these interfaces that determine where the lines between subsystems are drawn. It also determines the instrumentation supplied by the facility subsystems and that supplied by the receiver and data subsystems. There will be a considerable interaction between the engineering design contractor and the Project on these interfaces so that cost effective tradeoffs can be made.
16. *Establish Inter/Intra Site Communication Requirements*. This activity involves the communication between the elements internal to each of the two facilities. There will be a communication link between each site and the two involved institutions. There will also be communication links internal to each of the sites. The development and implementation of these links must be coordinated to be cost effective
17. *Contractor Reviews*. There will be three reviews of the engineering design contractor. These reviews were discussed in detail in Section 4.
18. *Contractor Activities*. Two sets of contractor activities are shown, the detailed engineering design and the construction of the LIGO facilities. The construction activities are shown for schedule completeness only.
19. *Implementation Plan*. The Project Implementation Plan, discussed in Sec. 4.3, is the composite approach taken to the logical development of the Project. It serves as the plan that will be pursued in the design and construction phases of the program and as a device for communicating the intent of the Project to outside groups.
20. *Independent Cost Assessment*. A contract will be let to a consultant group, which has no involvement in the Project, to independently evaluate the cost data prepared by the detailed engineering design contractor and the Project so as to ascertain whether the cost estimates are based on valid design approaches.

APPENDIX H
IMPLEMENTATION OF THE DETAILED ENGINEERING DESIGN

H.1 Background

There are three critical factors in our ability to be successful in the design, development, and construction of the LIGO. The first is a clear understanding of the vacuum subsystem, since it is costly and once installed is difficult to redesign or modify. The second factor is the detailed design of the LIGO to establish that the approach being taken is optimum from the standpoint of both function and cost. A third, and equally critical, factor is the development of the personnel and resource base to manage and direct the effort. We feel that our approach, discussed in Sec. 4, will provide us with the capacity to perform this effort.

We have proposed a series of tests and evaluations of the vacuum subsystem (Sec. 3) that will provide us with a knowledge of the critical components and techniques necessary to be successful. We are also looking to the future in developing receiver subsystem components that have the largest impact on performance. The mirrors for the Fabry-Perot and Michelson approaches have to be examined carefully prior to proceeding with construction since their design and/or development can have a significant effect on system performance and cost. The development of the ND:YAG laser, preferably with frequency doubling, at this early stage is necessary since the efficiency of the lasers impact the cost of both designing and constructing the laser cooling equipment, and also the cost of operating the system. The potential factor of 50 to 100 increase in efficiency substantially reduces both of these costs.

The detailed engineering design will provide us with a better estimate of construction cost before committing us to construction. The approach we discussed earlier will yield a set of detailed engineering drawings and a plan for the construction that can be used to evaluate the concept without making a commitment to proceed. We have also proposed that the cost estimates prepared by the engineering design contractor be independently assessed to ensure that we have a firm basis on which to proceed with construction. We have put a number of checks and balances, characterized by the reviews, comparisons of conceptual design approaches, and tests and evaluation of components, into the effort to enable us to understand where we are going and how we are to get there.

The development of a management structure, with its trained support staff, is essential to the effort. We are proposing a program that assumes continuity of effort in order to minimize the overall cost. The techniques we are proposing for managing, monitoring, controlling and assessing the performance of the entire effort are essential to our ability to be successful. These techniques, established in the engineering design phase, will be used also throughout the construction, changing only in the scale required for evaluating our progress against our plan. The availability and flexibility of the resources of the Jet Propulsion Laboratory provides us with a substantial capability to adjust and accommodate problems without having to maintain a large project staff.

We feel that we have taken a system approach that will provide for the successful construction of the facilities to meet the needs of the LIGO system within predictable performance, cost and schedule considerations.

H.2 Budget Estimate for System Construction

An estimate, derived entirely from data generated thus far in the conceptual design, is submitted for the reviewers' information. This estimate is for a configuration consisting of two 8 chamber, 4 kilometer systems as discussed in Section 2. This estimate is broken down, as outlined in the Work Breakdown Structure of Section 4, into tasks and subtasks to insure that all elements that have cost implications are included.

The four primary subsystems at each site are the vacuum, receiver, facility and data subsystems. The vacuum and facility subsystems have the greatest impact on system cost, comprising more than 90 percent of the capital investment in the program.

Table H-1 is a summary of the costs for construction of the LIGO in accord with our present conceptual design, in fiscal year 1985 dollars. The costs are separated into individual work elements in the Work Breakdown Structure. The costs are separated into those that are dependent on the antenna arm length and those that are fixed. As additional data are developed they will be incorporated into our cost estimates. We have a program underway to continuously examine the cost of various options in order to enhance our cost effectiveness.

As discussed in Section 2, we have also considered the cost of bringing the system up to full capability through the addition of three additional chambers in the apex building to provide an 11 chamber, 4 kilometer facility. This would allow the simultaneous operation of at least three receivers. The cost of the upgrade is approximately $3,455,000 in 1985 dollars, plus 12.5% contingency for a total of $3,887,000.

TABLE B-1

WBS SUMMARY AS A FUNCTION OF FIXED AND LENGTH DEPENDENT COSTS

ESTIMATE IN 1985 DOLLARS

SYSTEM COSTS $63,683,356

WBS #	TITLE	FIXED COST ELEMENTS	LENGTH DEPENDENT
		$25,997,218	$37,686,138
1000	PROJECT MANAGEMENT TOTALS	$1,649,056	$0
1010	PROJECT MANAGER		
1020	PROJECT TRAVEL		
1030	PROJECT DOCUMENTATION		
1040	PROJECT REVIEWS		
1050	PROJECT SAFETY		
1060	PROJECT SECURITY		
1070	FINANCIAL MANAGER		
1080	PROJECT SUPPORT		
1090	LAND ACQUISITION COSTS		
1100	ENVIRONMENTAL IMPACT REPORTS		
1200	BLANK		
1300	FUNCTIONAL REQUIREMENTS		
2000	SYSTEM DESIGN TOTALS	$5,535,102	$0
2010	SYSTEM ENGINEER		
2020	MECHANICAL ENGINEER		
2030	VACUUM/OPTICS ENGINEER		
2040	JPL SUPPORT		
2050	SYSTEM VALIDATION		
2300	FUNCTIONAL SPECIFICATIONS		
2400	OPERATION/MAINTANCE MANUAL		
2500	CONFIGURATION CONTROL		
3000	VACUUM SUBSYSTEM TOTALS	$4,625,059	$21,896,057
3010	CHAMBER ASSEMBLY, CENT STA (4)	$1,100,160	
3020	CHAMBER ASSEMBLY, MID STATION	$468,160	
3030	CHAMBER ASSEMBLY, END STATION	$468,160	
3040	CHAMBER SUPPORT ASSEMBLY	$608,160	
3050	VACUUM PIPE ASSEMBLY		$13,992,350
3060	SUPPORT ASSEMBLY, VACUUM PIPE		$1,877,064
3070	VACUUM PUMP ASSEMBLY	$890,400	$2,311,600
3080	VAC BAKE POWER DIST ASSY		$2,961,424
3090	CHAMBER BAKEOUT COVER	$120,000	
3300	FUNCTIONAL SPECIFICATIONS	$388,200	$171,800
3400	OPERATION/MAINTANCE MANUAL	$185,600	$105,300
3600	SPARES	$524,612	$348,116
4000	RECEIVER SUBSYSTEM TOTALS	$3,000,000	$0
4010	MASS SUSPENSION ASSEMBLIES		
4020	LASER ASSEMBLIES		
4030	FILTER/MODULATOR ASSEMBLIES		
4040	OPTICS ASSEMBLIES		
4050	POCKELS CELLS		

WBS SUMMARY AS A FUNCTION OF FIXED AND LENGTH DEPENDENT COSTS

4060	DISPLAY ASSEMBLIES		
4070	POWER SUPPLY ASSEMBLIES		
4080	ELECTRONIC CONTROL ASSEMBLIES		
4090	ANTICOINCIDENCE ASSEMBLIES		
4300	FUNCTIONAL SPECIFICATIONS		
4400	OPERATION/MAINTANCE MANUALS		
4600	SPARES		
5000	FACILITIES SUBSYSTEM TOTALS	$7,521,340	$11,079,440
5010	SITE DEVELOPMENT	$415,991	$815,991
5020	CENTRAL STATION BUILDING ASSY	$1,775,288	
5030	MID STATION BUILDING ASSEMBLY	$730,080	
5040	END STATION BUILDING ASSEMBLY	$730,080	
5050	PROTECTIVE HOUSING ASSEMBLY		$8,974,752
5060	POWER DISTRIBUTION ASSEMBLY	$606,531	$909,797
5070	LASER COOLING ASSEMBLY (.5 MW)	$544,000	
5080	TRAILER ASSEMBLY	$150,000	
5090	HOUSEKEEPING ASSEMBLY	$872,728	
5100	INTERCOMMUNCIATION ASSEMBLY	$50,000	
5110	FURNISHINGS	$204,330	
5120	SECURITY ASSEMBLY	$218,182	
5130	SEISMIC MONITOR ASSEMBLIES	$36,364	
5140	TRANSPORTATION VEHICLES	$66,666	
5150	EMERGENCY/BACKUP EQUIPMENT	$60,000	
5300	FUNCTIONAL SPECIFICATIONS	$361,100	$198,900
5400	OPERATION/MAINTANCE MANUAL	$180,000	$60,000
5600	SPARES	$464,200	$176,000
6000	DATA ANALYSIS SUBSYSTEM TOTALS	$600,000	$0
6010	PRIMARY PROCESSOR		
6020	STATION PROCESSORS		
6030	REALTIME DATA LINKS		
6300	FUNCTIONAL SPECIFICATIONS		
6400	OPERATION/MAINTANCE MANUAL		
6500	CONFIGURATION CONTROL		
8000	CONTINGENCY TOTALS @ 12.5%	$3,066,661	$4,710,641

APPENDIX I

MILESTONES FOR DEMONSTRATION OF TECHNICAL FEASIBILITY USING PROTOTYPE INTERFEROMETERS

An overall milestone that we expect to pass before the time for approval of construction of the large baseline system is the demonstration of a displacement sensitivity of 1 E -18 meters per root hertz* at frequencies of interest in a gravitational wave search. Such a displacement sensitivity corresponds approximately to a strain sensitivity of 7 E -21 in a bandwidth of 1 khz for an antenna with arms 5 km long.

(Note: In the following table, dates of some milestones already passed are indicated by X, and dates expected for passing some possible future milestones are indicated by ?.)

		1983			1984				1985				1986				1987		
		2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3
1. Displacement sensitivity (meters per root hertz)	1 E -14	X																	
	3 E -15		X																
	1 E -15					X													
	3 E -16					X													
	1 E -16							X											
	3 E -17							X											
	1 E -17											?							
	3 E -18														?				
	1 E -18																	?	
2. Seismically induced noise ** (meters per root hertz)	1 E -15	X																	
	1 E -16					X													
	1 E -17							X											
	1 E -18											?							
3. Thermal and mechanical noise (meters per root hertz)	1 E -15					X													
	1 E -16							X											
	1 E -17										?								
	1 E -18																	?	

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*The notation 1 E -18 is used here to represent the number 1×10^{-18}

**These noise data, measured on prototypes located in heavily populated areas, have been scaled to correspond with the reduced ground motion found at the planned sites for the large interferometers.

		1983			1984				1985				1986				1987		
		2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3
4. Light power to interferometer arms	10 mW	X																	
	100 mW															?			
	1 W																	?	
5. Beams between test masses:-																			
Cavity storage time achieved	10 microseconds	X																	
	100 microseconds		X																
	1 millisecond					X													
Delay line reflections achieved	56						X												
	198												?						
6. Operation in a gravity wave search:-																			
(a) for a periodic signal, period known		X																	
(b) for hidden periodicities from selected regions of the sky															?				
(c) for burst signals																		?	
7. Some ancillary experimental milestones foreseen:-																			
(a) Development of an automatic laser beam and cavity alignment system													?						
(b) Development of optical system for recombining cavity outputs																		?	
(c) Operation with higher power argon lasers and more efficient laser stabilization																?			
(d) Installation of cryopump system to improve vacuum in 40 m interferometer														?					
(e) Tests of mode locked NdYAG laser												?							
(f) Tests of high power electro-optic modulators																?			
(g) Tests of large diameter optical fibers												?							

APPENDIX J

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.