R & D Proposal

CALTECH/MIT PROJECT FOR A LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

CALIFORNIA INSTITUTE OF TECHNOLOGY

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

December 1987

COVER SHEET FOR PROPOSALS TO THE NATIONAL SCIENCE FOUNDATION

FOR CONSIDERATION BY NSF ORGANIZATIONAL UNIT (Indicate the most specific unit known, i.e. program, division, etc.)	PROGRAM ANNOUNCEMENT/SOLICITATION NO./CLOSING DATE
Gravitational Physics/Division of Physics	

SUBMITTING INSTITUTION CODE (If known)	FOR RENEWAL ☒ CONTINUING AWARD ☐ ACCOMPLISHMENT BASED RENEWAL ☐ REQUEST, LIST PREVIOUS AWARD NO.:	IS THIS PROPOSAL BEING SUBMITTED TO ANOTHER FEDERAL AGENCY? Yes___ No X ; IF YES, LIST ACRONYM(S)
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TITLE OF PROPOSED PROJECT
Caltech/MIT Project for a Laser Interferometer Gravitational Wave Observatory

REQUESTED AMOUNT	PROPOSED DURATION	DESIRED STARTING DATE
$18,118,396	Three (3) Years	1 June 1988

CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW:

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☐ Marine Mammal Protection	☐ Historical Sites	☐ Proprietary and Privileged Information
☐ Pollution Control	☐ Interdisciplinary	

PI/PD DEPARTMENT	PI/PD ORGANIZATION	PI/PD PHONE NO. & ELECTRONIC MAIL
Division of Physics, Mathematics & Astronomy	California Institute of Technology	(818)-356-3800 vogt@caltech.edu

PI/PD NAME/TITLE	SOCIAL SECURITY NO.*	HIGHEST DEGREE & YEAR	SIGNATURE
Rochus E. Vogt Director, LIGO; Prof. of Physics	345-30-2172	Ph. D. - 1961	[signature]
ADDITIONAL PI/PD (TYPED)			
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OTHER ENDORSEMENT (optional)			
NAME/TITLE (TYPED) W. Barclay Kamb Vice President and Provost	B Kamb	14 Dec 87	(818)-356-6336

*Submission of social security numbers is voluntary and will not affect the organization's eligibility for an award. However, they are an integral part of the NSF information system and assist in processing the proposal. SSN solicited under NSF Act of 1950, as amended.

NSF FORM 1207 (1-87)

Renewal Proposal

to the

National Science Foundation

CALTECH/MIT PROJECT

FOR A

LASER INTERFEROMETER

GRAVITATIONAL WAVE OBSERVATORY

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Table of Contents

PROJECT SUMMARY

This proposal requests support for a three year program of research and development towards the establishment of a laser interferometer gravitational wave observatory (LIGO) with sensitivities in the domain of theoretical expectations for gravity waves. This joint undertaking of the California Institute of Technology and the Massachusetts Institute of Technology is based on more than a decade of research and development of laser interferometer gravitational wave receivers. We propose to continue research and development of gravity wave receivers towards ever higher sensitivities and towards the design of operational full scale LIGO receivers. We will continue feasibility demonstrations and tests of critical components for the LIGO. We will complete the conceptual design of the LIGO, consisting of L-shaped interferometer receiver systems with 4 km sides at two cross correlated sites. We will undertake a Preliminary Design and Cost Definition task, leading to a proposal to NSF in 1989 for construction of the LIGO. The ultimate objectives of the LIGO program include (i) tests of Einstein's General Theory of Relativity, in particular, measurements of the graviton rest mass and spin, tests of general relativity in the domain of highly non-linear, dynamic gravity, and (ii) the opening of a window to the universe radically different from electromagnetic, cosmic-ray, or neutrino astronomy.

I. INTRODUCTION

Laser interferometer gravity wave receivers have been developed to the stage where it is possible to design full-scale instruments with sensitivities in the range of anticipated astrophysical signals. This proposal requests support for a three year program of research and development towards the establishment of a laser interferometer gravitational wave observatory (LIGO). The research and development activities leading up to this proposal were accomplished under separate NSF grants, with R. W. P. Drever (Caltech) and R. Weiss (M.I.T.) serving as Principal Investigators, respectively. Work since September 1987 has been performed with R. E. Vogt serving as Project Director, and R. W. P. Drever and R. Weiss acting as leaders of their respective science teams. Future operations under the new management structure are discussed in Part VII.

Important scientific results in the areas of basic physics and in astronomy and astrophysics are expected from the LIGO. Theoretical astrophysics now gives estimates of the strength of waves from supernovae and other stellar collapses to neutron stars, stellar implosions that form black holes, pulsars, coalescing neutron-star or black-hole binaries, rotating neutron stars, gravitational-spindown neutron stars, and other burst, periodic, and stochastic sources. These estimates indicate that there is a significant, though not high, chance that waves will be detected with the initial LIGO receivers. Detection is highly probable at the sensitivities of expected advanced receivers.

The LIGO project, a joint undertaking of the California Institute of Technology and the Massachusetts Institute of Technology, is based on more than a decade of research and development of laser interferometer gravitational wave receivers.

The National Science Foundation has supported Caltech and MIT for a number of years in their research on interferometric receivers and in their initial design studies of a LIGO. Funds from this proposal will carry these designs to the point where an accurate cost estimate can be made. This will lead in 1989 to a proposal to the NSF for the final engineering design and construction.

Receiver development during the next three years will be directed toward a design for the full-scale system. Higher sensitivity and extended frequency coverage will be pursued. In addition, the engineering of components and controls for the reliable operation required in the LIGO will begin. Fabrication and tests of large mirrors and analyses and tests of other features required for the full-sized system will be conducted. The conceptual design of the LIGO will be completed and functional requirements defined. These will form the basis for a Preliminary Engineering Design and Cost Definition of the LIGO vacuum facilities, the architectural and civil engineering work at specific sites, the receivers, and the data and instrumentation systems. This work will be done by an engineering firm. The design and cost estimate from this contracted work will then be used in the proposal for construction of the LIGO.

The LIGO will consist of a pair of cross-correlated receivers located far apart within the continental United States and housed in L-shaped vacuum systems; the arms of each system will be about 4 kilometers in length (Figure I-1). The two receivers, together with their electronics and data analysis system, make up a gravitational wave "detector." Cross-correlation of receivers at two sites will secure the identification of gravity waves.

The "observatory", consisting of the receivers and facilities at both sites, shall be under one management to optimize design tradeoffs, provide for simultaneous start-up, and assure a high live time. The LIGO will be designed as a facility with expandability to support multiple detectors of ever-increasing sensitivity as receiver technology develops.

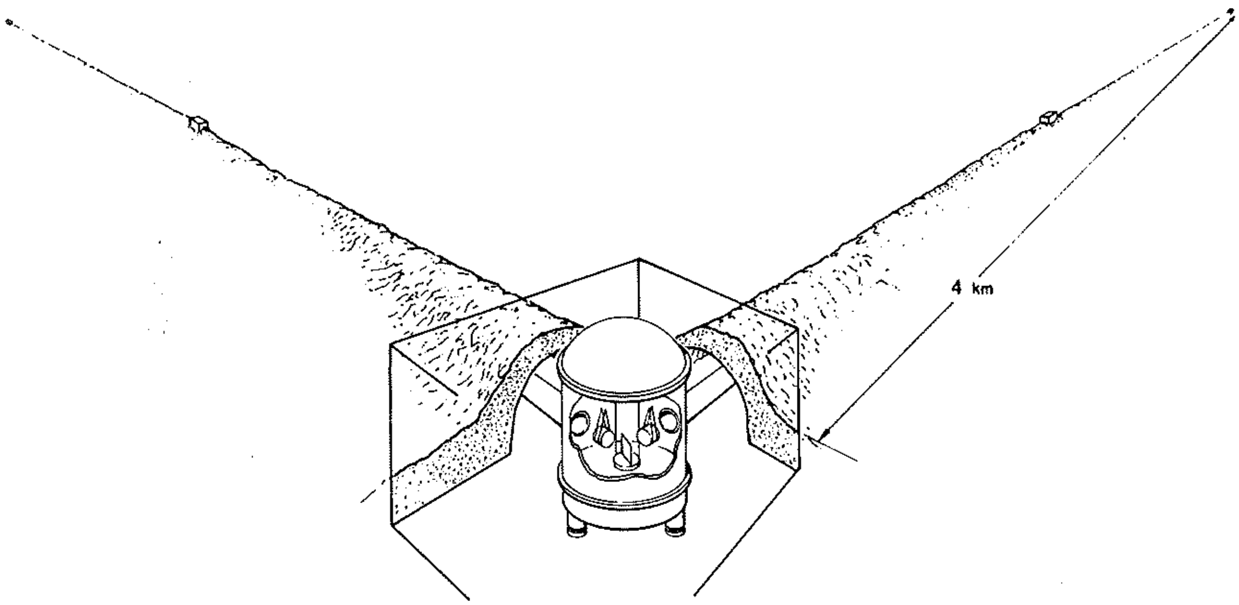

Figure I-1 Artist's conception of a LIGO receiver installed at one of the two sites.

The LIGO facilities will accommodate gravitational wave searches and receiver development concurrently. After shakedown, the LIGO will be used in a national program for gravitational astronomy, open to all qualified participants. It is expected that a world-wide network of gravitational wave detectors will eventually be built up around the LIGO. Such a network, not unlike the VLBA in radio astronomy, will be necessary for extraction of the full information carried by gravitational waves.

II. SCIENCE

This section presents in brief the scientific justification and goals of the LIGO Project. For greater detail on these issues and for references to the literature see Appendix A.

A. The Physics of Gravitational Waves and Interferometric Detectors

Gravitational waves are predicted by general relativity theory and by all other relativistic theories of gravity, and all the theories agree, in rough order of magnitude, on the strengths of the waves to be expected from astrophysical sources. However, the theories disagree on a wave's propagation speed (from which one can infer the rest mass of the graviton) and on its polarization properties (from which one can infer the graviton's spin). In general relativity the propagation speed is the same as light (the graviton has zero rest mass), and the wave's force field is transverse to its propagation direction and has quadrupolar symmetry (the graviton has spin two). The two polarization states of general relativity's wave are called + ("plus") and × ("cross") and are characterized by two dimensionless fields h_+ and $h_\times$.

A *laser interferometer gravitational wave receiver* ("interferometric receiver"; also called an "antenna"), in its simplest conceptual variant, consists of three masses that hang by wires from overhead supports at the corner and ends of an "L" (Figure II-1a). A gravitational wave pushes the masses back and forth relative to each other, changing the difference $L_x - L_y$ in the length of the receiver's two arms by an amount ΔL that is proportional to arm length, L, and to a linear combination of h_+ and $h_\times$:

$$\frac{\Delta L}{L} = [1/2(1+\cos^2\theta)\cos 2\phi]h_+ + [\cos\theta\sin 2\phi]h_\times \equiv h \,. \tag{1}$$

Here (θ, ϕ) is the wave's propagation direction. By laser interferometry one directly reads out $\Delta L/L$ and from its time evolution, the combination, called h, of $h_+(t)$ and $h_\times(t)$ in equation (1).

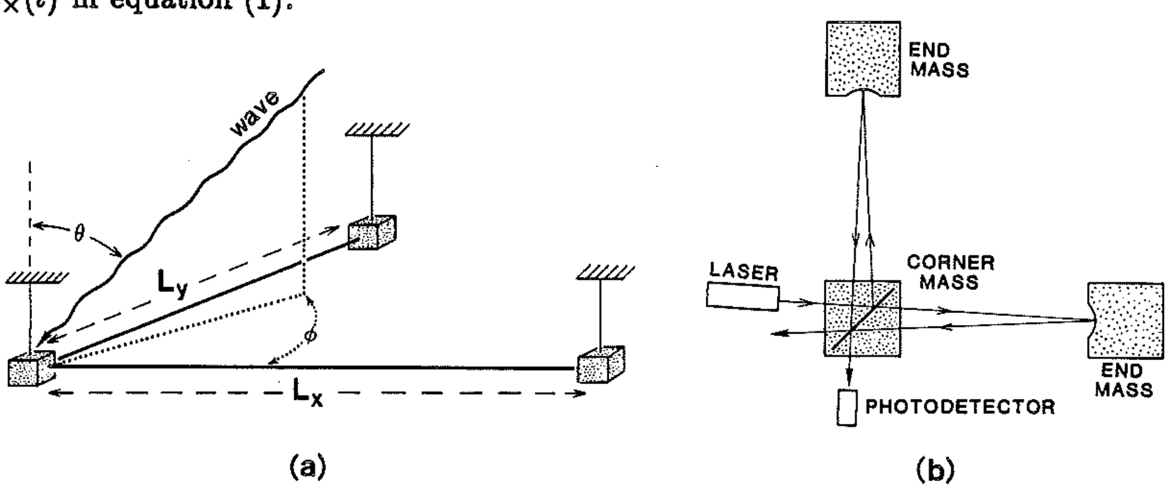

Figure II-1 Schematic diagram of a laser interferometer gravitational wave detector.

Laser interferometry in its simplest theoretical variant is performed as follows: Light from a laser shines on a beamsplitting mirror that rides on the central mass (Figure II-1b). The beam splitter directs half the light toward each of the two end masses, and mirrors on those masses return beams to the splitter where they are recombined. The gravity-wave-induced change ΔL in the arm length difference produces a relative phase shift in the recombining beams, and thence a shift in how much of the light goes into the photodetector of Figure II-1b versus how much goes back toward the laser. The photodetector output therefore varies in direct proportion to ΔL and thus proportionally to the combination of $h_+(t)$ and $h_\times(t)$ appearing in equation (1). In realistic variants of such a detector (Part V and Appendices F, G, H, below), the ΔL-induced phase shift is increased by placing mirrors on the corner mass as well as the ends, and then bouncing the light back and forth many times in each arm ("delay-line interferometric receiver") or operating each arm as a giant Fabry-Perot cavity ("Fabry-Perot interferometric receiver").

Since ΔL is proportional to L, the longer are the arms L, the greater will be the relative phase shift for the beams that propagate down the arms, and the more sensitive will be this interferometric receiver. That is why we are planning to upgrade from our present prototype receivers with $L \leq 40$ meters to a full-scale LIGO with $L = 4$ kilometers.

By cross correlating the outputs of several receivers with different orientations and different locations on earth, i.e., by using them as a single detector, one can read out the full information carried by the wave: the direction (θ, ϕ) of its source and the time evolution of its two *wave forms* $h_+(t)$ and $h_\times(t)$. One can also read out the spatial pattern of the forces that act on the detector's masses and from it infer the wave's polarization properties and thence the graviton's spin. If the wave's source is also seen with electromagnetic telescopes (optical, radio, X-ray, ...), e.g. if it is a supernova, then by measuring the delay between the electromagnetic and gravitational signals one can determine whether photons and gravitons propagate at the same speed and thus have zero rest mass.

The gravitational wave forms $h_+(t)$ and $h_\times(t)$ carry detailed information about their sources; and because the strongest sources in the LIGO's huge frequency band (10 Hz $\lesssim f \lesssim 10^4$ Hz) are likely to be neutron stars and black holes, the wave forms can bring us detailed information about the dynamical behaviors of these objects in violent events such as their births and collisions; cf. Figure A-3 in Appendix A. A stochastic background of gravitational waves from the big bang could bring us detailed information about the earliest moments of the universe; and coalescing, compact binary stars could act as standard candles for measuring the large-scale structure of the universe today; see Appendix A for details.

Gravitational and electromagnetic waves differ greatly: Gravitational waves should be emitted by coherent bulk motions of matter (e.g. collapsing stellar cores) and coherent, nonlinear vibrations of spacetime curvature (e.g. collisions of 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 relativistically strong, whereas electromagnetic waves come almost entirely from weak-gravity regions, since strong-gravity regions tend to be obscured by surrounding matter. Because of these differences, the information carried by gravitational waves is almost "orthogonal" to that carried by electomagnetic; and our present electromagnetically-based understanding of the universe is inadequate to predict with confidence the strengths of the gravitational waves bathing the earth. Obversely, if gravitational waves can be detected and studied, they may create a revolution in our view of the universe comparable to that wrought by radio astronomy.

B. Scientific Payoff from the LIGO Project

From the above discussion and the further details in Appendix A we cull the following list of scientific payoffs that might come from the LIGO Project. The Project is being designed and managed, so far as possible, in such a way as to maximize the likelihood that some or most of these payoffs will be achieved.

Possible Payoffs for Physics

- The verification of the existence of gravitational waves.
- Measurement of the rest mass and spin of the graviton: do they agree with general relativity's predictions, $m = 0$ and $s = 2$?
- Verification (by comparing theoretical and observed wave forms) that black holes exist and that their dynamics are as predicted by general relativity. Thereby test general relativity for the first time in the domain of highly nonlinear, dynamic gravity.

Some Possible Payoffs for Astronomy and Astrophysics

- Open up a new window onto the universe, a window that is almost certain to bring surprises and that may bring a revolution comparable to that which came from the radio window in the 1950s and 60s.
- Study the behavior of neutron stars in highly dynamical situations. Thereby extract information about the uncertain physics that governs neutron stars.
- Use the waves from binary coalescences as "standard candles" for the determination of the Hubble expansion rate and deceleration parameter of the universe (see App. A).
- Detect primordial gravitational waves from the big bang, and from them extract information about the initial conditions and earliest stages of evolution of the universe.

C. Estimates of the Strengths of the Waves at Earth and Comparison with Anticipated LIGO Sensitivities.

Whether these payoffs can be achieved will depend on whether detectors in the LIGO can reach the required sensitivities. Figure II-2 gives some indication of the prospects for this by comparing the wave strengths from various hypothesized burst sources with several benchmarks for detector sensitivity. (For the details underlying Figure II-2, and for similar figures for periodic and stochastic waves, see Appendix A.)

The most certain of the sources is coalescence of neutron-star binaries: Estimates based on pulsar statistics in our own galaxy suggest that to see 3 such events per year one should look out to 100^{+100}_{-40}Mpc distance. (See Appendix A for further details on this and all sources). For supernovae the event rate is known to be roughly one each 40 years in our own galaxy and several per year in Virgo, but the amount of radiation emitted is very uncertain. For black hole births, both the wave-emission efficiency and the distance to which one must look are highly uncertain.

The upper solid curve and stippled region in Figure II-2 indicate the present sensitivity of our 40-meter prototype. The middle thick curve and stippling indicate the sensitivity of an early detector that might operate in the LIGO (see Equation A.21, Appendix A).

Once the first detector has been operated near the sensitivity of the middle curve, there will follow in the LIGO a succession of ever improving detectors, continually pushing the sensitivity level downward (to smaller h) and leftward (to lower frequencies f). As a rough measure of where this might lead after a few years, we have drawn a lower sensitivity region corresponding to a "Possible Advanced Detector" (see Equation A.23, Appendix A). The only limit of principle on detector sensitivities in the LIGO is the "quantum limit" (dashed line)—and with cleverness, ways of circumventing it might be found.

By comparing the source strengths and benchmark sensitivities in Figure II-2 and in the periodic and stochastic figures A-4b,c (Appendix A), one sees that *(i) There are nonnegligible possibilities for wave detection with the first detector in the LIGO. (ii) Detection is probable at the sensitivity level of the advanced detector. (iii) The first detection is most likely to occur, not in the initial detector in the LIGO but rather in a subsequent one, as the sensitivity and frequency are being pushed downward from the middle curve toward the bottom curve of Figure II-2.*

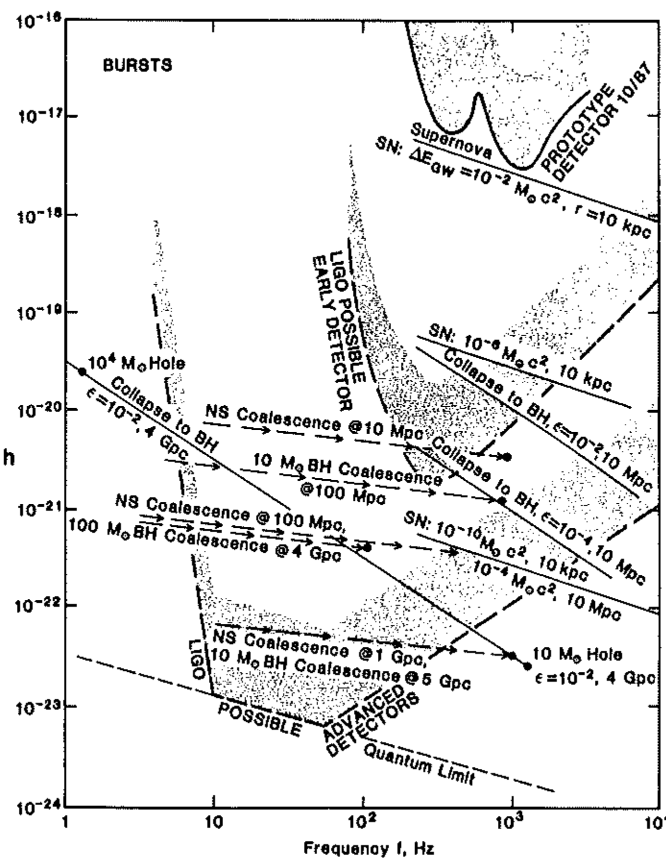

Figure II-2 The estimated wave strengths for various sources of gravitational-wave bursts (thin solid curves and arrows); and benchmark sensitivities for interferometric detectors today and in the proposed LIGO (thick curves and stippling above them). For analogous figures on periodic and stochastic gravitational waves and for the details underlying this figure see Appendix A. Abbreviations: SN—supernova; NS–neutron star; BH–black hole; $M_{\odot}c^2$–one solar rest mass (units for energy carried by the waves); ϵ—the fraction of the mass of a black hole emitted in the waves. The assumed distances to the sources include 10 kpc—10 kiloparsecs (center of our galaxy); 10 Mpc—10 megaparsecs (Virgo cluster of galaxies); 4 Gpc—4 gigaparsecs (the edge of the observable universe). For each detector the bottom curve is the sensitivity at unity signal-to-noise for a wave with optimal direction and polarization (the conditions under which detector sensitivity is normally quoted); and the top of the stippled region is the sensitivity for 90% confidence of detection of very rare events, e.g., once per month or year, with random source direction and polarization.

D. Other Methods of Detecting Gravitational Waves

The above discussion provides a basis for comparing the LIGO project with other methods of detecting gravitational waves (for a more detailed comparison and for references to the literature see Appendix E):

There is a rich potential for gravitational wave astronomy at frequencies below the LIGO's 10 Hz cutoff; but such frequencies probably cannot be reached with earth-based detectors. The best long-term promise in this band lies with interferometric detectors in space, which will rely in considerable measure on experience with the LIGO.

In the LIGO's frequency band, earth-based bar detectors have been under development since the early 1960s, a decade longer than interferometric detectors. Room temperature bars achieved an h-sensitivity for bursts of 3×10^{-17} in the mid 1970s (before the Caltech and MIT interferometric efforts began); and by cooling to 4K, they (Stanford and Rome/CERN) are now at 1×10^{-18}, a factor 3 better than our present 40-meter prototype. For the foreseeable future, bars will remain an important component of the world's gravitational wave research effort and they may well improve into the vicinity of 10^{-20}, adequate for detection of rare events in our own galaxy or the Magellanic clouds, but inadequate for extragalactic astronomy, the realm of large event rates.

Bar detectors cannot be lengthened to kilometer scales, with an accompanying large sensitivity improvement (recall: $\Delta L \sim hL$), because they rely on sound waves (speed ~ 1 meter per millisecond) for coupling their two ends, rather than light (speed 300 kilometers per millisecond). As a result, it is unlikely they will reach the LIGO's projected sensitivity region, $\sim 10^{-21}$ to $\sim 10^{-23}$ (the realm of extragalactic astronomy); cf. Figure II-2. Also, bar detectors have difficulty achieving large band width, and correspondingly can extract only limited information from any waves they discover. At present their bandwidths are $\Delta f/f \sim 0.01$ at $f \simeq 900$ Hz, and there is hope in the future of reaching $\Delta f/f \sim 0.2$. By contrast, the present prototype interferometers have $f_{\rm max}/f_{\rm min} \sim 10$, and the LIGO is projected to have $f_{\rm max}/f_{\rm min} \sim 1000$ (figure II-2) — adequate for essentially full information extraction.

III. HISTORY OF THE PROJECT

The LIGO project is based upon a significant body of research and technical development over a period of almost 30 years.

After Weber's pioneering work on bar detectors for gravitational waves in the 1960's [III-1], other groups began to develop gravity-wave detectors. In the late 60's, the idea of interferometric detectors was conceived independently by Weber, Weiss, and others. The basic design for a delay line variant of an interferometric receiver was described and the dominant noise sources were quantified in 1972 by Weiss [III-2]. The first operation of an interferometric receiver was conducted by Moss, Miller, and Forward in 1971-72 [III-3].

In the early 1970's, many groups, including Drever at Glasgow and others at Stanford, LSU, IBM, Bell Labs, Rochester, Munich, Rome, and Moscow began research with bar detectors. Several of these groups have continued a strong program of research with successive detectors. A switch from bar detectors to interferometers was made by the Munich group under Billing in 1975 and the Glasgow group under Drever in 1977. A year later, Drever at Glasgow introduced the concept of the Fabry-Perot variant of an interferometric receiver [III-4].

In 1979 Drever started experimental gravity-wave research at Caltech. In the same year the National Science Foundation convened the Deslattes Committee which recommended strong funding of the gravity-wave field, including new interferometer projects at Caltech (Drever) and at MIT (Weiss). MIT pursued a delay-line or Michelson interferometer development, while Drever continued development of Fabry-Perot receivers.

In 1981, Weiss at MIT, with the firms of Stone & Webster and A.D. Little, began a detailed study of the design and costs of a large-scale Laser Interferometer Gravitational-wave Observatory, or LIGO [III-5]. A presentation by Drever, Thorne, and Weiss in 1983 to the NSF Advisory Committee for Physics led to its strong endorsement of the LIGO concept. In 1984, Caltech and MIT formally joined in a project for the design, construction and operation of the LIGO facility, under Drever, Thorne, and Weiss as a steering committee. In the same year the National Science Board approved project planning and feasibility studies. Further studies of design and cost were undertaken with the Caltech Jet Propulsion Laboratory in this period.

In 1986, the NAS Physics Survey strongly endorsed the LIGO for ground-based research in gravity [III-6]. Concurrently, the International Society of General Relativity and Gravitation strongly endorsed the LIGO.

In November, 1986 an NSF sponsored Workshop was convened at Cambridge, Massachusetts to review the state of developments in the field with particular attention to plans for the LIGO Project. The Workshop was attended by 55 international participants and a report of the meeting was prepared by an eight-member panel from disciplines other than experimental gravity. The report was highly supportive of the program and endorsed a vigorous pursuit of its goals. The Summary of this January, 1987 report to the NSF by the Panel on Interferometric Observatories for Gravitational Waves is included in this proposal in Appendix D. Two recommendations of the Panel have already been implemented: management of the project has been transferred from the steering committee to a Project Director, Rochus E. Vogt, and a choice has been made of the type of receiver (Fabry-Perot) to be used in the initial operations with the LIGO.

IV. LIGO CONCEPT AND LONG-RANGE PLANS

A. Essential Features of the LIGO

The LIGO design will be guided by two goals: (i) maximizing the probability of detecting gravitational waves; and (ii) extracting maximum information from the waves. These goals dictate the following essential features of the LIGO design. (Here we justify each feature only briefly; for more detail see Appendix B).

1. Two widely separated sites under common management. The unequivocal detection of gravitational wave bursts amidst instrumental and environmental noise requires cross correlation of two receivers at widely separated sites. Common management is essential to guarantee that two receivers of nearly equal sensitivity are on line simultaneously at two sites, with a high live time.

2. Arm lengths of order 4 kilometers at each site. A high probability of discovering waves (e.g., a high confidence of reaching the most reliably understood source, neutron-star binaries in distant galaxies) requires sensitivities near those of the "possible advanced detectors" of Figure II-2. Such sensitivities can be achieved only with arm lengths of the order $L \approx 4$ km. Because event rates scale as $(h\text{-sensitivity})^{-3}$, a reduction of L to 1 km, for example, would reduce by 64 the event rate and substantially reduce the probability of detection.

3. The ability to operate simultaneously several receiver systems at each site. The operation of successive generations of continually improving receivers in the LIGO, pushing downward toward the "advanced detector levels" of Figure II-2, will require the ability to develop new, more advanced receiver pairs simultaneously with gravity-wave searches by the best existing receiver pair. This will be possible only if each site can support several systems simultaneously, with a minimum of mutual interference.

4. The capability for receivers of two different arm lengths. The rate of spurious, instrumentally and environmentally induced events at each site may be so high that extensive local vetoes are needed in addition to cross correlation between sites. Simultaneous operation of a 2 km and a 4 km receiver at each site provides a powerful veto, since real events must have signals proportional to arm length. Dual arm lengths will also be important for diagnostic studies of local noise.

5. A vacuum tube diameter of order 48 inches. Several prospective optical configurations involve a large number of optical beams simultaneously occupying the vacuum tube. (Examples: (i) a single delay-line receiver; (ii) a 2-km, 4-km Fabry-Perot pair with additional beams used in antiseismic isolation, operating simultaneously with a more advanced receiver system under development.) A diameter of 48 inches is required by such configurations to make negligible the scattering of light from one beam into another and negligible diffraction and scattering by the tube walls.

6. The capability of a vacuum level of 10^{-8} torr. Fluctuations in the index of refraction of residual gas produce wave-imitating fluctuations in the light beams' phase delays. To keep this noise negligible requires for the first LIGO receivers a vacuum of only 10^{-3} torr of hydrogen or 10^{-4} torr of air; but "advanced " receivers (Figure II-2) will require 10^{-8} torr.

7. A minimum lifetime of the facilities of 20 years. Since the facilities will become a working physics laboratory and astronomical observatory with a rich spectrum of investigations, we must plan for a long life. Experience in other fields suggests 20 years as a reasonable minimum. In its mature phase (after the early gravitational-wave searches) the LIGO will be operated by Caltech and MIT as a facility open to investigations by experimenters from other institutions, capable of supporting several simultaneous investigations (see the discussion of national and international cooperation in Appendix C).

8. Adequate support instrumentation.

These essential features are incorporated into the conceptual design of the LIGO, currently under development. That design includes: (i) a selection of sites based on scientific, geophysical, and logistic considerations (the tentatively chosen sites are Edwards AFB, California and Columbia, Maine); (ii) stainless steel vacuum tubes and instrumentation chambers; (iii) enclosure of the vacuum tubes in a housing (e.g., a culvert) and insulation with an earthen berm. For details see Appendix B.

B. Plans and Schedules for the Entire LIGO Project

The LIGO Project will be accomplished in three phases: (i) completion of the conceptual design, the subject of current activity; (ii) a preliminary engineering design and cost definition phase to be supported by an industrial contractor, the subject of this proposal; and (iii) a detailed engineering design and construction phase, to be the subject of a future proposal. Our schedule is shown in Figure IV-1.

The current phase, completion of the conceptual design, will proceed while this proposal is being considered by the National Science Foundation. It is based largely on an earlier feasibility study by MIT/A. D. Little/Stone & Webster, and subsequent trade-off studies supported by the Caltech Jet Propulsion Laboratory. The focus of this activity, described in more detail in Part VI of this proposal, will be to complete the design requirements and baseline definition of the LIGO facilities, to complete those site studies necessary to support the preliminary engineering design (including final selection of primary and backup sites), and to prepare a Request for Proposal for the Preliminary Engineering Design and Cost Definition effort. These activities should be complete by the end of June, 1988.

Upon NSF's approval of funding for the second phase (this proposal) and completion of our preparations, we will solicit competitive proposals for a Preliminary Engineering Design and Cost Definition of the LIGO facilities. This will result in a negotiated Fixed Price Level-of-Effort contract with an experienced architectural and engineering firm to perform engineering design to the level of detail necessary to produce a reliable estimate of the costs of the LIGO facilities (see Part VI). The results of this intensive nine month effort will lead to the preparation of a proposal to the National Science Foundation for the construction the LIGO, which we expect to submit in September, 1989. During the six month interval required for NSF review of the construction proposal, we will complete preparations for the procurement and implementation of contracts for the final engineering design data (construction documents) and construction activities. NSF's final approval for the LIGO is expected in Spring 1990 on the basis of the construction proposal.

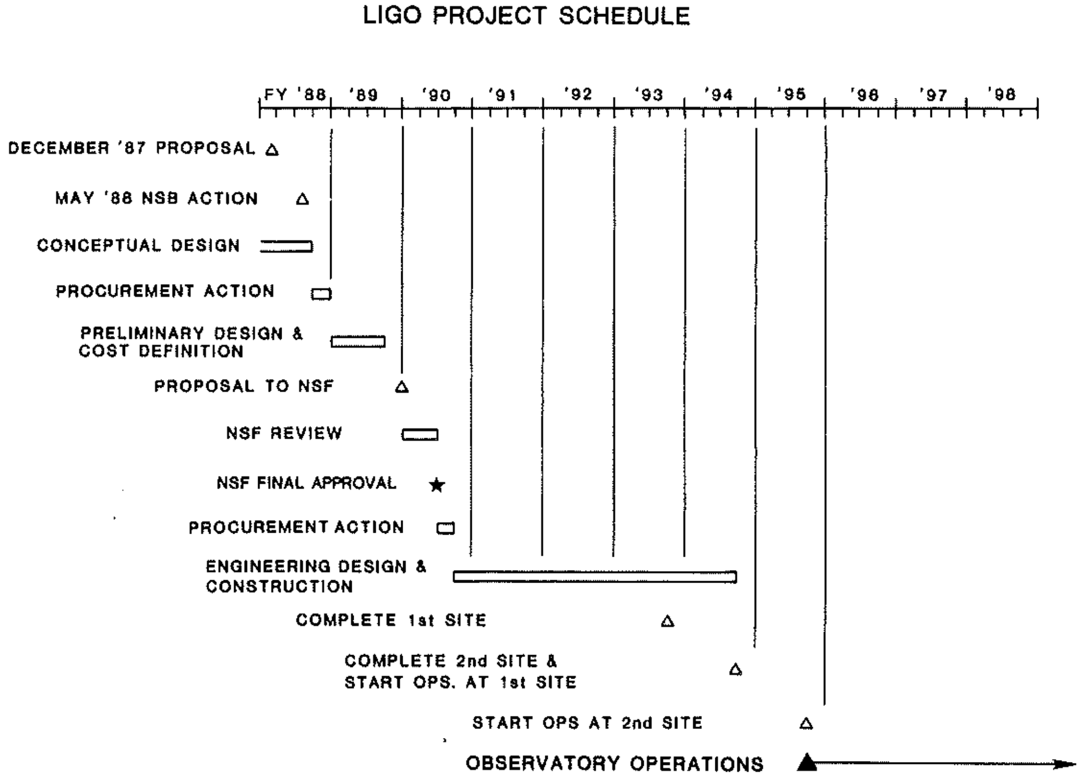

Figure IV-1 Schedule for the LIGO Project

The final engineering design and construction phase is a four year effort planned to begin in Summer 1990. Activities in the first year will concentrate on completion of detailed engineering design documentation, consisting of architectural drawings, specifications, detailed construction schedules and other construction documents. Site development will proceed in parallel, including construction of access roads and distribution of water and electrical power to the sites. Procurement of long lead-time items will commence. Construction of facilities at one site will proceed during the second and third years, and construction at the second site will proceed during the third and fourth years. This staggered construction plan will permit one engineering and construction team to implement the substantially identical vacuum systems at both sites, maximizing the benefits of experience gained from construction at the first site.

Upon completion of construction activities and acceptance testing at each site, we will proceed with start-up operations and installation of first receivers. We expect that testing, initial facility operation and debugging, and receiver installation, testing and debugging will take one year at each site. The first LIGO antenna should be operational by Summer, 1994, and the completed Observatory should be ready to begin operations in Summer, 1995.

V. RESULTS FROM PRIOR NSF SUPPORT

The preceding work has been supported under separate NSF grants to the science teams at Caltech and MIT (see also Part VII):

Award #: PHY–8504136
Amount of Award: $3,986,319
Award Period: July 1, 1985–February 29, 1988
Title of Project: "Investigations in Experimental Gravity and Gravitational Radiation"
Principal Investigator: Ronald W. P. Drever, Caltech

Award #: PHY–8504836
Amount of Award: $3,389,600
Award Period: June 1, 1985–February 29, 1988
Title of Project: "Interferometric Broadband Gravitational Antenna"
Principal Investigator: Rainer Weiss, MIT

Grant funds were applied to research and development activities in gravity-wave receivers, the principal focus of the program, and to preparatory work towards the establishment of the LIGO facilities, (large scale vacuum systems and their enclosures, support structures, and observatory sites). The latter activities were coordinated by a "project manager" who reported to a steering committee, consisting of the principal investigators, Drever and Weiss, and K.S. Thorne, chairman. These efforts laid the groundwork for a joint LIGO facility, reflecting to various degrees a unified program which in September 1987 became formally a reality with the appointment of the present project director R. Vogt and the operational merging of the formerly autonomous programs at Caltech and at MIT. Exchanges of personnel are now taking place, and the 40-meter (Caltech) and 5-meter (MIT) facilities will be operated henceforth as shared facilities.

Work accomplished under the preceding grants may be roughly divided into three areas.

1. Work on prototype receivers including enhancements of their sensitivities.
2. Development of techniques to achieve the aimed for capabilities of the LIGO receivers, but not necessarily related to sensitivity improvements of the present prototypes.
3. Preparatory work and engineering development for observatory facilities other than receivers.

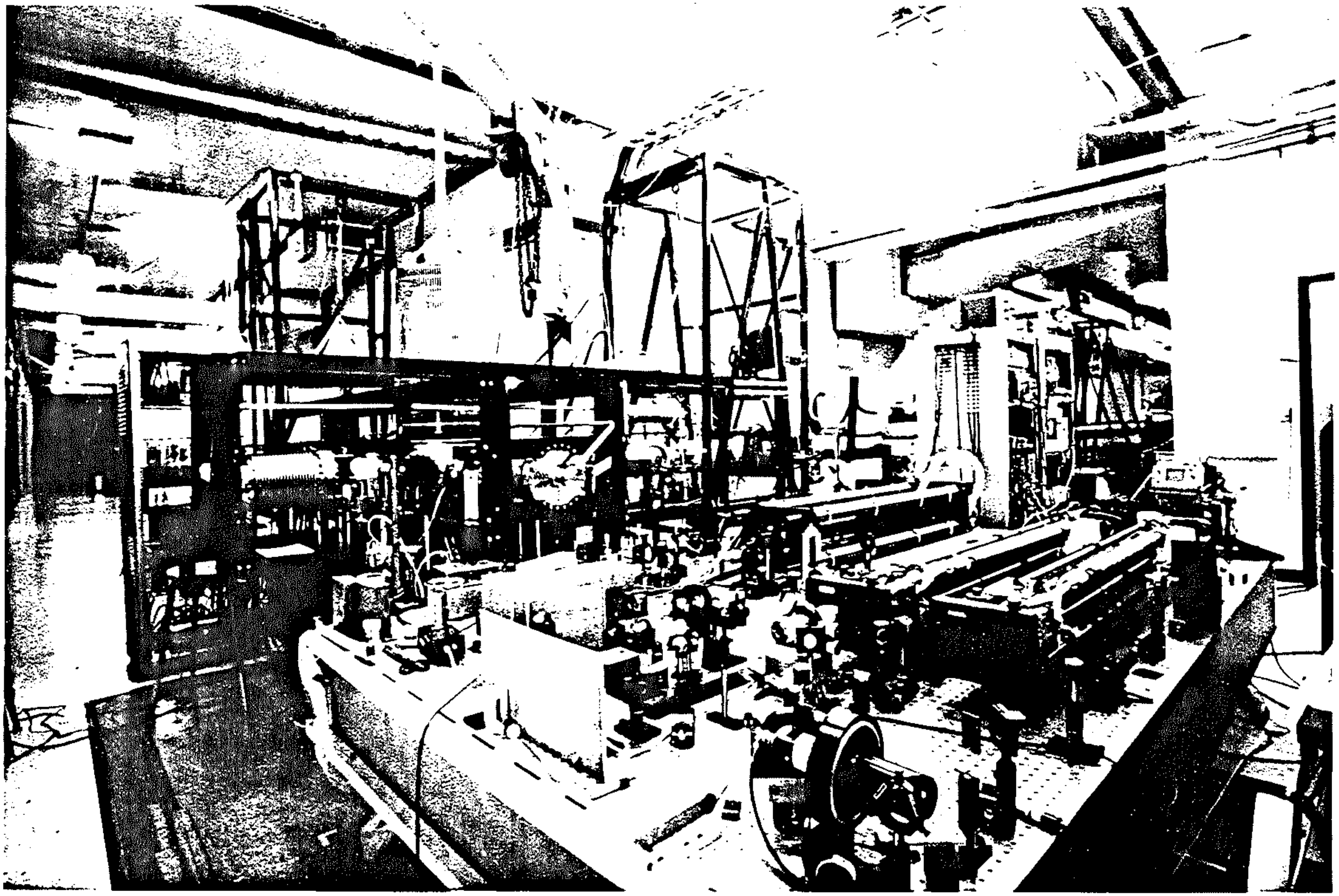

Figure V-1. The 40-meter interferometer at Caltech, as of March, 1987. The central chamber houses the beamsplitter and test masses with mirrors pointing down vacuum pipes stretching to the ends of two orthogonal hallways. A pair of high-power argon ion lasers, visible in the foreground, sends light through a chain of optics into the interferometer.

A. Prototype Receivers

Currently, the Caltech/MIT LIGO team has two operational laser interferometer developmental facilities, a Fabry-Perot type (40-meter armlength) on the Caltech campus, and a Michelson (1.5 meter, delay-line) type on the MIT campus, both operating with argon ion lasers. A third (5-meter) facility, suitable for both Fabry-Perot and Michelson development on a scale appropriate to the LIGO, is under construction at MIT.

1. The 40-meter Facility

a) Fabry-Perot Concept

The research program on the 40-meter facility (Figure V-1) is directed towards developing, testing, and improving gravitational wave receiver designs [References V-1, V-2, V-3] of the Fabry-Perot type appropriate for the LIGO. The current performance of this instrument is about three orders of magnitude better in strain sensitivity than that obtained when put into operation in 1983 (see Figure V-2).

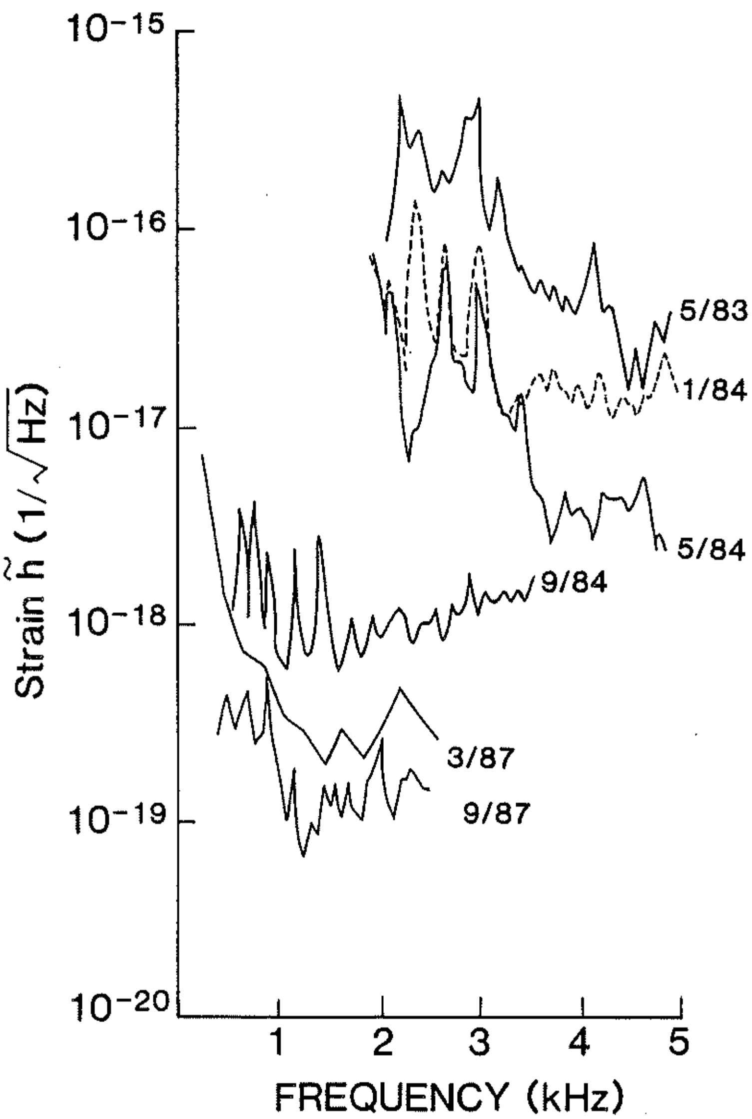

Figure V-2: Progress of the 40-meter prototype. The output of a gravity wave detector is $h(t) \equiv \Delta L/L$, where ΔL is the difference of arm lengths (equation II-1). This output fluctuates stochastically because of the detector's noise. The fluctuations at frequency f are characterized by the square root of the spectral density of h: $\tilde{h}(f) \equiv \sqrt{S_h(f)}$. This "amplitude sensitivity" $\tilde{h}$, which has dimensions of $Hz^{-1/2}$, has the property that the root-mean-square amplitude of the fluctuations at frequency f and in a bandwidth $\Delta f = 1/(\text{averaging time})$ is $h_{rms} = \tilde{h}\sqrt{\Delta f}$. Correspondingly, when searching for gravitational-wave bursts which have $\Delta f \simeq f$, the wave strength detectable at unity signal-to-noise is $h_{rms} = \tilde{h}\sqrt{f}$; it is this that was plotted in Figure II-2 above. For further discussion see the paragraphs following equation (A.18) in Appendix A.

This series of six spectra shows how the "sensitivity" $\tilde{h}(f)$ has improved over the years. Each improvement is attributable to one or more modifications made to the prototype. The latest four advances were associated with (1) the first use of ultra-low loss mirrors (5/84), (2) the addition of separated compact test masses (9/84), (3) the installation and rebuilding of a high-power laser, and refinement of electronic servos maintaining resonance in the interferometer (3/87), and (4) the installation of fused silica test masses and an in-line mode cleaner (9/87).

The concept of the Fabry-Perot gravity-wave receiver (References V-4, V-5, and V-6) is illustrated in Figure V-3. Light from a laser passes through a beamsplitter to two long Fabry-Perot optical cavities formed by low-loss mirrors attached to four suspended test masses defining the orthogonal arms of the detector. The reflectivity of the prototype end mirrors is made as high as possible (99.995%), and that of the input mirrors is made slightly lower (99.990%). (The transmission of the input mirrors is 0.010%; their losses to absorption and scattering are << 0.010%). One or both of the mirrors in each arm is curved to make a stable optical resonator. There is a large resonant build-up of light intensity in each cavity when the cavity length is an integral multiple of a half-wavelength of the light. If losses are negligible, the cavity light (labelled C1 or C2) passing back out through the input mirror for each arm has an equilibrium amplitude equal to twice the amplitude of the light coming to the cavity from the laser. It has exactly opposite phase to that of the light (labelled F1 or F2) externally reflected by the front mirror, so interference between the two components leaving each front mirror gives a resultant reflected beam equal in intensity to that of the beam incident on the cavity. However, the light from within the cavity has travelled back and forth many times between the mirrors attached to the masses (10,000 times in the example mentioned), so any change in the cavity length gives an effective change in optical path and thence in phase for light emerging from the front mirror that is increased by this large number. A gravity wave that causes the length of one cavity to increase and that of the other to decrease will give phase changes of opposite sign in the emerging light from the two cavities, which may be detected with a sensitivity limited in principle only by the statistical fluctuations in the number of photons detected.

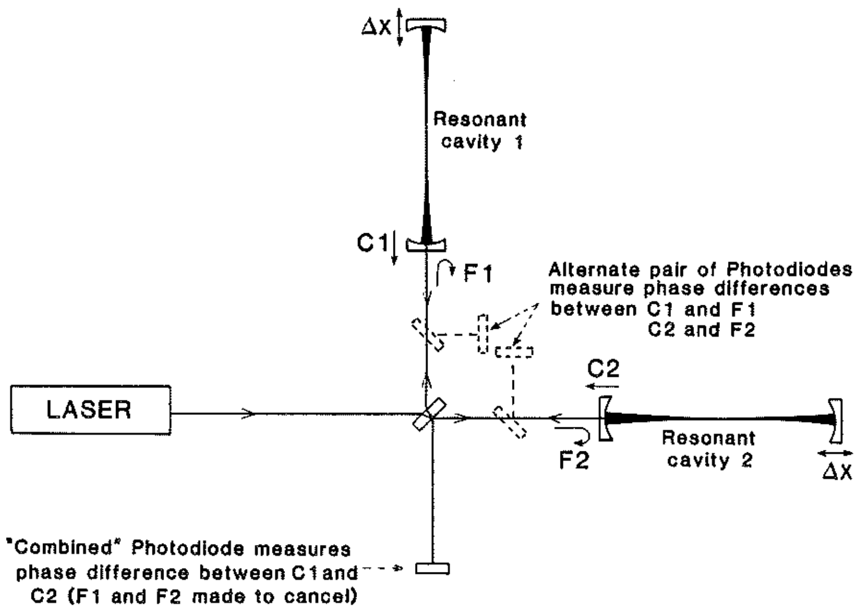

Figure V-3: Principle of Fabry-Perot gravity wave receiver.

The differential phase change may be measured in two ways: either by allowing the two output beams to interfere with one another at the main beamsplitter, and observing the effect in the resultant "combined" light with a photodiode; or by measuring the phase change in each cavity separately by diverting the output light to photodiodes (shown by dotted lines) that observe interference between the light emerging from each cavity and that reflected from its own input mirror. The 40-meter system has used the latter method up to now.

A technique for precisely stabilizing and controlling the laser wavelength to match a cavity resonance is an essential part of the concept, and is carried out by phase modulating the laser beam at a radio frequency, obtaining a measure of deviation from resonance by coherently demodulating the photodiode output, and using the error signal to fine-tune the laser or the length of the cavity. The arrangement is shown, in simplified form, in Figure V-4.

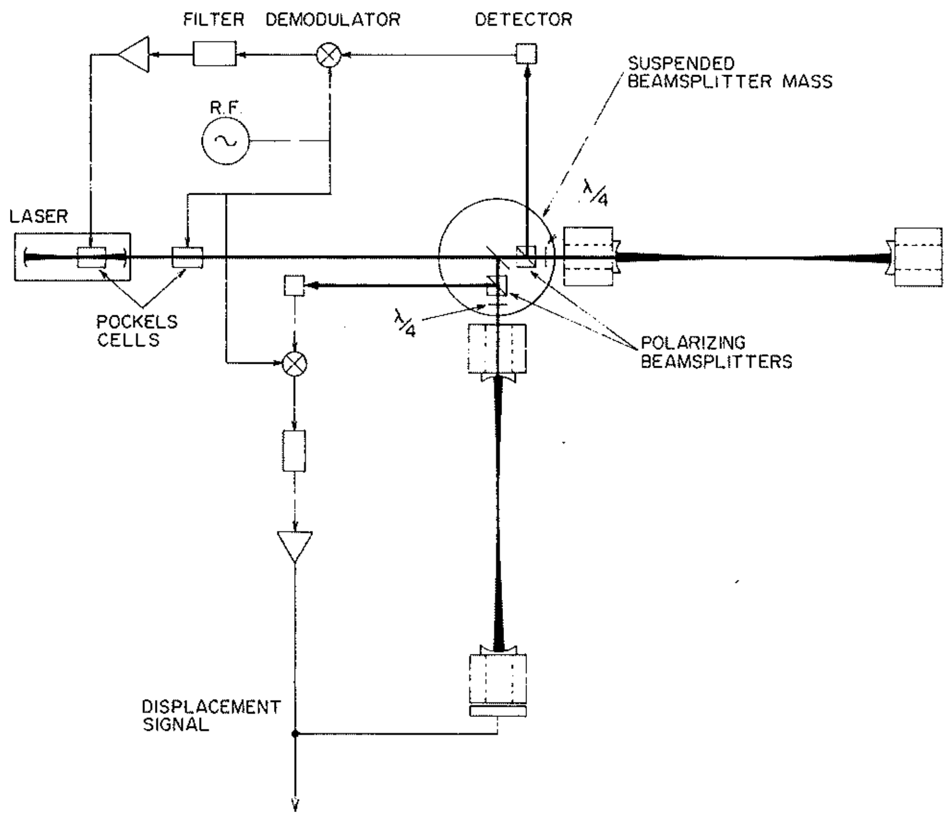

Figure V-4: Simplified schematic of prototype Fabry-Perot receiver operating in a mode where the laser's frequency is locked to the upper arm's cavity, and the gravity-wave signal $h = \Delta L/L$ is read off the lower arm's cavity.

The mirrors at present (Autumn 1987) are optically contacted to fused silica test masses, hung by thin steel wires from a suspension system that isolates the test bodies from external forces while allowing precise control of mirror angle and position. The alignment of the mirrors is sensed using optical levers employing auxiliary helium-neon lasers; low-frequency data on the position of the masses relative to local ground comes from auxiliary optical sensors, while data concerning the difference in cavity lengths are derived from the main interferometer. The input laser beam enters the vacuum system enclosing the apparatus via a single-mode optical fiber, which reduces seismic and acoustic beam jitter. In addition to the four cavity–mirror masses, two auxiliary isolated structures (one suspended by wires and one on antivibration stacks) carry beamsplitters, isolators, lenses, and other optics that are less sensitive but must still be isolated from external disturbances.

b) Advances in Performance of the 40-meter prototype gravity-wave detector

(i) Overall Results. At the beginning of the grant period, the sensitivity of the prototype interferometer was already high (an enormous improvement had been made in 9/84, shortly before the grant period began): the gravity-wave amplitude (July 1985) sensitivity was $\tilde{h} = 5 \times 10^{-19}/\sqrt{\text{Hz}}$ (see caption of Fig. V-2 for discussion of $\tilde{h}$). This was comparable to or better than that of any other interferometric receiver, and it was achieved using a longer baseline than any other (30% longer than the next largest gravity-wave interferometer, one at Garching, West Germany). During the grant period many improvements were made, resulting in a further advance in sensitivity. The current gravity-wave amplitude sensitivity is indicated as a function of frequency in Figure V-5, in the form of the spectral density of strain noise. Around 1.3 kHz the most recently measured sensitivity $\tilde{h}$ is $8 \times 10^{-20}/\sqrt{\text{Hz}}$. This corresponds to a sensitivity for gravity wave bursts, with $f \sim 1000$Hz, a factor of 3 worse than the best cryogenic bar gravity wave detectors, but with a bandwidth greater by at least a factor of 1000, along with time resolution better by a factor of at least 100. In terms of flux sensitivity—the unit used for optical telescopes or radio antennas—the sensitivity improvement over the grant period is about a factor of 36.

(ii) Conclusions from these results. The strain sensitivity achieved corresponds to a sensitivity of position measurement of the test masses and mirrors of close to 3×10^{-18} meters $/\sqrt{\text{Hz}}$. This sets upper limits to several sources of noise which might have been important, including

a) thermal noise
b) seismic noise (confirming other tests that show it to be small)
c) noise from strain release in the suspension wires or in the masses themselves.

If the displacement sensitivity were maintained at this level in a 4 km system the gravity wave sensitivity would be $8 \times 10^{-22}/\sqrt{\text{Hz}}$, or 4×10^{-20} for a 1 millisecond gravity wave burst.

(iii) The experimental advances that have led to this sensitivity improvement:

Installation of a higher power argon laser. At the beginning of the period the interferometer was powered by a Lexel argon laser of nominal all-line output 4 watts. Installation of a Coherent Innova large frame argon laser of nominal all-line power 20 watts, and actual power at 514 nm in a single mode about 3 watts, made possible a significant increase in power into the interferometer (though the performance in Fig. V-5 was achieved with an input power of only 25 mW). The laser as supplied by the manufacturer had considerably larger frequency noise than the smaller laser. This was overcome eventually by a number of steps, including *a)* removing the laser cavity mirrors from the laser frame and mounting them directly on a heavy optical bench less affected by vibrations from flow of cooling water, and *b)* improving the frequency stabilization servo system—which uses a Pockels cell within the laser, supplemented by a piezo-driven laser cavity mirror for slower larger-range control.

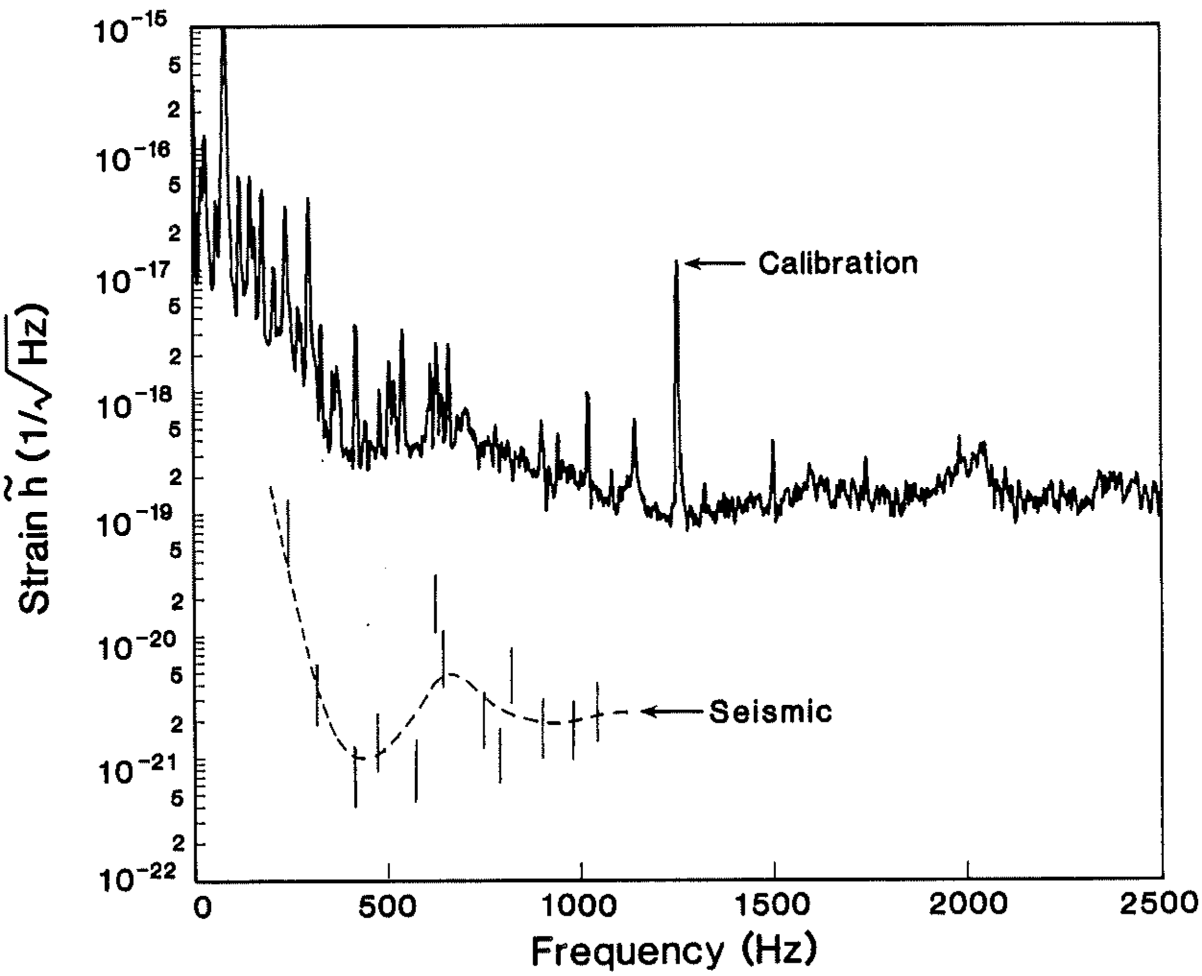

Figure V-5: Sensitivity of the 40-meter prototype, $\tilde{h}$, as of October 1987. The peak marked "calibration" is the effect of imposing a 10^{-15} meter rms sine wave motion on one of the test masses (given the 4.7 Hz bandwidth of this measurement, the calibration corresponds to $5 \cdot 10^{-16}$ meters $/\sqrt{\mathrm{Hz}}$; (to convert from strain to displacement, multiply the scale by 40 m) or $\tilde{h} = 1.2 \cdot 10^{-17}/\sqrt{\mathrm{Hz}}$. At 1.3 kHz and above the sensitivity agrees (within the estimated uncertainty factor of 1.5) with the calculated shot noise limit [V-7], for the measured available photodiode power of 25 mW. The broad peak near 2 kHz is probably an artifact of imperfect calibration, and the collection of peaks below 500 Hz is probably from mechanical resonances in the beamsplitter mass, steering mirrors, and the laser. The lower curve is a fit to the response of the detector to external vibrations, sampled at several discrete frequencies. The data, obtained by attaching a commercial vibration tester to the table supporting one of the vacuum chambers and scaling the resulting "gravity wave" signal to the ambient noise, shows that seismic motion contributes a negligibly small fraction to the total noise in the signal.

Development of the electronic feedback system has allowed the loop bandwidth to be increased to give a unity-gain frequency of about 1 MHz, and allowing significant increase in loop gain at low frequencies. A very high degree of frequency stabilization is now achieved, such that the servo loop error signal can be brought close to the photon shot noise. The independent check on residual frequency noise made by the operation of the two arms of the gravity wave interferometer has shown that residual frequency noise is less than 1 in $3 \times 10^{18}/\sqrt{\mathrm{Hz}}$ over timescales of order 1 millisecond. This corresponds to an effective linewidth over these time scales of order 10^{-4} Hz: an exceptional degree of frequency stability in a laser of this type and power.

Development and installation of low noise test masses. The design of the test masses has gone through successive stages of refinement as various sources of spurious noise have been found to originate in them. At the beginning of the present funding period the test masses were aluminum cylinders, with the fused-quartz substrates of the low-loss mirrors acoustically connected to them by vacuum grease, to allow differential thermal expansion. Experiments at Glasgow indicated that such grease joints could generate low-level noise; and measurements at Caltech of mechanical Quality factors ("Q") of complete test mass assemblies confirmed that the damping and elastic properties of the grease could cause the mirrors to act as a low-Q oscillators coupled to the masses, generating thermal noise. The grease was replaced by harder joints made by a low-loss bonding technique. This gave high mechanical Q and lower noise, but also resulted in serious distortion of the mirrors due to mismatch of expansion coefficients between mirrors and test masses. Finally, as at Glasgow, the problem was solved by making the masses themselves of fused-quartz cylinders and forming the bond to the mirrors by optically contacting the mating surfaces, relying on molecular forces to make the joint. This technique gives good noise performance and is currently used for all test masses in the 40-meter system. (The possibility of applying the low-loss mirror coatings to the test masses themselves is being considered, although there are some practical problems in doing this).

Replacement of piezo-electric transducers between mirrors and test masses by magnetic and electrostatic drive to the masses themselves. There has long been suspicion that piezo transducers between the mirrors and test masses—which were used to give fast adjustment of the cavity mirrors for locking the cavities into resonance with a laser beam—could be a source of noise, by such phenomena as the electrostatic analogue of the Barkhausen effect. The piezo transducers were, therefore, removed, and the system was redesigned in such a way that fast control accelerations could be applied to two of the test masses by interaction of applied magnetic fields with small magnets attached to the masses. This has proven very successful, with an operating frequency limited mainly be the fundamental resonance of the masses (which is about 30 kHz with the present design), and has contributed to the improved noise performance.

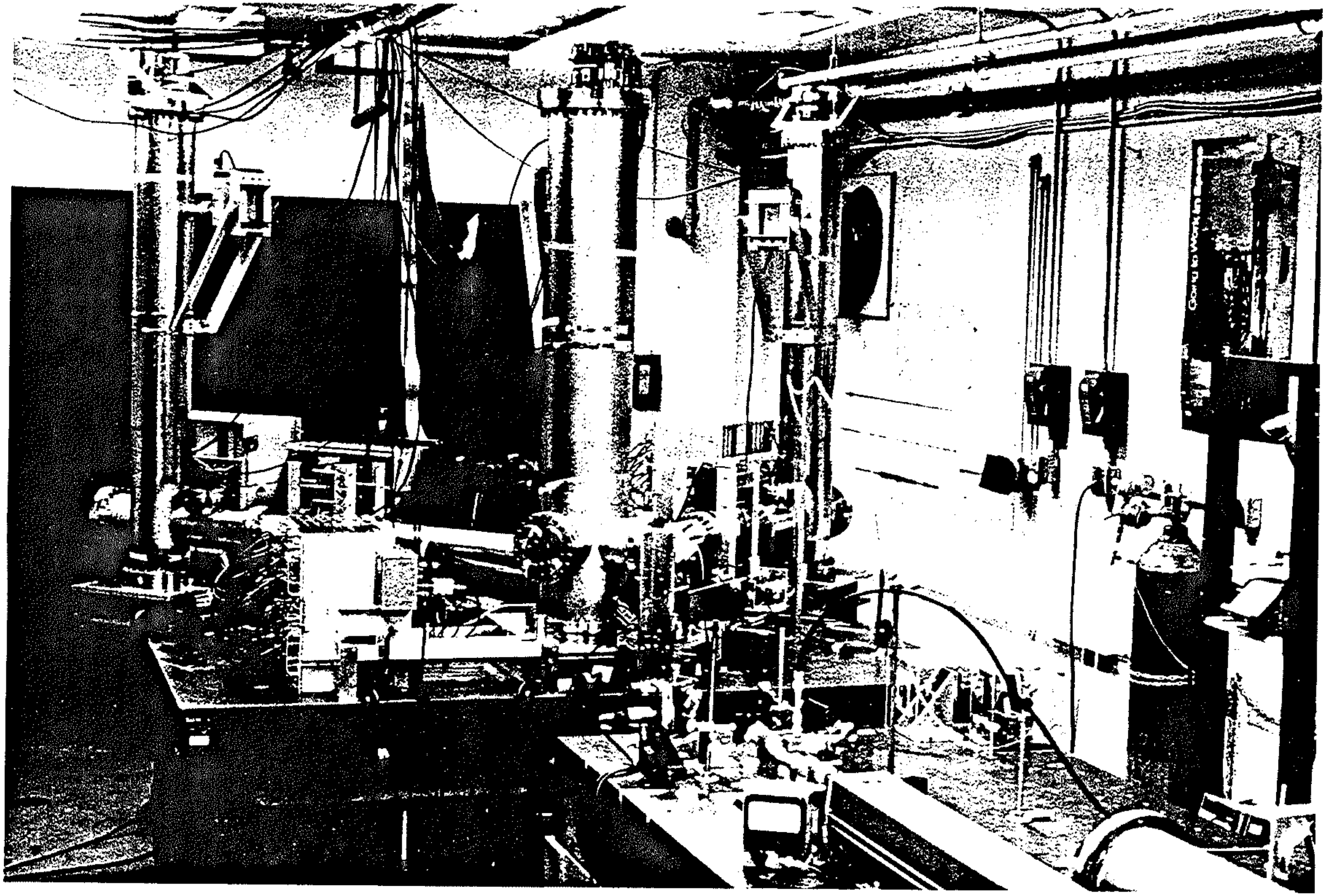

Figure V-6: A photograph of the 1.5-meter delay line facility.

Use of a narrow-band transmission Fabry-Perot cavity to filter the laser beam. The continuing search for sources of noise gave evidence for production of noise by non-linear mixing processes in some of the feedback systems used to lock the main optical cavities into resonance with the laser light. Fluctuations in the laser amplitude, frequency, and beam geometry at frequencies well above the gravity-wave frequency, are a possible source of such processes. To remove this noise, the laser beam is now passed through an optical filter (Fabry-Perot cavity) of 200 kHz bandwidth which is kept in resonance by a suitable servo arrangement. Use of this technique, which had been incorporated earlier in the 40-meter system as a means of reducing fluctuations in beam position and then deferred, has been accompanied by an improvement in sensitivity. Work is currently in progress to study further the reason for the improvement in sensitivity obtained with this "mode cleaning" cavity and to develop the technique further.

2. The 1.5-meter Facility

a) Delay-line (Michelson) concept

The concept for a delay line Michelson interferometer gravitational wave detector was developed in 1971 [V-8]. The instrument (Figure V-6) became operational in 1983 and has been used to demonstrate basic receiver concepts.

The delay line Michelson prototype receiver is a practical implementation of the simple interferometer described in Part II.A (see Figure V-7 for block diagram). The major difference is that after being divided at the beam splitter, the light enters two orthogonal open cavities formed by mirrors on the corner and end masses. The light makes multiple transits in these cavities to increase the optical phase shift associated with a change in cavity length. The light enters and exits the cavities through holes in the mirror. The light emerging from the cavities passes through electro-optic crystals that impress an RF phase modulation, the equivalent of a small periodic variation in length, on the light before recombination at the beam splitter. When the instrument is locked to a fringe, two light beams leave the beam splitter; one is the sum of the recombined electric fields (the bright fringe) and the other is the difference (the dark fringe). A photodetector and associated electronics are used to interrogate the modulation of the dark fringe and thereby split the fringe. The precision by which the fringe can be split is determined by the light power in the bright fringe, at present the dark fringe is split into 10^6 parts in 1 millisecond. The signals developed by these means are then used to control the optical length of the cavities to hold the instrument on a single point of a fixed fringe. In practice, this is the "white light" fringe—the fringe associated with light that has spent equal times traversing the two cavities, the position of which is independent of the laser frequency. The optical path length control is asserted by feedback to the electro-optic crystals and to electrostatic controllers that move the mirrors. All effects that tend to lengthen one cavity and shorten the other, such as gravitational wave forces and noise forces, are measured in the feedback signals.

The mirrors, which form the end points of the cavity, are suspended by fibers so that for frequencies above the resonance frequency of the suspension, they respond freely to gravity waves. The suspensions have very low intrinsic damping to reduce the coupling

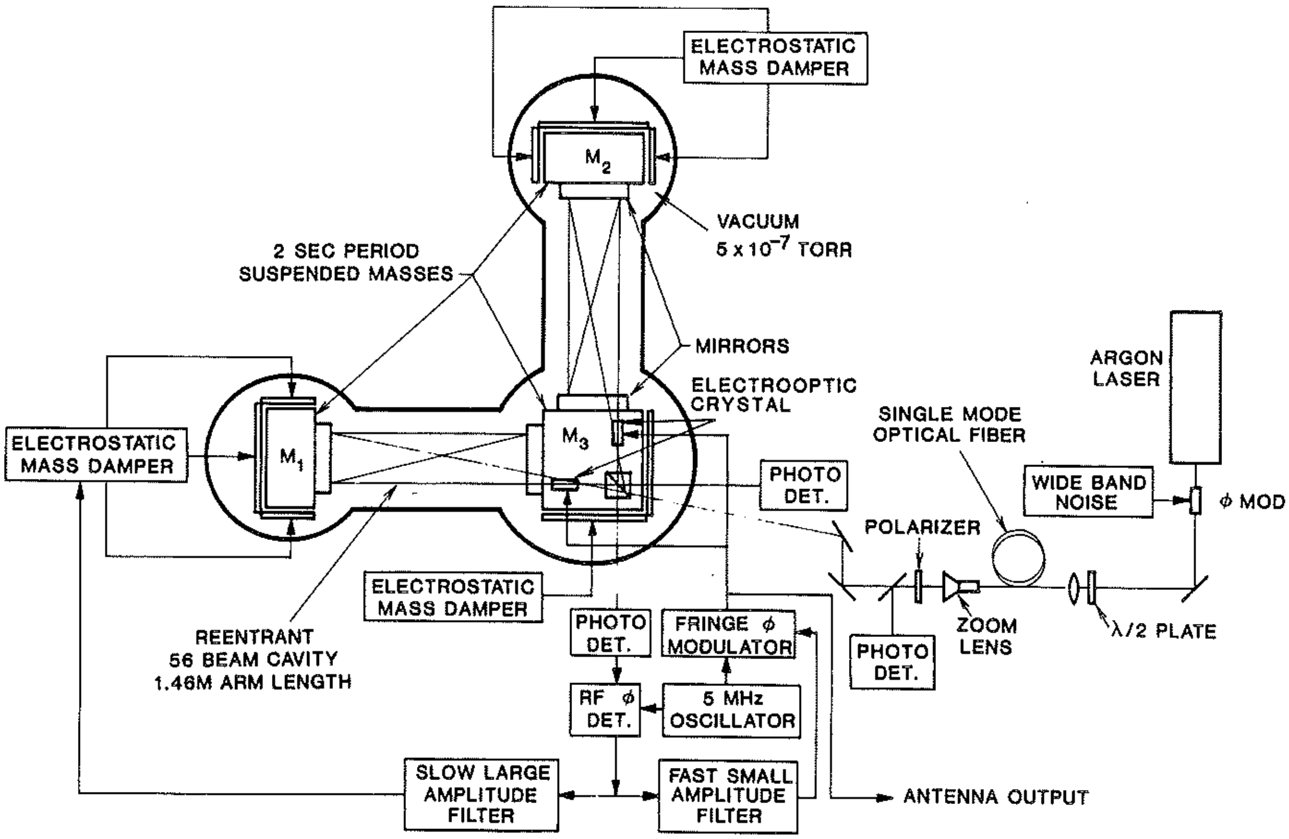

Figure V-7: Schematic of 1.5 meter delay line prototype.

to externally driven seismic and acoustic disturbances as well as to minimize their thermal noise off resonance. The mirror motions at the suspension resonance frequencies are damped electronically in all six degrees of freedom by a system of capacitive position sensors and electrostatic controllers. A more extensive description of this prototype receiver is given in Appendix H and Reference V-9.

b) Results

At the beginning of the present grant period, the 1.5 m prototype had not long been in operation and its sensitivity was rather poor. Improvements in the amplitude sensitivity during the grant period were substantial: a factor of about 200 in amplitude sensitivity at a frequency of 1kHz (the present noise spectrum is shown in Figure V-8). This was the result of diagnosis and correction of various noise sources in different parts of the spectrum.

c) Improvements

The sensitivity of the 1.5-meter receiver at low frequencies (0–2 kHz) was improved by the installation of a series of new suspension systems, beginning with a vacuum compatible horizontal isolation system (a stack of stainless steel plates and Teflon rods), and ending with the complete replacement of the original suspension with a single wire

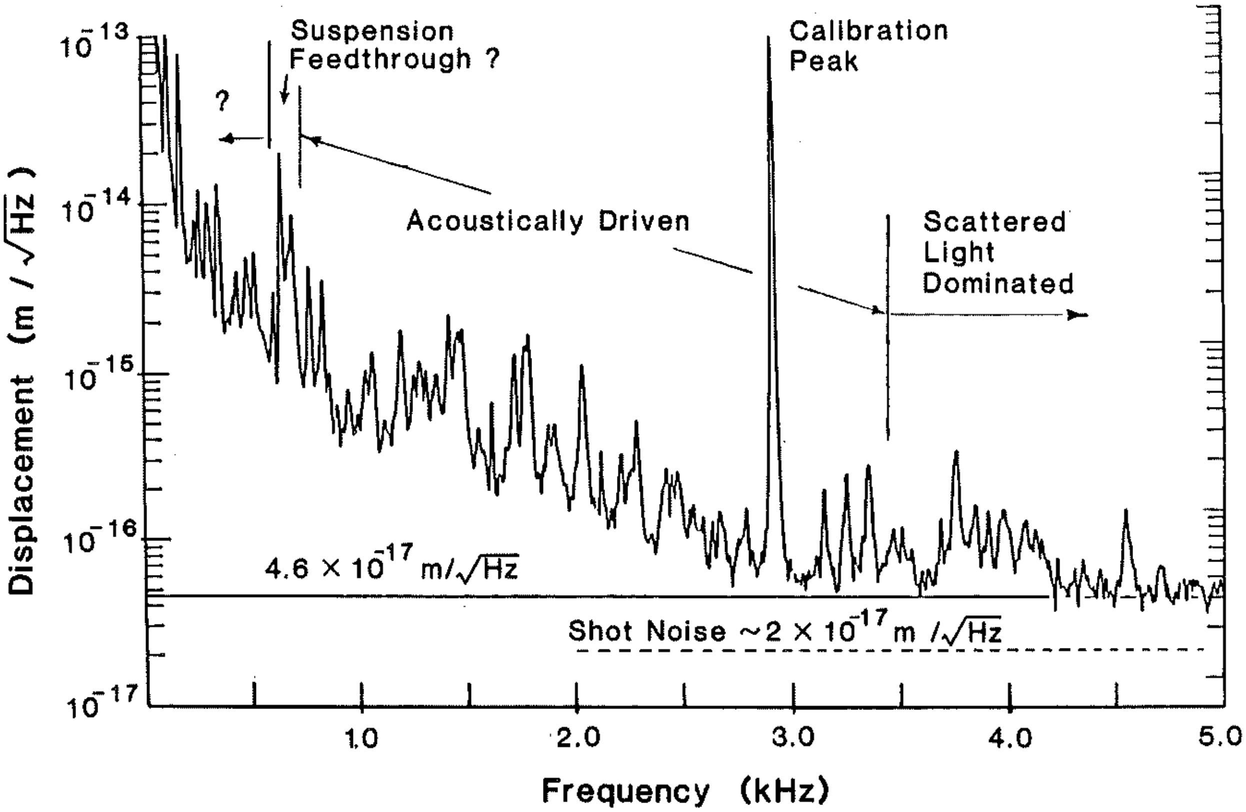

Figure V-8: Typical displacement noise spectrum from the 1.5 meter prototype. The displacement noise is given in units of meters in a one second integration time as a function of observing frequency. The strain noise is the position noise divided by the length of the cavity, 1.5 meters. The spectrum was taken with 60 milliwatts of power emerging from the symmetric output of the interferometer. The system has been run at over 100 milliwatts but the noise spectrum is not improved, indicating that the noise is not dominated by shot noise.

system. Coarse mechanical positioning of the suspensions was mechanized with the installation of motorized micrometers.

At mid-range frequencies (1-5 kHz) the noise floor of the prototype was improved by acoustically shielding the apparatus from the room with a foam and rubber curtain.

High frequency noise ($\geq$ 5 kHz) was reduced with the installation of a broadband phase modulator to suppress the effects of scattering. The shot noise limit was reduced slightly with the installation of a higher power laser, after extensive modifications to the power supply to reduce the intrinsic noise.

The front end electronics for the main photodetectors were improved. The output optics were modified to reduce reflection losses at the photodetectors, and work is in progress to install an optical fiber as an output coupler.

A data acquisition system capable of recording large amounts of continuous data with precision atomic timing was added and used to collect data.

d) Noise analysis techniques

Direct measurements of the effect of mechanical vibration and acoustic noise on the interferometer output were made. Forces applied to the top of the wire suspensions using a magnetic driver and a piezoelectric transducer (PZT) determined the vibration transfer function; except at resonant peaks, direct feedthrough did not dominate the interferometer noise spectrum. Driving the external mode-matching optics with the PZT showed those components to be the coupling path for acoustic noise.

A separate facility was set up to test suspension designs. These tests led to the purchase of a Ling electromechanical driver and to the design of an auxiliary suspension vacuum chamber as part of the new 5 meter facility.

The development of methods for detecting and reducing the effects of scattered light led to the implementation of two methods for suppressing the effects of scattering: one method based on phase modulation with broadband gaussian white noise, the other on pseudo-random digital noise.

A vibrating wire amplitude modulator was constructed to measure the transfer function from audio frequency laser amplitude noise to interferometer noise. These measurements showed that amplitude noise was not a dominant noise term.

A circuit was constructed that allowed readjustment of the arm-length difference of the interferometer, one fringe at a time without losing fringe lock. This was used to investigate the sensitivity of the interferometer to laser frequency noise and to find the region near the white light fringe. The noise was reduced by 10 dB in the process.

A technique for examining the fringe signal on the photodetectors and separating the contributions of phase noise and amplitude noise was developed and used to guide the choice of operating conditions for the scattering suppression techniques. It also led to the development of new Brewster angle Lithium Tantalate electrooptic modulator geometries.

Methods to characterize the noise and modal properties of optical fibers were also developed.

e) Conclusion

A number of important contributions to the noise spectrum of the 1.5-meter interferometer were successfully identified. Several of the required improvements, such as moving the input coupling optics inside the vacuum chamber and the installation of separately suspended optical components, simply could not fit in the restricted vacuum system of this prototype. This was crucial in the decision to build the 5-meter system.

3. The 5-meter Facility

In the spring of 1986 design work began on a new 5-meter prototype interferometer. The vacuum system was designed to house either delay line Michelson receivers or Fabry-Perot receivers with optics large enough for a 4 km system; and the vacuum system uses techniques applicable to a 4 km system. The vacuum system was installed and qualified in Summer 1987 (see Part VI.B).

B. Development of Capabilities for LIGO Receivers

1. Work performed at the 40-meter facility

During the present grant period, many experimental techniques have been developed with the aim of controlling many sources of noise that have to be kept under control but may not yet be serious in the 40-meter prototype receiver:

a) Seismic Isolation for the 40-meter receiver.

(i) Measurement of Achieved Isolation. The seismic isolation system used from the beginning in the 40-meter receiver is a simple passive system, with a 4-stage lead-rubber stack within the vacuum system as a major element, together with the natural pendulum isolation of the test mass suspension, and provision for external air suspensions—which are normally not used. The isolation system is based on well-established methods used in bar gravity-wave detectors, and has shown no sign of high-frequency feedthrough. Experimental measurements of attenuation have been made with the interferometer, exploiting the fact that each end station is on a separate foundation giving isolation from the ground and from one another. The optical bench forming the base of one end station was vibrated by a powerful vibration generator at a range of frequencies, at amplitudes which were increased until feedthrough was apparent on the interferometer. The imposed motion was monitored with an accelerometer and seismometer, and compared with the natural ground motion. Assuming the feedthrough is linear, the data were scaled to indicate an upper limit to the feedthrough of ground noise, and the results are shown by the lower curve in Figure V-5. This indicates that the attenuation of the isolation system is indeed satisfactory at frequencies above a few hundred Hz even for the ground noise at Pasadena, a built-up area with busy roads. Scaling to the measured seismic noise at potential LIGO sites indicates that the isolation system used in the 40-meter instrument should be adequate alone for initial receivers in the LIGO above a frequency of about 400 Hz. For LIGO receivers aimed at lower frequencies, however, further isolation will be needed and for this we plan to develop active systems in addition to passive systems.

(ii) Introduction of a system for enhancing low-frequency seismic isolation. The passive isolation system in the 40-meter interferometer has proven convenient and satisfactory at frequencies above a few hundred Hz, but it does transmit very low frequency motions (of order 10 Hz and lower) imposing large dynamic range requirements on the servo systems that hold the cavities in resonance; this can make acquisition of lock difficult at times, such as when there is nearby traffic. A simple helium-neon interferometer has been added to monitor the distance between the suspension points in one arm of the system, with the intention of feeding back the changes so that the two suspension points track one another and give a first-order cancellation of low frequency disturbances. The technique looks promising.

b) Development of a High Performance Laser Intensity Stabilization System.

The use of radiofrequency modulation techniques makes the basic interferometer insensitive in first order to laser intensity noise in the gravity-wave frequency region, but at the high sensitivity involved second-order couplings can be important. The performance of available commercial laser stabilizers is limited, partly due to nonhomogeneity in the laser beam and changes in the beam pattern caused by the action of the electrooptic intensity modulator usually employed to control the beam. A stabilizer with higher performance has been developed for use with the 40-meter system, in which a length of optical fiber follows the modulator to remove fluctuations in beam geometry before the intensity is sampled by the monitoring photodiode. This system gives a high degree of stabilization. In typical operation the interferometer can be made sufficiently insensitive to intensity noise for stabilization to be unnecessary, but it is used as a test for intensity noise feedthrough at every new advance in detector sensitivity.

c) Further Development of an Automatic Cavity Alignment System.

Precise control of beam and mirror alignment is important in interferometric gravity wave detectors. In the 40-meter detector the mirror and test mass orientation is monitored by optical levers and maintained steady by servo systems which suitably adjust the relevant suspensions. Setting up this system for optimum alignment is time-consuming, and drifts occur over several hours. A new technique for making the system optimize its own adjustment was devised just prior to the current grant period, as an extension of the basic radiofrequency laser frequency stabilizing system. The alignment system measures the gradient of phase difference between the wavefronts of the light emerging from a Fabry-Perot cavity and the incident beam reflected from the input mirror, and can adjust the alignment to make the wavefronts coincide. An experimental model of this system has demonstrated satisfactory operation on one of the 40-meter arms of the interferometer while the cavity is in resonance, but in its simplest form the system requires manual attention if the resonance is lost for any reason. A recent further development has been the addition of a computer control system that monitors operation of the alignment servos, keeps the manual optical lever servo system in correct adjustment while the automatic system is operating, and switches over to the optical lever system if the automatic system fails or the cavity falls out of resonance. This is the first stage in the planned automation of the interferometer, which will greatly improve the operating efficiency of the 40-meter instrument and will be essential for the longer arms of the LIGO system.

d) Other Research Developments.

Several other areas of development and research have been advanced significantly. We summarize some of them here.

(i) Studies of thermal effects in low-loss cavity mirrors: The work is still in progress, but already it indicates that the practical sizes of the LIGO mirrors are such that heating problems will not be serious.

(ii) Development of an electrostatic control system for test masses: A constant-charge technique for giving electrostatic forces independent of position of the mass has been used in a feedback control system, and looks promising.

(iii) Experimental studies of the noise from piezoelectric transducers. These studies have set an upper limit to the Barkhausen effect that is small enough to be insignificant in our present mode of use of the devices.

(*iv*) Redesign of the vacuum system: A design has been developed for a larger vacuum tank, pipes, and seismic isolation system to enable the 40-meter system to be more effectively used for optical systems with many more components suspended in vacuum (such as recycling interferometers), and to accommodate larger test masses. A tank is being prepared for this upgrade to the facilities, and the laboratory building is being modified. More details are given in Section VI.

2. Work performed on the 5-meter facility

Development of techniques in seismic isolation

A prototype model of a multiple double pendulum suspension (Figure V-9) has been designed and constructed. The model is the size appropriate for Fabry-Perot mirrors for a 4 km baseline. Careful noise budgeting of all control elements should make all stochastic noise terms associated with suspensions negligible above 100 Hz. The model includes control of all twelve degrees of freedom using optical position sensors, magnetic actuators on the outer mass, and astatized (zero force gradient) electrostatic actuators on the mirror. If scaled up for 4 km delay line mirrors, the electrostatic actuators could be used to servo the mirror figure.

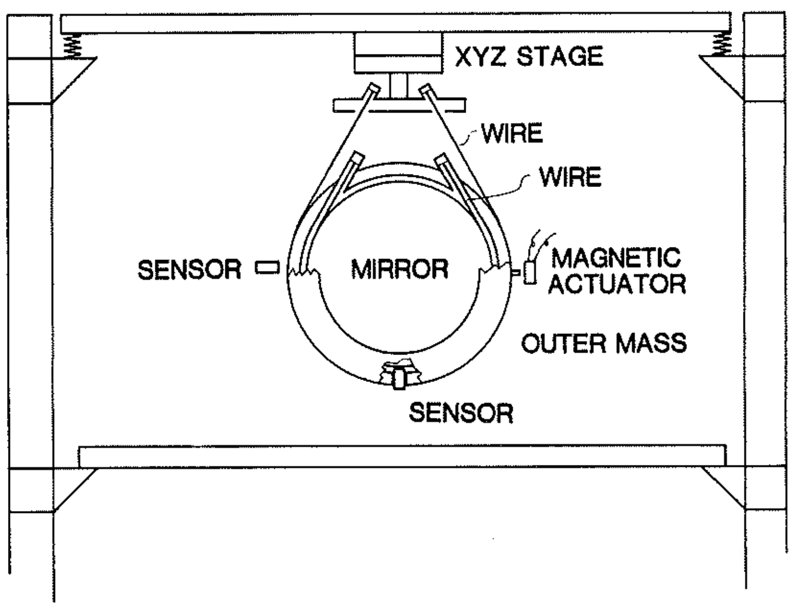

Figure V-9: A schematic diagram of the multiple suspension system under development for the 5-meter prototype.

A magnetic suspension (Figure V-10) to serve as an outer stage in the vibration isolation chain has been designed and constructed. Its major advantage will be as a mass-spring system without the pernicious internal mechanical resonances of conventional springs. It also is a compact way to build a suspension with a low resonant frequency, and damping should be adequate without the use of vacuum incompatible materials.

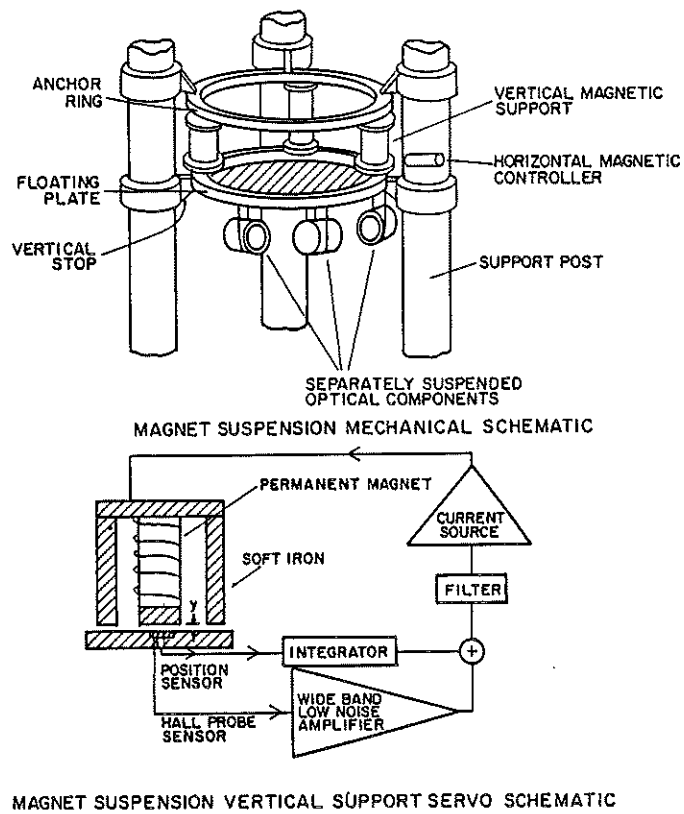

Figure V-10: Schematic diagram of the magnetic suspension being developed.

Two new designs of optical position sensors have been prototyped and tested. One is an optical shadow sensor based on quadrant photodiodes. A compact unit holds an infrared LED and the quad cell, sensing the shadow of a dark mask on a nearby flat polished surface. A more sensitive interferometric sensor (Figure V-11) based on single-mode laser diodes and optical fibers has also been built and tested. It holds the promise of position sensitivity near 10^{-14} meters/$\sqrt{\mathrm{Hz}}$. Both types of sensors have been designed with vacuum compatibility and large dynamic range in mind. They are suitable for small-scale quantity production to meet the demand for roughly 50 per interferometer.

3. General Developments in Support of Receiver Technology

a) Development in optics

Research was carried out on electro-optic modulators and fibers for high power applications both at 0.514 and 1.06 microns. The electrooptic coefficients, dielectric loss tangent at RF frequencies, and the transmission at 0.5 microns of Potassium Titanyl Phosphate (KTP) was measured. The material has a laser damage threshold similar to quartz. Techniques have been developed to make Brewster angle Lithium Tantalate phase modulators with small piezoelectric coupling. The material exhibits low optical loss and a high damage threshold at 1.06 microns and, furthermore, a small loss tangent at RF frequencies. A research program was undertaken with industry to develop large diameter single mode fibers to increase the power that could be transmitted by fibers. A single mode fiber with 12 micron core diameter was developed for use at 0.5 microns.

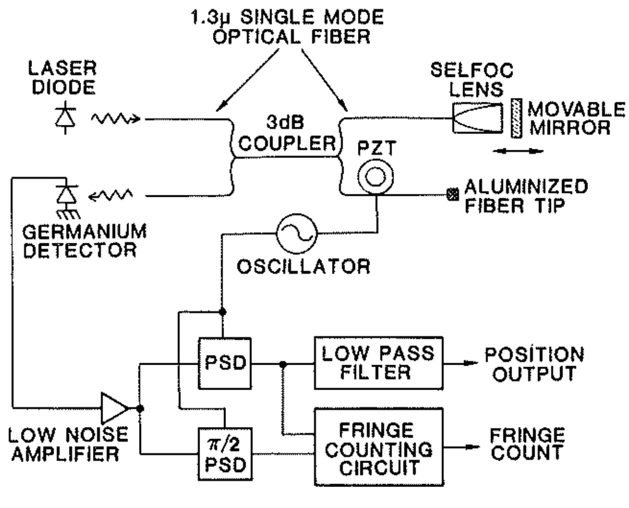

Figure V-11: Schematic diagram of a fiberoptic position sensor. If further tests using a suspension feedback diode laser are successful, the sensor will be adopted for standard use in suspension damping systems. The output of a single laser can be divided by fiber stars to illuminate up to six of these sensors.

b) Nd:YAG laser research

Early in the present grant period a study was made of laser light sources that could develop up to 100 watts CW efficiently and have the frequency, amplitude, and mode purity required in precision interferometry. A promising system identified was the Nd:YAG laser which during the last three years has undergone remarkable development. The invention of the laser diode pumped single crystal ring oscillator by Prof. Byer at Stanford [V-10] (now commercially available) has offered the field a new laser with unprecedented low intrinsic frequency and amplitude noise. Our measurements of a 5 mW unit indicate a frequency noise less than 20 $Hz/\sqrt{Hz}$ at frequencies as low as 100 Hz. The amplitude noise is approximately 15 times shot noise at 1 kHz and approaches shot noise at high frequencies. The laser is well suited to be the master oscillator in an amplifier chain or as a seed for the injection locking of a power oscillator.

A cooperative program with the GE Research Laboratory (Dr J. Chernoch) was initiated to test Nd:YAG zig-zag slab lasers as power oscillators or as a final amplifier stage for a high power system [V-11, V-12]. Measurements were made of the gain per pass of a small slab laser head (loaned by GE to the LIGO project) to evaluate it as an amplifier. GE is concurrently measuring the power that survives in a single radial mode of a new slab head operating at 700 watts CW multi-radial mode.

This Nd:YAG research has been directed to developing a source at 1.06 microns; new developments [V-13] show promise for frequency doubling.

4. Development of Data Analysis Techniques and Searches for Gravitational Radiation

Both the 1.5-meter and the 40-meter prototype receivers have been operated in gravitational wave searches. Even though the receivers are development devices and of insufficient sensitivity to have much chance of seeing waves, we believe it is important to evolve techniques to search for gravitational waves in their prototype data streams. There are several reasons for doing this: the techniques will find application in the LIGO project and the process of developing and using them highlights the problems that will be encountered in an actual observation run on the LIGO, thereby aiding the LIGO design. Furthermore, in a university setting it is important that Ph.D thesis work be involved with actual physical measurements.

The 1.5-meter prototype accumulated 30 hours of data distributed over two weeks in June, 1985. The data were analyzed (see Appendix I) for gravitational wave bursts by cross correlation theoretical wave-form templates in the 800 Hz to 5.5 kHz band [V-14]. The same data were also searched for periodic sources between 2 and 5 kHz, of unknown period and unknown position in the sky. The analysis, using a computational technique to remove the Doppler shift due to the earth's motion, gave a null result [V-15]. This search, which required use of a supercomputer, highlighted the severity of the computational problems that must be faced in LIGO searches for periodic sources.

An algorithm was developed to search for the characteristic "chirp" of coalescing binary star systems [V-16].

An analysis was performed of the relative projected sensitivities of the best current acoustic antennas and current interferometric antennas for bursts originating from galactic impulse events such as SN 1987A [V-17].

Coincidence runs following SN 1987A

The optical observation of Supernova 1987A on 23 February 1987 and the discovery of coincident signals in the archives of two neutrino detectors, consistent in timing and flux with the optical observations and with models of core collapse, was impetus for a series of coincidence runs between Caltech and MIT. Approximately five hours of high-bandwidth data, including atomic standard timekeeping, were collected on March 8 and March 10. The University of Glasgow participated, making these the first three-way coincidence experiments with interferometric gravitational wave detectors. The receivers, which were all down at the time of the supernova, were brought on line, the coincidence runs were organized, and the runs were successfully completed all within two weeks of the discovery of the supernova. Analysis of the data for burst signals and periodic signals is now underway.

C. LIGO: Large Baseline System Development

1. Conceptual Design and Cost Studies

The essential requirements (Part IV) for the LIGO facilities were formulated during the present grant period. A functional requirements document and the conceptual design of the LIGO for use as input to an engineering design were partially completed. Engineering and cost tradeoff studies were carried out on many of the cost driving elements of a LIGO facility. These include: *(i)* the vacuum pumping strategy (cryopumps, sputter pumps, and trapped diffusion pumps were evaluated; the preliminary choice is turbomolecular pumps for initial evacuation and ion pumps to hold the vacuum); *(ii)* tubing design (corrugated thin wall stainless steel tubes, aluminum tubes, and nested tubes differentially pumped were evaluated; the preliminary choice is spiral welded stainless steel with periodic stiffening rings, an established and low risk technology); *(iii)* protective cover for the tubes (no cover, corrugated culvert, corrugated pipe arch, concrete used on surface, partially buried and completely buried configurations were evaluated; the preliminary choice is bermed concrete). As a guide to the trade-off studies a detailed work breakdown structure (WBS) and associated trial schedules were developed to highlight relationships between cost items and to identify long lead items and hidden costs. The tradeoff studies are not complete and will be continued during the next year to evolve the best compromise between economy and risk.

2. Observatory Site Activities

A second iteration after an initial 1983 study of sites was made in New England, California, Nevada, Illinois and Utah. Edwards AFB in California and Columbia, Maine were selected as possible sites for further study for reasons of topography, remoteness from manmade noise sources while retaining access to transportation, power, labor, and material for construction, and having reasonable proximity to Caltech and MIT, respectively. Preliminary work to evaluate the sites was carried out. Seismic noise measurements were taken at both sites. At Columbia an aerial and ground survey was made and preliminary geotechnical work was done at locations suspected of having subsurface rock formations. An archaeological survey was performed and negotiations to evolve an environmental impact statement were begun. The ability to acquire the sites was evaluated. At Edwards a Memorandum of Understanding, dealing with security issues, but not committing us or the Air Force to the site, was signed with the Air Force. At Columbia the land is privately owned and exploratory contacts were made with landowners using a local lawyer and assessor.

A LIGO sites working group was established to determine the scientific requirements for sites so as to optimize both the near term goal of discovery of gravitational waves and the longer term needs for gravitational wave astronomy. Results of this study are reflected in Appendix B.

3. Receiver Designs for the LIGO

a) Conceptual design of a Fabry-Perot receiver system for initial operation in the LIGO

Work with the 40-meter system and with earlier Fabry-Perot interferometers has given us sufficient experience and confidence in the techniques to make possible a fairly complete design of an initial Fabry-Perot receiver for the LIGO; and such a design has been developed recently. An outline of key aspects of this design is given in Appendix F to this Proposal. It is worth noting that development of this design has stimulated several new technical concepts, such as methods (i) for reducing demands on mirror precision, (ii) for keeping modulators out of high-intensity beams, (iii) for controlling alignment and other parameters, and (iv) generally for constructing a series of economical and effective interferometric detectors.

b) Conceptual design of a Delay Line Michelson receiver for initial operation in the LIGO

Two conceptual designs for a 4 km Michelson delay line receiver to meet the initial goals of the LIGO have been analyzed and an analytic model has been developed to estimate the contribution of known noise sources (Appendix G). The design study has identified components that would need development should such a receiver be constructed. These are large aperture (15 cm) electrooptic modulators, large diameter single mode optical fibers and long focal length, 87 cm diameter mirrors. Mirror specifications (substrate material, surface polish, figure and slope errors) have been developed with industry. Ray trace analysis has been performed on delay line configurations using separate input and output coupling holes to determine sensitivity to mirror distortion and fringe phase changes due to motions transverse to the optic axis. The design of a 5 meter prototype based on one of the conceptual designs has been completed.

c) Selection of prime receiver

The Fabry-Perot receiver system has been selected as the prime instrument for the initial LIGO operations (see Section VII) and will be the focus of LIGO receiver development both at the 40-meter and the 5-meter prototypes. The delay-line system will be maintained as an alternate and backup to the Fabry-Perot.

4. Scientific analyses to set the requirements of a 4 km facility

A complete calculation of scattering by residual gas in the LIGO has been made. This calculation confirms earlier estimates of the vacuum requirements.

Preliminary calculations of scattering by mirrors and tube walls have been made to determine a baffling strategy for the LIGO. The initial results indicate that scattering by tube walls and baffles driven by ground motion will not be a concern at frequencies above 100 Hz and probably will not be a serious problem at lower frequencies. More extensive (and difficult) calculations are needed to firm up our conclusions in the low frequency regime.

5. Development of a technique to measure small angle scattering

The system shown in Figure V-12 was developed, using fiber optics, to investigate the scattering around the focus of a spherical mirror when the surface is illuminated by a gaussian laser beam. At present, the system measures scattering as close as 800 microradians to the specular direction. The system has application to tests of large baseline mirrors; and its results have been an important input to our calculations of scattering effects in the LIGO (see above).

D. Collaborative Efforts

The following collaborative efforts with other researchers were established:

1) Prof Dan de Bra, Stanford University—work on magnetic suspension systems; mode: exchange of analysis and data.
2) Prof Neil Comins, University of Maine, (Orono, ME)—work on data analysis algorithms; mode: exchange of ideas and software.

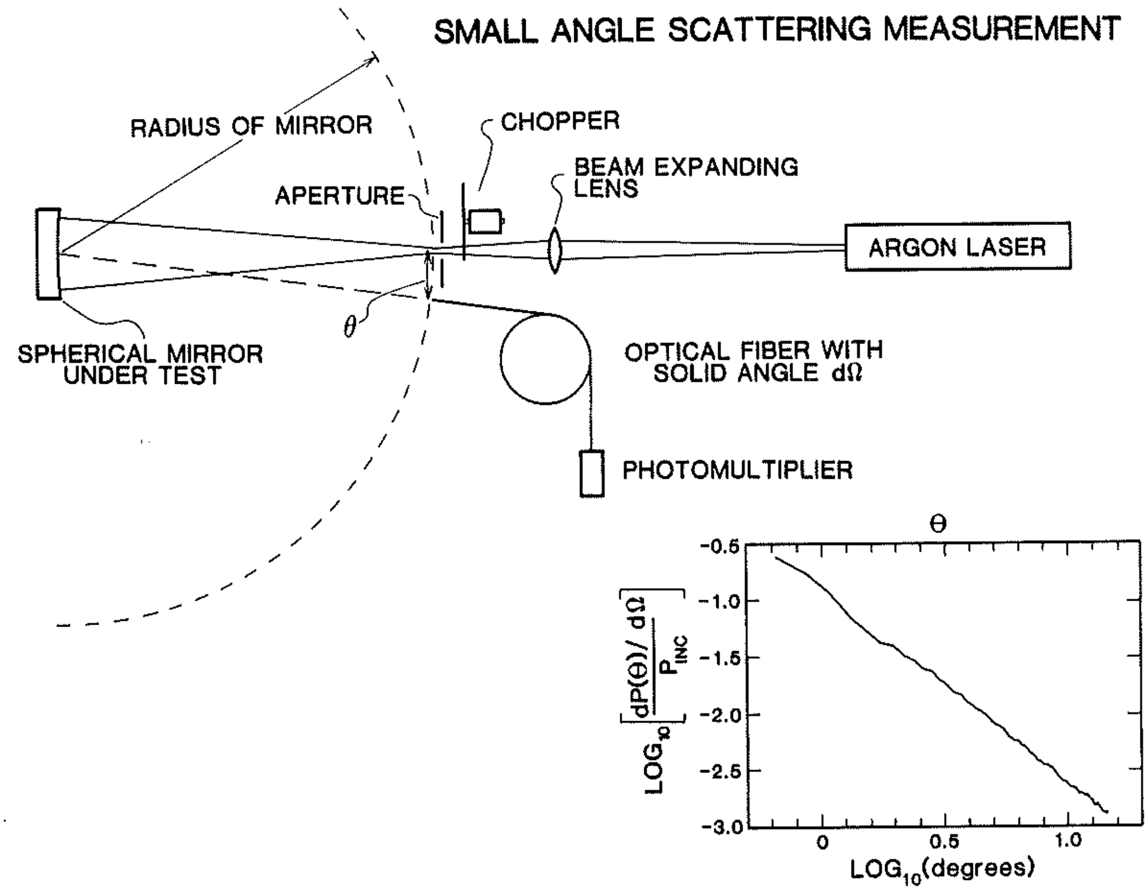

Figure V-12: A technique to measure small angle scattering. The technique has been developed to measure the small angle scattering of spherical mirrors in the laboratory. The curve in the lower right hand corner is the scattering function for one of the mirrors used in the 1.5-meter prototype.

3) Dr J.Chernoch, General Electric Research Laboratories, Schenectady, N.Y.—work on slab zig-zag Nd:YAG laser oscillators and amplifiers; mode: cooperative program to study properties of GE slab laser for application to gravitational wave research. GE has lent the LIGO project a slab laser for tests, and GE is testing most recent version of slab laser in single radial mode.
4) Dr. A. Mooradian, MIT Lincoln Laboratory—work on diode pumped oscillator and amplifier, Nd:YAG laser, ; mode: exchange of information and access to unclassified technology at Lincoln.
5) Dr. R. Schilling, Max Planck Institute, Garching, Germany— work on recycling of light with internal interferometer phase modulation (paper with NSF acknowledgement in preparation); mode: visitor to MIT April 1987 to October 1987.
6) Dr. H. Ward, Glasgow University—work on automatic cavity alignment system; mode: several extended visits to Caltech.

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F. Relation of Completed Work to Proposed Work

The proposed 3-year program (see Part VI) is a direct continuation of the R&D program supported under the present grant arrangement between NSF, Caltech, and MIT. The goals of a long range development program towards the LIGO were established at the time of our last proposals, three years ago, and remain unchanged. Administratively, a change from a loose association between the Caltech and MIT science teams to a unified program under a Project Director has recently been implemented.

Prototype development in the 40-meter facility, both to improve the sensitivity and to develop the receivers for a longer baseline system, will continue. The partially completed 5-meter system will be brought on line. The work on high power lasers, both argon and Nd:YAG systems, will grow. The research on the 1.5 meter prototype will phase out during 1988 after the current research on a fiber output coupler is completed. The most significant change in the experimental program is that the effort to develop a Michelson delay-line system as a receiver for the LIGO will be deferred so that the entire research group's energy can be applied to the development of the Fabry-Perot receiver system.

Work on the design, engineering and cost estimation of the LIGO will continue. During the next six months the conceptual design and functional requirements of the observatory will be completed preparatory to a proposed preliminary engineering design task in industry. Work will continue to establish primary and secondary sites for the observatory.

VI. PROPOSED WORK

This section describes the work that we plan to carry out during the three years of this proposal.

A. Receiver Development

The principal goal of the receiver development program is to establish the basic design for the first pair of LIGO receivers. The design will be established in sufficient detail to permit the final design, engineering and construction to begin at the end of the proposed grant period. A secondary goal is to carry out research on new concepts and techniques that will enhance the sensitivity and frequency coverage of LIGO receivers. The two goals have substantial overlap in that, within the constraints of maintaining reliability and minimizing the uncertainty in the extrapolation from prototype to LIGO scales, the initial receiver will be the most sensitive configuration we can design at the end of this grant period.

Receiver development will be a coordinated program of the Caltech and MIT Science Teams and the LIGO Engineering Section, using the 40-meter and 5-meter facilities. The Fabry-Perot system has been chosen for the first operational receivers in the LIGO.

The proposed receiver work is roughly divided into three areas:

First, the continuation of ongoing research to improve the performance of the prototypes. The prototypes will be the basis for the initial LIGO receiver and will offer the best means to uncover problems in overall receiver concepts. Substantial effort will be made to improve the laboratory facilities for the prototypes so as to make the research more efficient and to permit testing of the prototypes using full-size LIGO-scale receiver components.

Second, the development of techniques that are needed to achieve the aimed-for sensitivities in the LIGO, but are not necessarily related to direct improvements in prototype sensitivity. Some parts of this work will be carried out on the prototypes, and other parts in separate laboratory facilities.

Third, the analysis, modeling, and experimental testing of critical aspects of the LIGO receiver components and receiver/facility interface, with emphasis on aspects that could be influenced by the scaling from the prototype to LIGO dimensions.

We shall now discuss these three areas of research in detail.

1. Improving Prototype Receiver Sensitivity.

The receivers described in Part V have been developed to a sophisticated level. In the last 5 years the sensitivities of successive versions of Fabry-Perot receivers in the 40-meter vacuum system have been improved by more than 3 decades in amplitude—a flux sensitivity improvement of nearly 10 million times. As a result, this instrument, in its present prototype form, is within a factor three in sensitivity of the more mature cryogenic bar gravity-wave detectors, while having enormously greater bandwidth.

In spite of these achievements, our ultimate goals require major further improvements in receiver sensitivity. The development of advanced receivers involves a judicious mix of analytical and intuitive skills. These skills are in ample supply on the two science teams of the project, and it is the Director's responsibility to ensure that they are used most effectively. In general, effective receiver development requires operation of the best possible prototype instrument at every stage, since the relative magnitudes of predicted or "discovered" effects cannot be determined, and solutions developed, with any less sensitive apparatus. Thus, the step-by-step quest for better sensitivity in both the 40-meter and 5-meter prototypes will remain critical to receiver development. Among the already identified new tasks, for which detailed planning has started, are these:

(a) Modifications of Argon Lasers to Achieve Higher Power.

The argon ion lasers now in use (Coherent Innova 100-20) are the most powerful lasers of their type commercially available. Their single-mode output is rated at five watts; the two lasers in the 40-meter facility were selected for high power, and have been tested at 7 watts single mode. The method used to stabilize the laser, adjusting its wavelength with an intra-cavity Pockels cell, reduces the maximum output power to 2 watts. The highest quality Pockels Cells exhibit losses on the order of 1% per pass, and their lifetime is limited by radiation damage.

The Pockels cell used to stabilize the laser will be replaced by a fast-response piezo-driven mirror. The servo bandwidth attainable with a moving mirror is limited by sound-speed propagation delays to approximately 200 kHz, significantly less than the bandwidth achievable with a Pockels cell. To recover lost high-frequency response an external Pockels cell will be used to correct residual short-term phase fluctuations, as demonstrated at JILA [VI-1] and already applied to gravity-wave detectors [VI-2], including the 40-meter prototype.

(b) Development of beam recombining interferometers.

The basic arrangement for a gravity-wave detector using recombined Fabry-Perot cavities is illustrated in Figure VI-1. Here a beamsplitter divides the laser beam into two equal parts that pass via Pockels cell phase modulators PC1 and PC2, driven in antiphase with one another by a radiofrequency generator, to optical cavities formed between low-loss mirrors. A small fraction of the light coming back out of each cavity is diverted to auxiliary photodiodes (D2 and D3) by slightly reflecting mirrors shown as dashed lines in the diagram. Signals from these diodes are coherently demodulated (as described in Appendix H) to provide measurements of the phase differences between the laser light and the light resonating within each cavity. These phase differences may be used to stabilize the frequency of the laser, and also to feed back a length correction to each cavity to maintain it in resonance with the light. Most of the light emerging from the cavities is not diverted, but instead returns to the beam splitter, which recombines the two beams. The diode D1 monitors the recombined light, providing a direct measurement of the phase difference between the output light from the two cavities; this is the main interferometer output.

The Fabry-Perot cavity interferometers used to date have been similar in principle, but not identical to this arrangement. One simplification has been to divert all the output light from the cavities to the diodes D2 and D3, and use their signals not only for feedback control but also as the main interferometer output. (This is the system described in Part V, Figure V-4.) Thus, the modulators PC1, PC2 and photodiode D1

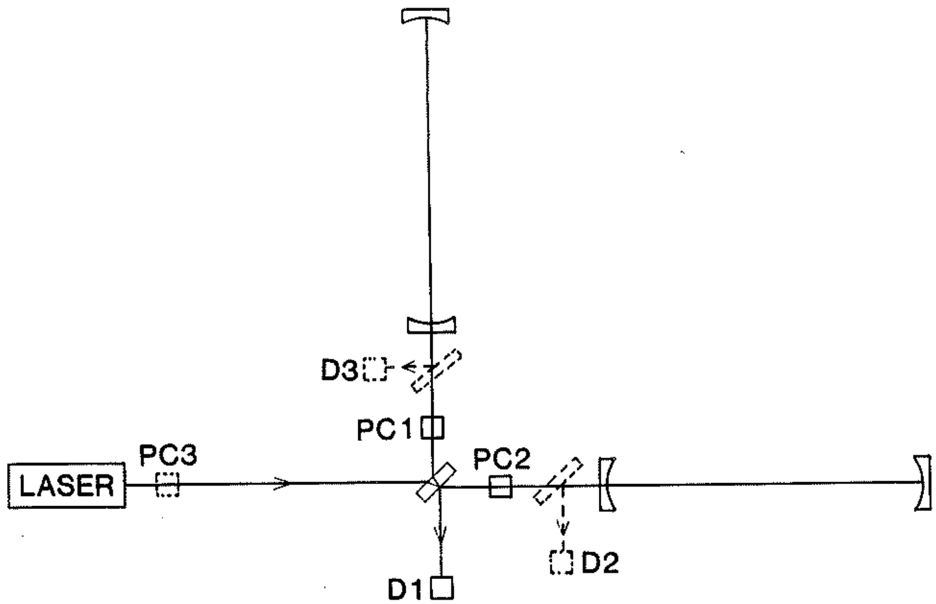


Figure VI-1: Simplified diagram for a beam recombining Fabry-Perot interferometer.

in Figure VI-1 have not yet been installed. With the experience we now have in the operation and precise position control of optical components in vacuum, we plan to rebuild the 40-meter Fabry-Perot prototype as an optically recombining interferometer system early in our program. Figure VI-1 is schematic in the sense that several techniques to achieve optical recombination in a Fabry-Perot will be analyzed. A particularly interesting variant is shown in Figure VI-2 where the RF phase modulation is achieved by placing the modulator in an auxiliary arm of the interferometer to reduce the optical power in the Pockels cell. The beam recombination feature will be implemented in the 5-meter system from start-up of operations as a Fabry-Perot prototype.

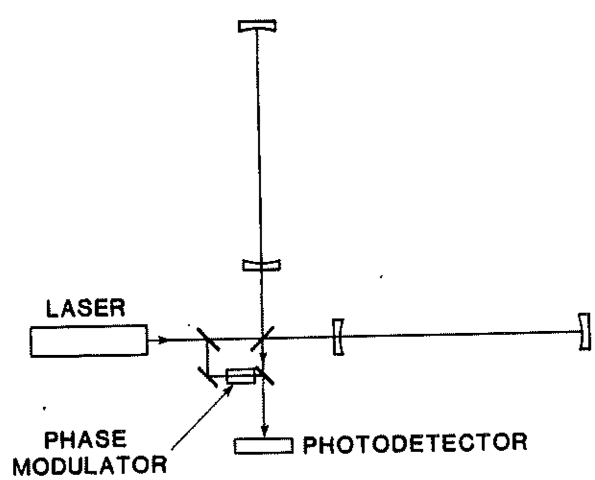


Figure VI-2: Beam recombination with auxiliary arm.

(c) Development of Techniques for Automatic Optimization of Beam and Mirror Alignment, and other Autonomous Control Systems.

Another improvement in the prototypes we intend to carry out early in the program is the further development of techniques for automatic optimization of beam and mirror alignment, and other autonomous control systems.

The cavity mirrors in the long-baseline interferometers are suspended freely so that they may respond to gravity waves. The alignment of these mirrors and of the laser beams impinging on them has to be precisely maintained. In current interferometers this is done by servo systems that sense the alignment using optical levers and position-sensitive photodiodes or using a number of capacitive or optical position sensors, and then apply feed-back forces to the test masses through the suspension wires or by electrostatic or magnetic means. An automatic method of optimizing the adjustments has been devised in the course of developing the Fabry-Perot receivers. The technique, illustrated schematically in Figure VI-3, senses misalignment by an extension, to geometrical parameters, of the reflection-locking technique on which the interferometers are based. The system measures the gradient in phase difference between light from the cavity and laser light reflected from the input mirror, at two planes in the output beam. The errors in alignment or position are processed to give correction signals that adjust the orientation of the mirrors or the position and direction of the laser beam.

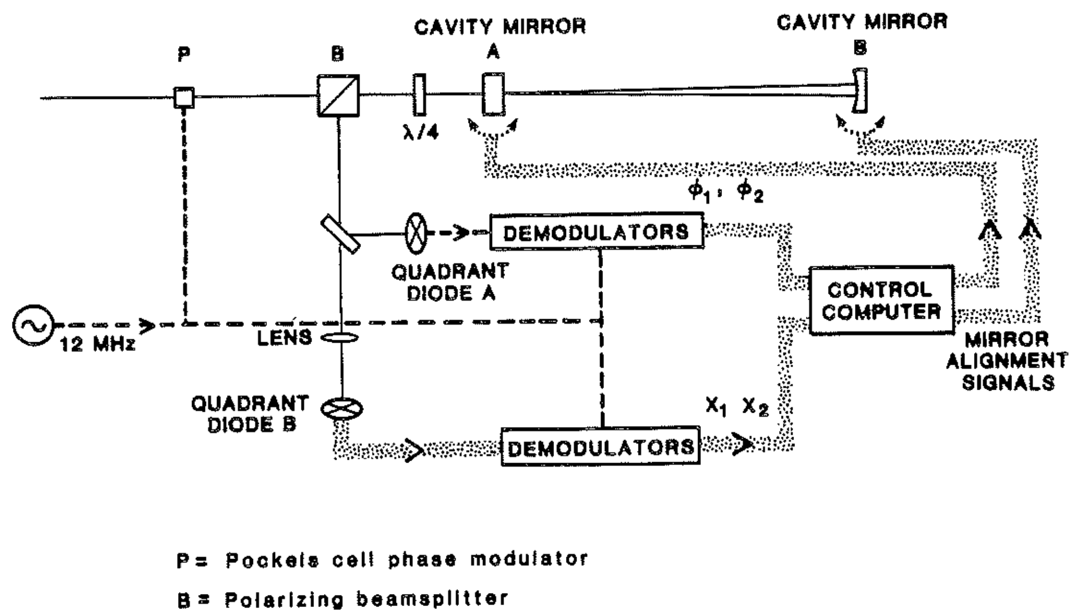


Figure VI-3: Method for automatic optimization of mirror alignment.

Successful operation of this system has been demonstrated in the 40-meter interferometer [Section V-B-1(c) above], and further development is in progress to make the automatic system switch back to a non-automatic mode that maintains alignment during periods when the cavity may be out of resonance. We plan extensions of this system to many other parts of the interferometer, supplemented by further control systems capable of maintaining accurate adjustment of all critical parts of the interferometer. This will be a continuing development, over a long period, and it is likely to improve the performance of the prototype interferometers, and also to become an important part of the LIGO receivers.

2. Development of Techniques Required to Achieve the Aimed-for Sensitivities in the LIGO.

(a) Laser light sources.

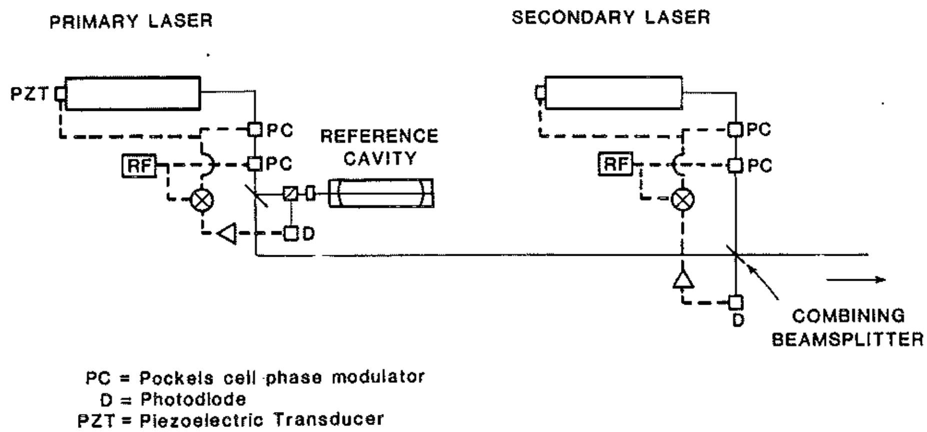
Desirable properties of lasers for both prototype and LIGO receivers include:

1. High power, continuous-wave output in a single transverse and longitudinal mode. Pulsed operation could be acceptable if the mean power is high, the repetition rate is at least 10 kHz, and optical phase coherence can be maintained from one pulse to the next. The goal for the initial LIGO receivers is 100 watts. This can be reduced to 10 watts if light recycling is used [subsection (b) below].
2. The output beam profile should be as close as practicable to that of a pure Gaussian mode, or have an amplitude profile that can be efficiently transformed into such a mode. This is required to allow efficient matching into optical cavities and other systems.
3. Optimal wavelength. A laser capable of generating light of short wavelength is desirable for two reasons: the power needed for a given shot-noise limited sensitivity is proportional to the wavelength (equation A-21, Appendix A); and the dimensions of mirrors and other optical components—and thus the diameter of the beam pipes—scale as $\lambda^{1/2}$. Thus, the cost of the installation is reduced by shortening the wavelength. However, the wavelength must be consistent with the availability of low-loss mirrors and efficient photodetectors. Frequency multiplying may be an effective way of obtaining short wavelength from energy-efficient longer-wavelength lasers, such as diode-pumped Nd:YAG lasers.
4. A long term goal is that the laser efficiency for conversion of input power to useable light power should be as high as possible. This requirement reduces operations costs for the LIGO when the number of interferometers operating simultaneously is large, as it affects the power and cooling demands.
5. The lasers must be reliable and not incur unreasonably high costs in replacement parts.

Because the laser is such a critical component in the project, we intend to maintain a dual program in laser development consisting of the refinement of the argon laser system as well as the development of the Nd:YAG.

(a-1) Addition of Argon Lasers

A single argon ion laser, even operating at full power, is not adequate to achieve the best projected sensitivity of the LIGO receivers, especially at frequencies greater than 1 kHz. A method for stabilizing several lasers to a reference cavity and summing their outputs has been devised, and will be tested during the proposed period. Figure VI-4 shows the optics and electronics used to add two lasers coherently. The ultimate system will sum at least four lasers. In addition to providing more output power, the use of several lasers will add reliability to the detector—the failure of one laser will not halt operations.



VI-4: A method to increase optical power by coherent addition of lasers.

(a-2) Nd:YAG Laser Development.

The major advantages of the Nd:YAG system are its relatively high efficiency, $\approx$ 1 to 5%, its high output power, and its low intrinsic frequency noise and low amplitude noise at RF frequencies.

Cooperative arrangements link the LIGO project with ongoing high-power Nd:YAG laser and amplifier research programs at General Electric and at the MIT Lincoln Laboratory. Stabilizing the frequency and amplitude of the laser is the basis of our proposed work during this grant period.

The laser system we intend to develop is shown in Figure VI-5. It consists of a primary diode pumped ring oscillator developed by Prof. R. Byer [VI-3] at Stanford. The oscillator is followed by a diode pumped amplifier. Recent progress and near-term projected advances in diode laser pump technology indicate that within the next year it should become possible to construct diode pumped amplifiers with the capability of delivering a few watts. An amplifier with 60 db gain (using flash lamps) has been demonstrated [VI-4]. In present plans the final stage will be a GE slab head pumped by lamps, but the final stage might be diode pumped if the laser diode program continues to advance at the projected rate. The frequency of the master oscillator is stabilized by reference to a cavity using the reflection technique developed for the argon laser system.

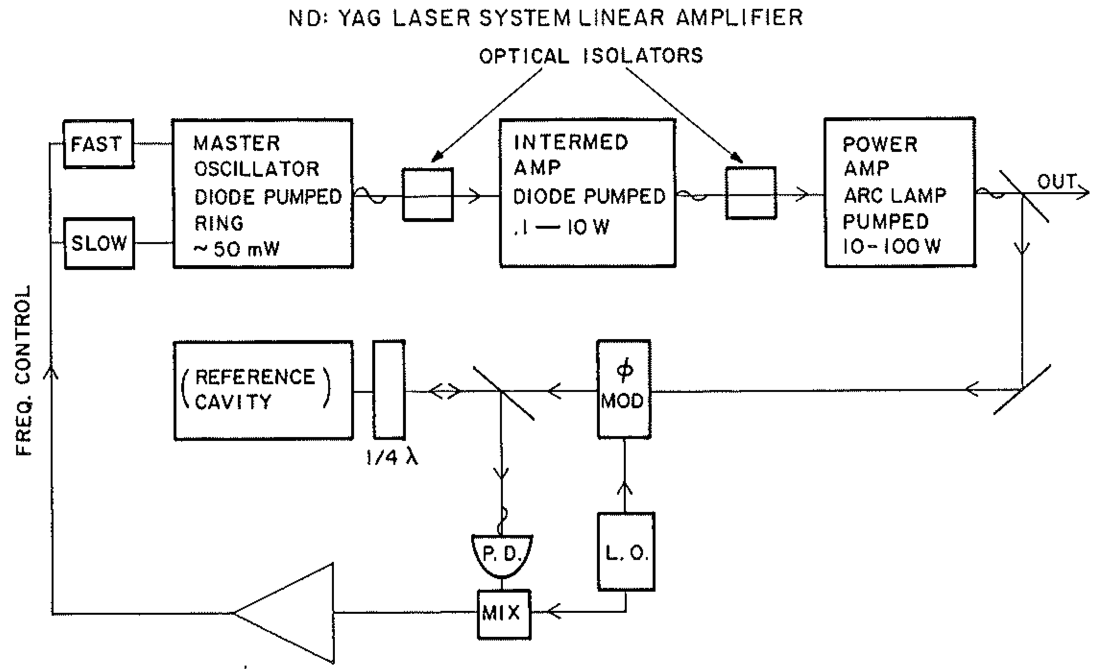


Figure VI-5: Schematic of the proposed frequency- stabilized Nd:YAG oscillator/amplifier combination.

(b) Experimental development of Light Recycling and Optically Resonating Receiver Techniques.

Advanced receivers in the LIGO will almost certainly use "light recycling" or "optically resonating"; and even the initial receiver might use recycling.

Light Recycling [VI-5] exploits the fact that our present Fabry-Perot mirrors have such low optical losses that light can be stored for periods up to a millisecond in the 40-meter cavities; and correspondingly longer storage times are possible in a kilometer-scale system. Once the storage time has reached half the gravity-wave period, however, further increases in storage time do not produce much improvement in the photon shot noise limit to sensitivity. Thus, in a LIGO-scale Fabry-Perot interferometer it would be convenient to choose the transmission of the input cavity mirrors to make the storage time approximately half the gravity-wave period. With so short a storage time, most of the input light would return back from each cavity to the beamsplitter. It is convenient and efficient to arrange that the output photodiode is at a dark region in the interference pattern, with the high frequency phase modulation giving a small phase dither around the minimum-intensity point. Under these conditions most of the light leaves the system through the other side of the beamsplitter. It then becomes possible to re-use this light, by returning it to the interferometer in the correct phase to reinforce the input laser light. This return can be achieved by an additional mirror in front of the laser. This "broadband recycling system" is shown, in principle, in Figure VI-6a. The sensitivity improvement achievable by this arrangement depends on the length of the interferometer arms and the mirror losses (equation A-24a in Appendix A), and is indicated in Figures II-2 and A-4a by the right hand part of the curve labelled "possible advanced detectors".

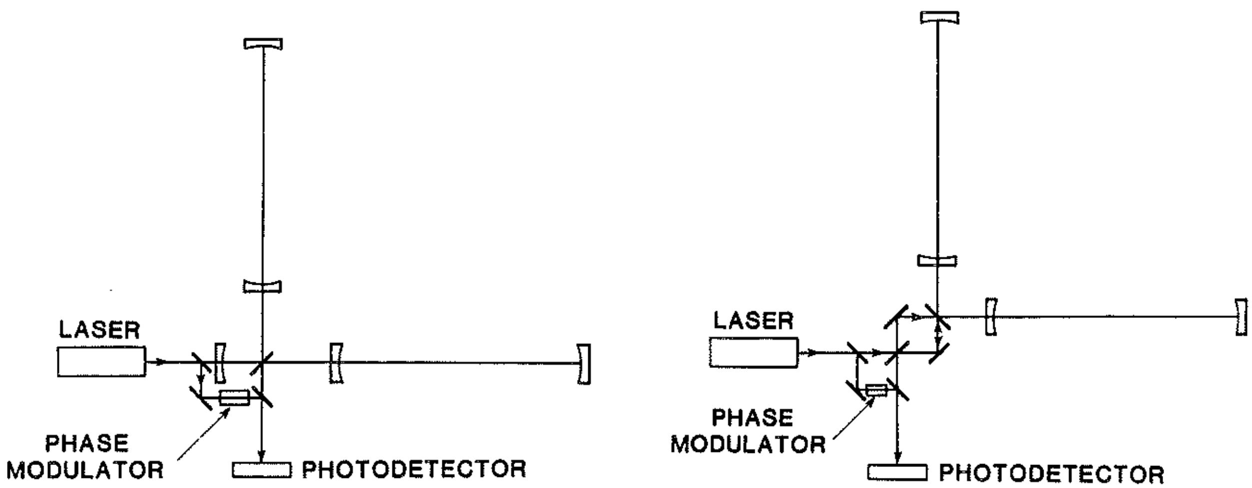


Figure VI-6a,b: VI-6a (left); broadband recycling system. VI-6b (right); optically resonating system.

Optically Resonant Recycling [VI-6] is applicable in the detection of periodic and stochastic gravity waves . The optical arrangement, as illustrated in Figure VI-6b, involves coupling the two optical cavities to one another via a mirror of high reflectivity, which takes the place of the usual beamsplitter. The coupled cavities then have two main resonance modes, one of which is arranged to correspond to the frequency of the laser light, and the second to a sideband produced by modulation of this light at the gravity-wave frequency. A continuing periodic gravity-wave can build up a signal in this second mode during the overall light storage time—which may be many gravity-wave periods—to give a much enhanced response. Detection of the resonant phase signal may be made by the auxiliary interferometer shown at the lower left of the main system. This "optically resonant" receiver gives a larger enhancement in sensitivity at its resonant frequency than the broadband recycling system; but it does so at the price of a narrowing of the bandwidth. Expressions for its shot noise limits to sensitivity are given in equations (A.24b, c) of Appendix A and are illustrated in Figures A-4b and A-4c.

Light recycling and optical resonating are planned for the LIGO, but in the 40-meter prototype the currently available mirrors do not give long enough storage times for recycling or resonating to be useful at frequencies $f \leq 1$ kHz. We propose, during this grant period, to test and develop recycling. We may do so at frequencies higher than 1 kHz so as to partly compensate for the difference in storage time between the prototype and the full-scale LIGO system.

In addition to light recycling and resonating, there is a third technique that shows promise for advanced receivers: the use of "squeezed light" in the interferometer [VI-7]. We do not plan to work on this during the proposed grant period, but will likely pursue it in the more distant future.

(c) Test Masses and Mirrors

(c-1) LIGO Test Masses

A lesson learned early in the development of prototype receivers is the critical nature of the test masses, especially their spectrum of mechanical vibrations. The design criteria for test masses are:

- Minimum thermal noise. Internal vibrations, including the inescapable thermally excited modes of energy $\frac{1}{2}$ kT, threaten to mask signals. Thermal noise is minimized by
    1. Selecting materials and construction techniques for high mechanical Q.
    2. Keeping the lowest resonant frequency well above the gravity-wave signal band.
    3. Maximizing the mass, within the constraint of high resonant frequencies. This will also reduce the quantum limit (equations A-25 in Appendix A) and the effects of fluctuating forces of residual gas molecules..
- High optical purity. The test masses at the interferometer input must be transparent; and their optical properties are critical in recycling applications: the material must be low in optical loss, optical inhomogeneity, and scattering.
- Surfaces that will accept a super-polish finish and ultra-low loss optical coatings.

The test mass material currently used in the 40-meter prototype, fused silica, has high mechanical Q [VI-8] and is commonly used as a substrate for high quality optics. Pieces roughly double the linear dimension of the present masses in the prototype will serve in LIGO receivers optimized for 1 kHz and above. We propose during this grant period to acquire fused silica masses of this size (20 cm diameter by 10 cm thick), verify that their mechanical and optical losses are low, and eventually install them in interferometers. We will also investigate sapphire as a candidate test mass. Its mechanical properties are unsurpassed [VI-9] and early experiments [VI-10] indicate it may be an excellent substrate for low-loss optics.

(c-2) LIGO Mirrors

Mirrors reside at the heart of a gravity-wave receiver, and their properties determine the receiver's ultimate sensitivity and frequency range. Desirable properties of the mirrors are:

- Low loss. The mirrors installed in the 40-meter prototype have scattering and absorption losses in their dielectric coatings small enough to optimize sensitivity for signals at 500 Hz and above. Similar mirrors installed in a 4-km interferometer will extend the frequency range downward and permit enhancing the sensitivity by recycling.
- Capability to withstand high power. The power incident on the main cavity mirrors in a LIGO receiver will be spread over a large enough area that heating damage is unlikely, even at the highest projected power levels. The still higher intensities incident on auxiliary cavities will be managed by using mirrors with low

absorption loss and by decreasing the intensity of the resonant light—this can be accomplished without reducing the useable power by building the cavities several meters long.

- Low scattering. The interferometer mirrors are likely to be the dominant source of scattered light. This potential source of noise may be reduced by using mirrors with the same low scattering loss as the mirrors currently used in prototype research.

The Project has entered a contract with the Guidance and Control Division of Litton Industries, to supply mirrors for receiver development. We have worked in close cooperation for several years with their internal research and development group and have received from them custom-coated prototype mirrors with losses as low as 40 parts per million. We have devised methods previously unavailable in the industry [VI-11] for testing the mirrors, and we expect this collaborative arrangement to result in still better mirrors as the testing and production techniques are refined to fit the LIGO requirements. During the grant period we will acquire from Litton ultra-low loss mirrors of 12 cm diameter, and test them in the prototypes. This size mirror can be coated in existing chambers at Litton without extensive retooling, and it is an appropriate size to serve as the test-mass mirror for the LIGO midstations. Because, however, it is probably too small for the full-length interferometers, we will investigate contracting for modifications to existing coating chambers to produce larger mirrors.

(d) Seismic Isolation Development Toward Lower Frequencies.

The seismic isolation demonstrated in the prototypes (Part V, Figure V-5) is adequate for the first receiver in the LIGO at kHz frequencies. There are, however, important reasons to continue the development of improved seismic isolation, especially at low frequencies. These are:

1. The expectation that the probability of detecting sources is higher at lower frequencies.
2. Improved isolation has multiple benefits in the prototype research by reducing the dynamic range required of servo controllers, and reducing upconversion by nonlinear couplings in the suspensions and the fringe noise from parasitic interferometers.

We propose to continue work on a dual approach to the problem. One part is local isolation, with multiple vibration isolation systems at each suspended element; the other is global isolation for the important degree of freedom along the optic axis of the interferometer. The two methods are complementary, and both are also adaptable to active isolation systems which will be needed to achieve the ultimate low frequency performance of the LIGO.

(d-1) Description of the Anti-Seismic Suspension Point Interferometer

Global isolation along the optic axis will be introduced, during the proposed grant period, using a suspension-point interferometer on the 40-meter prototype. Already about half completed, this instrument incorporates two unequal-arm Michelson interferometers to sense relative motions of the suspension points for the mirrors at the two ends of each arm (Figure VI-7). At frequencies below 100 Hz, the seismic noise feeding through the suspension wires dominates other noise by a large factor. Moreover, at frequencies above 1 Hz the suspension point moves more than the test mass below. Therefore, even a relatively low-sensitivity single-bounce interferometer can provide useful suspension-point signals. The signals will be fed back to piezoelectric translators near the points of suspension, reducing seismically-induced relative motions of the suspension points as much as 100-fold. Because of the isolating effect of the wire suspensions, reduction of this seismic noise will not affect the gravity wave signal as measured at the test masses.

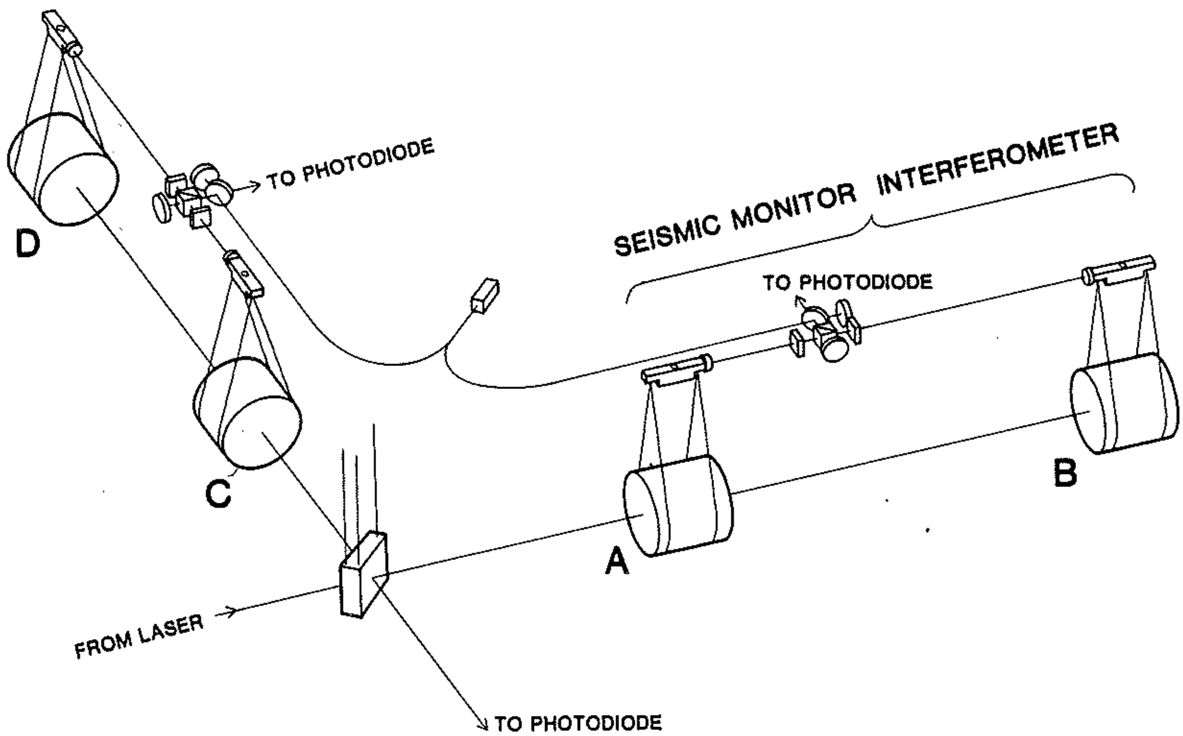


Figure VI-7: Anti-Seismic Suspension Point Interferometer.

(d-2) Multiple Suspension Development

Local isolation at frequencies below 1000 Hz will be improved during the proposed grant period. To bring the seismic noise at a remote site to a level comparable to the other noise terms projected for the initial sensitivity of the LIGO requires a total isolation of 200 db at 10 Hz and 160 db at 100 Hz. No single stage system is expected to be able to provide this degree of isolation. However, it should be attainable using multiple vibration isolation systems which, as one advances toward the mirror, exhibit progressively less thermal noise. In the simplest systems, the isolation just comes from the passive action of masses and springs, although in practice it is usually necessary to use active feedback to damp their resonances. More advanced designs will use servos to improve the isolation by locking the motion of an outer mass in the hierarchy to that of an inner one, thereby lowering the effective resonant frequency. Although vibration isolation along the optical beam direction is the most critical, cross coupling and imperfections in the alignment of the interferometers argue for nearly isotropic isolation.

A prototype of a new suspension system for the mirrors of an interferometer is now under construction for the 5-meter system (Part V, Figure V-9). The principal aspects of the design strategy are 1) to provide several stages of passive isolation in a cascade of mechanical resonators, including a substantial amount of isolation for the degrees of freedom transverse to the optical axis, 2) to make the mirror itself the final isolated mass in the cascade, 3) to use active (cold) damping for all degrees of freedom, and 4) by servos to achieve active reduction of resonant frequencies (active isolation).

This suspension, before installation in the prototype interferometer, will undergo tests in an auxiliary chamber designed for suspension research which is a new facility for the LIGO project. Subsequent work will be done to improve the suspension design with measurements of damping in pendulum wires under stress and with tests of new sensors and actuators, vacuum compatible passive isolation stacks, and active isolation servo loops.

(d-3) Magnetic Suspension Development

Magnetic suspensions are being developed as an outer stage of a local, multiple isolation system. The properties of a magnetic suspension that make it interesting for gravitational wave research are: 1) they are well suited to high vacuum, 2) the spring (i.e. the magnetic field) has none of the internal resonances which compromise the isolation of mechanical springs, 3) one can attain long periods, of the order of 100 seconds, in a compact geometry. The disadvantage is the low Q due to eddy current losses and it is for this reason that (until room temperature superconductivity becomes a reality) magnetic suspensions must be followed by a high Q suspension to act as a filter for thermal noise.

The magnetic suspension now under development is shown in Part V, Figure V-10. It is intrinsically stable for motions in the horizontal plane with oscillation periods determined by the field geometry. The support forces are provided by permanent magnets trimmed by coils driven through a servo system to achieve stability for vertical translation and for rotations about axes in the horizontal plane. The system has been floated and supports 150 kg using three Alnico magnets. When completed and tested successfully, the system will be incorporated as the first stage of isolation in the 5-meter prototype.

(d-4) Interferometric Fiberoptic Position Sensor

One candidate system for standardized production by the LIGO project is a fiberoptic position transducer that will find application in passive and active vibration isolation systems. A schematic of the transducer is shown in Part V, Figure V-11. The position sensor is a phase modulated Michelson interferometer. An operating prototype has been developed that uses a 1 milliwatt laser diode at 1.3 microns. The electronics is designed to give both analog signals within a single fringe and digital information for fringe counting to accommodate large motions.

The measured position sensitivity of the detector using a multi-mode laser is at present 2×10^{-11} m/$\sqrt{\text{Hz}}$. With a single mode diode laser, the system should have a sensitivity of 2×10^{-14} m/$\sqrt{\text{Hz}}$ and a larger dynamic range. A distributed feedback diode laser will be tried within the next year.

3. Analysis, Modeling and Experimental Study of Aspects of the LIGO Receivers that are Difficult to Test at Prototype Scale.

Extensive analysis has been carried out to determine the sensitivity scaling properties of interferometric gravitational wave detectors from small to large baselines for fundamental noise terms (See, e.g., Reference [III-5]). The analysis has been used to determine the essential properties of the LIGO (see Part IV.C).

In going from the present prototype experiments to the LIGO, some parameters in the experiment design and some noise terms uncovered in the implementation of the receivers will change with the scale. In particular, the optical beam size and delay times of signals grow, while the relevant angles for alignment, diffraction and scattering decrease. The analysis of the influence of these scale changes needs more work and this is proposed as part of a combined analytic and experimental program during this grant period. There are several important areas.

(a) Mirror Scaling and Scattering.

The mirrors for the LIGO will be larger than in the present prototypes. Coating uniformity, surface roughness, surface figure and slope error, substrate transmission and wavefront distortion, the internal mechanical losses and resonant frequencies, and the thermal properties of the mirrors all depend, to varying degree, on mirror size.

The influence of scattering by mirrors as a function of antenna length is an important issue. The mode dimension (spot size) grows as $L^{1/2}$, so that scattering angles relevant to the interferometer's performance diminish as $1/L^{1/2}$. General experience with mirrors is that the scattering amplitude becomes larger as a reciprocal power of the scattering angle the closer one approaches to the specular beam (cf. Figure V-12 above). This phenomenon is not fundamental; rather it represents the increasing technical difficulty of controlling mirror figure and slope errors over larger scale lengths on the mirror. The effect of scattering from mirrors could therefore become more serious as the interferometer grows in length. Preliminary studies and a survey of present optical polishing capabilities indicate that there is sufficient margin for the scaling; however further analysis and experimental work is needed. We hope early in the proposed period to specify the mirrors for the initial LIGO receiver and to begin tests of mirror prototypes.

Scattering by the tubing walls and baffles is another area where the scaling to larger lengths must be analyzed further. The relevant angles of scattering and diffraction at the tube walls decrease as $1/L$. The worrisome issue is the phase modulation of the scattered light at the output of the interferometer due to motions by the tube walls and baffles driven by ground noise. This noise source is substantially reduced by keeping the beams as far as possible from the vacuum walls, by proper baffle design, and by the use of spatial filters at the output of the interferometer. Preliminary analysis indicates that there is a safety margin, but a complete analysis, especially to determine an optimum baffle design, must still be carried out. The analysis may require the development of Monte

Carlo computer codes for scattering and diffraction by coherent light. Codes developed by Breault Associates of Tucson, Arizona appear to need only small modification for the LIGO analysis, but they will require a supercomputer to run.

(b) Servo System Analysis for the LIGO

The delay time in some of a receiver's servo systems must increase with increasing arm length. Examples are global beam positioning and pointing servos that have sensors and controllers at opposite ends of the beam tubes, and interferometer fringe locking systems that position controllers on the mirrors. It is important that delay times be kept small enough not to impose serious constraints on servo bandwidths and in turn on servo loop gains. A model for scaling to the LIGO size will be developed during the grant period. This model will include known noise sources that influence beam position, beam pointing, frequency stabilization and fringe lock.

(c) Tests in Available, Other Large Systems.

Much of the scaling can be handled by analysis and modeling, but there may arise a need to test mirrors, scattering, and servo system properties on a larger scale than is now available in the 40-meter system before we commit to final designs for the receivers and facility. As part of the proposed work during the coming year we will determine whether it is useful to set up specific length scaling tests in existing vacuum systems or other facilities such as those at Marshall Space Flight Center at Huntsville or White Sands Proving Ground. Some tests being contemplated involve straightforward scattering measurements of large radius mirrors using the techniques shown in Part V, Figure V-12.

B. Buildup of Experimental Facilities

Introduction

The facilities at MIT and Caltech require expansion and enhancements to accommodate the receivers under development. More specifically, in order to build receivers appropriate in scale and sensitivity for the LIGO we will need increases in electrical power, laser cooling, vacuum system capacity, and computer facilities.

1. Unified Data Acquisition and Analysis

Receiver development will benefit from the use of common hardware and software in the prototype interferometers. Standardized formats for recording and exchanging data will be implemented, and data analysis algorithms tailored for application to LIGO signals will be developed. Interferometers at MIT and Caltech will use similar systems of high-speed analog-to-digital converters, atomic-standard timekeeping and high-density archival storage of data. High-bandwidth cross-continent data links will be evaluated.

2. Unified Development of Control Instrumentation

Commercial modular electronic instrumentation—a combination of the CAMAC and NIM standards—will be used wherever appropriate. A large number of position sensors and transducers (on the order of one hundred) will control suspended masses and optical components. These devices will be standardized. Interferometric fiberoptic position sensors (Figure V-11 and Section VI.A) are being developed. Small computers will be integrated with much of the control circuitry, especially mechanical and low-bandwidth optical servos. The project will also standardize specific, often used circuits such as low noise, high voltage, wide band amplifiers and RF mixer systems.

3. Buildup of the 5-meter Facilities

The vacuum system (tanks, pumps, and associated gauges) for the new 5-meter facility has been installed and tested in recently renovated high bay facilities (Figures VI-8, VI-9). Three cylindrical tanks will hold the interferometer, and a fourth tank will be used to test suspensions and other components. The pumping system is configured to permit separate pumpdown of the interferometer vacuum system and of the auxiliary vacuum system, so that either may be accessed without interrupting the operation of the other. The system is constructed from stainless steel, and its dimensions are shown in Figure VI-8. Each tank consists of a base through which electrical and optical connections will be made and a top to which the beam tubes are attached with quick-release flanges. All of these large flanges are sealed with Viton O-rings. Numerous smaller ports are sealed with copper gaskets. There is rapid clear access to all of the internal components of the interferometer.

The pumping system consists of turbo and ion pumps backed by a mechanical pump. Turbo pumps are used for the initial pumpdown and ion pumps for holding the vacuum. After cleaning with detergent and hot water, the outgassing rate has been measured as 2×10^{-9} torr-liters/sec-cm^2 of condensible gas and 5×10^{-10} torr-liters/sec-cm^2 of non-condensible gas.

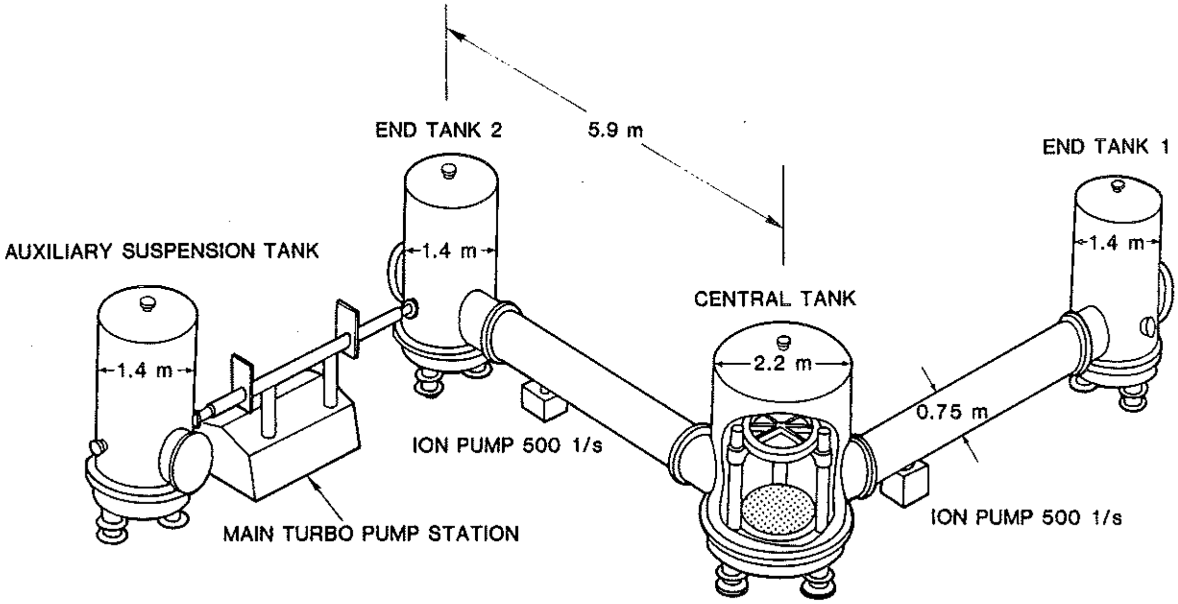


Figure VI-8: Vacuum system for the 5-meter facility

An internal framework to support the test masses is being fabricated. The weight will be supported on three posts in each tank, and the posts will be bridged with vacuum compatible optical tables. The framework will be acoustically isolated from the vacuum enclosure.

4. Enhancements to the 40-meter Prototype

(a) Vacuum System. The present 20 cm diameter pipes in the 40-meter vacuum system provide inadequate clearance for the orientation control beams and the main and auxiliary interferometer beams that are required for planned receiver development. We wish to replace them with 60 cm pipes. At the same time, future receiver development will require replacing the 45 cm diameter chambers housing the end masses by chambers 1 to 1.5 meters in diameter. Larger end chambers will also provide a better match to the 1.8 meter central chamber, which is now being fitted out and will be installed early in 1988. The cranes at the end stations will have to be modified or replaced with larger cranes to handle the larger components, and minor modifications to the laboratory building may be required to increase overhead clearances. A new chamber at the central station will hold a mode cleaner several meters long, and smaller chambers will house cavities to filter the output beams.

(b) Laser Power Capability. The electrical power and cooling water capacity need to be doubled to accommodate a total of four high power argon ion lasers. Each laser dissipates 50 kW.

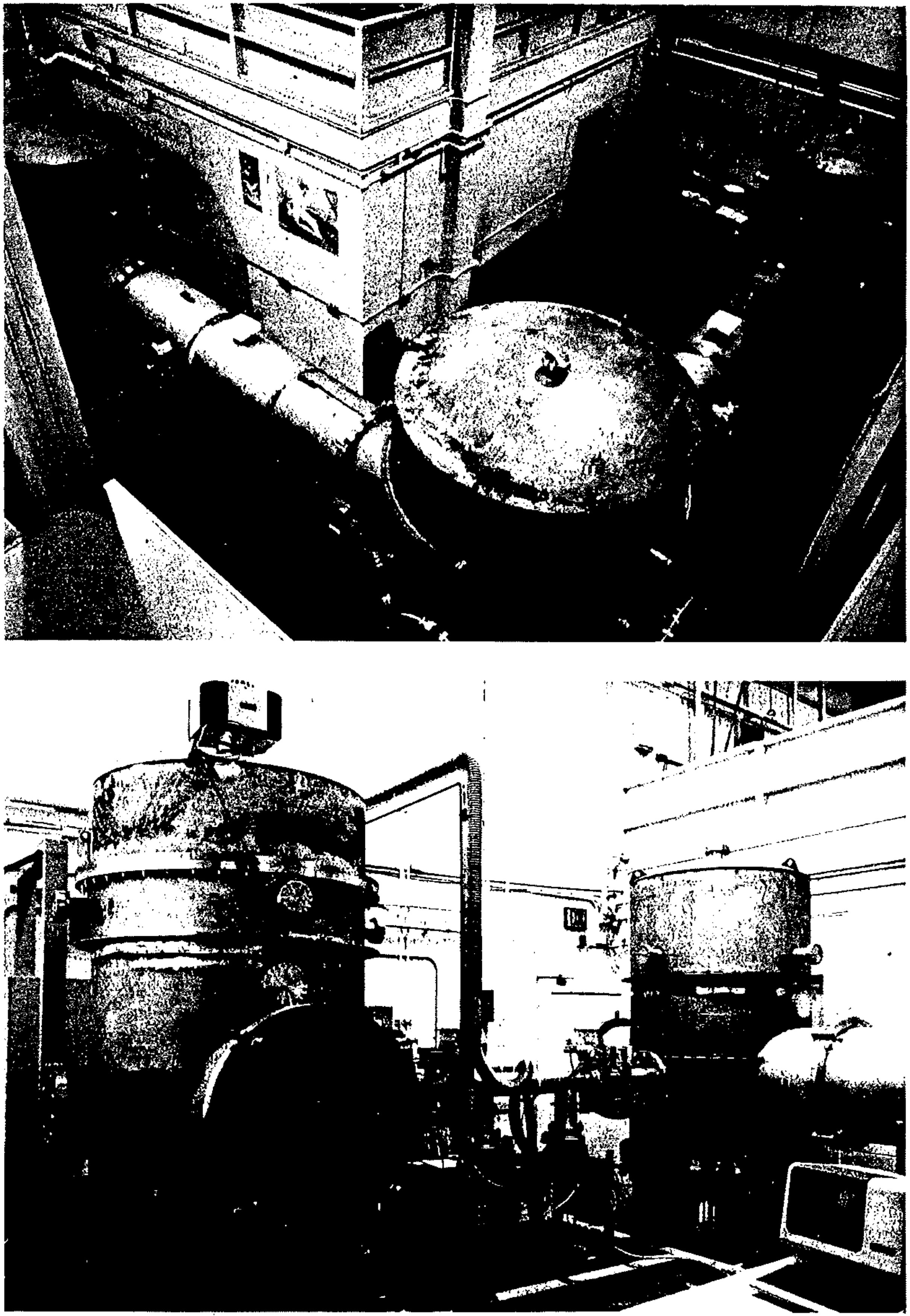


Figure VI-9 Two views of the vacuum system for the 5-meter facility.

C. Conceptual Design for the LIGO

Completion of the conceptual design of the LIGO is scheduled for Fall 1988. It will provide the basis for the Preliminary Engineering Design and Cost Definition. The critical conceptual design issues relating to the LIGO vacuum system, the receiver-facility interfaces, and the capability for multiple-use are being studied by LIGO science working groups in cooperation with the engineering staff.

Vacuum System. The overall concept for the LIGO vacuum system (see Part IV) has been defined by earlier work including the MIT–Stone & Webster–A. D. Little study and efforts by the Caltech Jet Propulsion Laboratory. Detailed vacuum design issues that require further study and definition include:

1) Methods to achieve desired material outgassing rates (Section VI.E, below);
2) Light scattering and the design of baffles (Section VI.A.3(a) above);
3) Environmental requirements:
    a. Acoustic, seismic and other vibrational noise limits,
    b. Allowable temperature excursions.

Receiver-Facilities Interfaces. The receiver design is currently not a pacing item in the LIGO schedule. Critical issues related to receiver interfaces with the vacuum system and other facilities, however, must be resolved before starting the Preliminary Design. These include specifications for support structures, optical ports and electrical feedthroughs, and laser power and cooling requirements.

Multi-Use Concept. The first LIGO search for gravity waves will be made with a detector consisting of two interferometric receiver systems, one in each facility. The LIGO, however, is being designed to accommodate multiple receivers. The tube diameter of 48 inches is large enough to handle 4 to 6 beams simultaneously in the Fabry-Perot configuration. In addition, new receivers will be installed and developed at the sites without need for breaking the vacuum of the operating receivers, thus allowing them to continue their search without interruption. This aspect of the conceptual design, which involves the judicious placement of vacuum tanks, gate valves, and support structures for the test masses, will also be completed before the Preliminary Design and Cost Definition.

D. Sites

The two sites for the LIGO will be selected by Spring, 1988 so that sufficient survey work can be completed before the start of the Cost Definition contract. Scientific issues relevant to the selection of a pair of sites within the continental United States were identified and quantified by a LIGO Site Selection Working Group in August, 1987. This study showed that the chosen preliminary site pair, Edwards, California and Columbia, Maine, is acceptable in terms of scientific criteria. Other factors such as site topography and availability are being studied and backup sites are being identified.

E. Vacuum Prototype

A prototype vacuum system is being built to test, demonstrate, and validate critical technology. Tests with this system include:

1. Evaluation of outgassing of the selected tube materials including the effects of surface preparation and cleaning techniques, bakeout procedures, and rates of outgassing as a function of time;
2. Studies of ion pump performance with sub-millisecond time resolution to determine gas-bursting characteristics;
3. Demonstration of key technology areas such as outgassing behavior of welded joints;
4. Measurement of outgassing rates of materials and components intended for use in the receiver systems;
5. Development of instrumentation to monitor gas column density in the 4 kilometer tubes.

This system is designed with bakeable metal/metal seals and valves to permit outgassing measurements of small surface area sections of tube material prepared with different surface cleaning techniques. A full diameter "demonstration" section of the LIGO beam tube using the fabrication, cleaning, and baking methods planned for the LIGO will be subsequently tested. The system will later be used to determine the outgassing properties of receiver components.

Results of tests with the vacuum prototype will be used to specify materials and procedures for use in the engineering design and in the eventual construction of the LIGO vacuum system.

F. Preliminary Engineering Design and Cost Definition

The LIGO receivers, data acquisition and data processing equipment, while quite sophisticated, are relatively low capital cost elements of the LIGO. In this section, we focus attention on the relatively expensive capital parts of the LIGO: vacuum chambers, tubes, valves, pumps and controls; buildings to house the vacuum chambers, tubes, and work areas; power supply and distribution; laser cooling equipment; supporting utilities; environmental monitoring; safety and security; communications and ancillary equipment; and access roads, erosion control, landscaping and related site development work. These items are collectively referred to as "LIGO facilities."

A significant effort has been put forth in defining and demonstrating the feasibility of the LIGO vacuum facilities, buildings and ancillary facilities. Past studies by A. D. Little, Stone & Webster, and the Jet Propulsion Laboratory have shown that the LIGO facilities can be implemented within a reasonable extrapolation of current technology. These feasibility studies, however, have been inadequate to establish definitive cost estimates. The cost uncertainties can be resolved only by going forward with at least a preliminary (partial) systematic engineering design utilizing the full resources of industry. This approach will result in detailed design specifications and will expose and resolve any outstanding or unidentified technical and cost issues.

The objective of the preliminary engineering design activity is to systematically conceive, evaluate and document the implementation aspects of the LIGO facilities to a level of detail sufficient for complete, accurate and reliable cost estimates. The tangible result of this phase of work will be a proposal to the National Science Foundation for the construction of the LIGO. The engineering design process is a continuous one, starting with these preliminary design activities and leading to construction documentation in the form of working drawings, piece part and process specifications, and detailed construction flow plans and schedules. This full design process will be approximately one third complete at the time of submission of the construction proposal, and will be suspended at that point to permit full review and approval by the NSF. We are recommending this split engineering design approach as the least costly means to provide the NSF with the full information needed to make an informed decision on the construction of the LIGO.

The LIGO facilities engineering design will be carried out by an experienced architectural and engineering firm under contract to Caltech. Starting from the functional specifications and baseline design to be completed during the current conceptual design phase, the contractor will be asked to deliver the following work products:

a. Progressively prepare schematic design documents, preliminary design or design development documents, drawings, outline specifications and other data required to fix and describe the size and character of the project in the areas of architectural, structural, civil, electrical and mechanical subsystems, materials, processes and such other elements as may be appropriate.
b. Identify areas of technical or cost risk, and study and report on alternative solutions which promise to reduce cost or risk, and enhance reliability. Develop plans to manage and control significant risk areas that remain in the design.
c. Prepare a written description of the LIGO facilities in report form including design criteria, potential seismic or corrosion problems, suitability of site soils, and preliminary foundation recommendations.
d. Identify and prepare detailed drawings and specifications for any long lead procurements and for site development activities that are necessary prior to the start of facilities construction.
e. Prepare an Implementation Plan for the completion of the engineering design, generation of construction documentation, bidding, construction, construction supervision and quality control activities required for completion of the LIGO facilities. Include such technical, schedule and cost data as necessary to permit an accurate assessment of readiness.
f. Prepare an estimate of construction costs based upon the preliminary design data, including an analysis of cost uncertainty.

1. Procurement of the Preliminary Engineering Design Contract

Competitive proposals to perform the preliminary engineering design work will be solicited from architectural and engineering firms who can demonstrate a competent performance history on projects with the scope of the LIGO facilities design. To broaden the field of candidate firms, contractors will be encouraged to form teams, combining the technical and management resources of companies specializing in aspects of the LIGO design requirements, provided only that they propose a method of organizing the work between them in a manner that provides a complete solution. One firm or team will be selected based upon criteria yet to be determined. A request for proposal will be prepared and released upon completion of the conceptual design activities and approval of funding by the NSF. After contractor selection, we intend to negotiate a firm fixed price level-of-effort contract; this contract form is ideally suited to the highly interactive technical development effort required for a state-of-the-art scientific facility.

2. Management of the Preliminary Engineering Design Contract

Contract management is accomplished through the effective use of management tools provided in the formal contract document and informal techniques applied to supplement these control procedures. The primary goal of procedures and techniques implemented in contract management is to assure that adequate control is maintained at all times. Contract change control and contractual direction will be given to the contractor in writing. Requests for changes to contract compliance documents, work requirements, or schedules will be submitted by the contractor after appropriate coordination.

Formal contract status reviews will be held with the contractor monthly. Additional meetings and program reviews may be called as required. Small working level meetings with contractor personnel will be held as frequently as appropriate to quickly resolve specific issues.

Both the formal reviews and working meetings will address technical and programmatic issues as required.

The contractor will prepare a detailed schedule of how the work elements will be performed by the appropriate contractor's operating group. Detailed task schedules must be consistent with the master program schedule. They must present a clear, systematic plan of accomplishment in sufficient detail to provide full visibility of the contractor's performance.

Status reports submitted by the contractor represent a significant means of monitoring contractor manloading and schedule control. To assure that the contractor's system is accurate, it is essential that the contractor have a closed-loop system of internal reporting, covering manloading and schedule progress against planned milestones. The focal point for this information is the contractor's program manager.

On-site contractor surveillance, technical and status interchange and frequent telephone contact will supplement the continuing flow of reports. Action to correct a schedule deviation or a technical problem must be immediate and positive. Once the cause of a problem is determined, a recovery plan is established and implemented.

NSF visibility into all program activities of the contractor will be accommodated. Every effort will be made to satisfy requests for data, meetings or facility visits relating to the contracted efforts.

G. Proposal for Construction

Approximately 16 months after NSF funding of this proposal, we intend to submit a proposal for the construction of the LIGO. We will propose to enter into a contract with the NSF to provide all services and materials required to complete the engineering design, and to develop, construct, test, calibrate, and operate the LIGO facilities including the first receivers. We will offer a plan to accommodate multiple users of the facilities from institutions other than Caltech and MIT. The construction proposal will include such technical, programmatic, cost, and supporting data as are required to permit an in-depth evaluation by the NSF.

VII. ORGANIZATION AND MANAGEMENT

A. Background

The LIGO is a collaborative effort between the California Institute of Technology and the Massachusetts Institute of Technology. The initial (1984) Caltech-MIT agreement towards the development of the LIGO was implemented as a relatively loose cooperation between two essentially autonomous research and development programs under a three-person Steering Committee (Drever, Thorne (Chair), and Weiss) with the groups pursuing a competing receiver development (Fabry-Perot at Caltech; delay-line at MIT). The common element of the collaboration was the development of joint vacuum facilities for the receivers, under the direction of a project manager reporting to the Steering Committee.

As the LIGO development project evolved, it became increasingly apparent that intellectual and financial resource limitations and quality considerations dictated closer collaboration and a tighter management structure for adequate progress. The 1986 Cambridge Review Panel's recommendations along these lines (Appendix D) were strongly endorsed by NSF management and the Caltech and MIT administrations.

In September 1987, Professor Rochus E. Vogt (former Provost of Caltech and former Chief Scientist of JPL) was appointed Director of the LIGO Project. He has taken steps to establish an engineering group for the LIGO and to fuse, focus and strengthen the efforts of the Caltech and MIT science groups. For example, a prime receiver (Fabry-Perot concept) has been chosen for initial LIGO operations, with a second receiver (delay-line concept) continuing development, at lower level, as an alternate and backup. It is fully realized by both Caltech and MIT that only a unified project under a firm management (respecting the uniqueness and creativity of each science group) can do justice to a successful implementation of this very complex scientific and engineering project, within schedule and budget.

B. Organization

The present organization of the LIGO Team is shown in Figure VII-1. The Director has overall responsibility for the organization, integration and coordination of the LIGO effort. He will be responsible for the management, control and accounting of LIGO resources, and for communications and reporting to the NSF. The Director will solicit advice on scientific and engineering strategies from a Science Steering Group composed of the Co-investigators, and a Design Review Board consisting of engineering and technical management experts from outside the LIGO Project. These advisory groups function in addition to the traditional oversight mechanisms applied by NSF.

The science groups at Caltech and MIT are headed by Professors Drever and Weiss, respectively. They will focus upon joint efforts under a unified development program, but taking full advantage of the strength to be gained from the diversity unique to these two strong science and engineering institutions. The two groups will concentrate on aspects of receiver research and development, and will provide substantial scientific support to the planning and engineering of the LIGO facilities. A modest but significant strengthening of both groups, necessary for a task of the magnitude of the LIGO, is planned over the next few years. Both the Caltech and MIT administrations have authorized the resources for the addition of tenure-track faculty to the LIGO Project, and recruitment efforts are underway. Additional postdoctoral staff and some technical support personnel are also planned. Professor Thorne and selected members of his research group will provide theoretical and analytical support to the project, as needed.

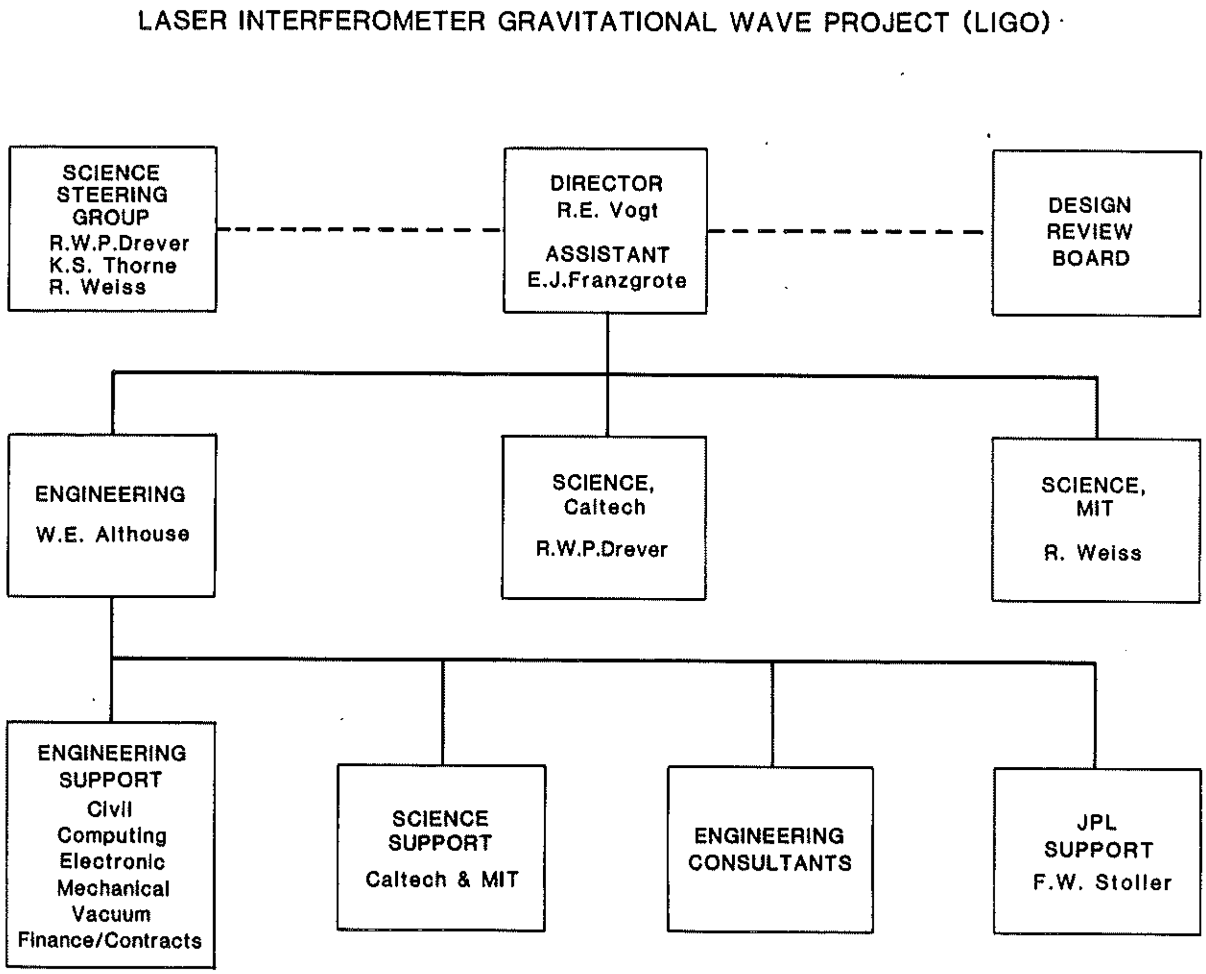


Figure VII-1: LIGO Organization Chart.

The engineering group, in close cooperation with the science groups, will be responsible for the planning and engineering of the LIGO facilities and supporting equipment and services, including management and supervision of the preliminary engineering design contractor, and will provide engineering services for the development of receivers to be installed in the LIGO. The Chief Engineer, William E. Althouse, is in place and has begun to assemble a core group of engineering and support personnel to carry out these tasks. Full advantage is being taken of ready access to the diverse engineering strength of Caltech's JPL for supplementary specialist support as needed.

C. Personnel

Present plans anticipate that the scientific, engineering and support personnel will be composed of the following staff:

Professorial Faculty

R.E. Vogt, Caltech (P.I., P.D.)	Director, Professor of Physics
R.W.P. Drever, Caltech (Co-I.)	Professor of Physics
K.S. Thorne, Caltech (Co-I.)*	Professor of Theoretical Physics
R. Weiss, MIT (Co-I.)	Professor of Physics
to be appointed, Caltech	Assistant Professor of Physics
to be appointed, MIT	Assistant Professor of Physics

Scientific Staff

A. Abramovici, Caltech	Staff Scientist
E.M. Burka, MIT	Research Scientist
A. Cadez, Caltech	Visiting Associate
H.Y. Gursel, Caltech	Staff Scientist
A.D. Jeffries, MIT	Research Scientist
P.S. Linsay, MIT	Principal Research Scientist
J.C. Livas, MIT	Postdoctoral Associate
P.R. Saulson, MIT	Principal Research Scientist
R.E. Spero, Caltech	Member, Professional Staff
M. Tinto, Caltech*	Research Fellow
to be appointed, Caltech	Staff Scientist
to be appointed, MIT	Postdoctoral Associate
to be appointed (2), Caltech	Research Fellow

* Salary supported under Thorne's NSF grant.

Professional Staff

W.E. Althouse, Caltech	Chief Engineer
R.L. Benford, MIT	Research Engineer
E.J. Franzgrote, Caltech	Assistant to the Director
J.H. Harman, Caltech	Electronics Engineer
B.C. Moore, Caltech	Vacuum Engineer
to be appointed, MIT	Research Engineer
to be appointed, Caltech	Civil Engineer
to be appointed, Caltech	Mechanical Engineer
to be appointed, Caltech	Software Engineer
to be appointed, Caltech	Finance/Contracts

Technical Support

B.A. Tinker, Caltech	Electronics Technician
S.I. Vass, Caltech	Vacuum Technician
to be appointed, MIT	Electronics Technician
to be appointed, Caltech	Electronics Technician
to be appointed, Caltech	Vacuum Technician

Secretarial Support

C. Akutagawa, Caltech	Caltech Science Group
B. Behnke, Caltech	Director's Office
B. Busch, MIT	MIT Science Group
to be appointed, Caltech	Engineering Group