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Title: "Interferometric Broad Band Gravitational Antenna"

Principal Investigator: Rainer Weiss

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Massachusetts Institute of Technology
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NATIONAL SCIENCE FOUNDATION

PROJECT SUMMARY

FOR NSF USE ONLY			
DIRECTORATE/DIVISION	PROGRAM OR SECTION	PROPOSAL NO.	F.Y.

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

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Rainer Weiss, Principal Investigator

TITLE OF PROJECT

"Interferometric Broad Band Gravitational Antenna"

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

The aim of the research is to detect gravitational radiation of astrophysical origin. The direct detection of gravitational radiation has been a first rank goal in both physics and astrophysics for the past decade. The observations would provide confirmation of a major prediction of relativistic gravitation -- the waves themselves. They could determine the propagation speed and polarization states of the radiation field and provide detailed information of relativistic gravitation in the untested strong field -- high velocity regime at the radiation sources. In an astrophysical context, the detection of gravitational radiation will most likely open a new view on the universe.

The technique of laser interferometry between "free" masses is used to determine the gravitational wave metric perturbations. A detection system comprised of two 5 km long antennas separated by continental baselines is required to achieve sensitivities that will intersect present estimates of the astrophysical gravitational wave flux incident on the earth.

The project is a joint effort of the California Institute of Technology and the Massachusetts Institute of Technology. The plan is to have the detection system operational before the end of this decade.

INTRODUCTION

The aim of the proposed program is to search for gravitational radiation of astrophysical origin at sensitivities sufficient to intersect current estimates of the gravitational radiation flux incident on the earth. The detection of gravitational radiation has been a first rank goal in both physics and astrophysics for the past decade. The direct detection of gravitational waves would give confirmation of a major prediction of Relativistic Gravitation -- the waves themselves. It would determine the propagation speed and polarization states of the radiation field and most likely provide detailed information of relativistic gravitation in the untested strong field high velocity regime existing in the sources of the radiation. In an astrophysical context the detection of gravitational radiation will most likely open a new view on the universe, for if the precedent set by the other astronomies is a guide, the first sources detected will not have been anticipated while those that are anticipated will be different than we thought.

The technique proposed is to use laser interferometer gravitational wave detectors. The detectors measure the change in propagation time of light in a gravitational wave and are broad band; sensitive to all classes of gravitational wave signals -- impulsive, periodic and a stochastic background. The development of prototype interferometric detectors has advanced in laboratories at MIT, Caltech, the Max-Planck Institute and at Glasgow to a stage where the next step in the field is the application of the techniques developed in the prototypes to interferometers with baselines long enough to achieve scientifically interesting sensitivities.

This proposal describes the work to be carried out at MIT as part of a collaborative research program with Caltech to develop, design, construct and operate a large baseline interferometric gravitational wave detection system. As described in the accompanying joint Caltech-MIT proposal, the system is renvisioned to consist of two large vacuum installations in the shape of an "L",r separated by over 1000 km. These will house laser interferometers referred to as receivers.

The scope of the proposed work, schedule and budget assume that the large baseline antenna project will come to fruition on the following schedule. During 1985 and up to October 1986 a detailed engineering design of the vacuum system, construction, and siting of the antenna facilities will be carried out. The design will be done by subcontractors who will require substantial interaction with scientists in the two research groups. The end of the design should put the project in the state where procurement and construction can begin. The present plan is to initiate procurement of vacuum apparatus and to formulate Requests for Proposal from contractors in October 1986. Receiver installation is expected to take place at the end of construction and the first search for gravitational radiation with this new system is expected in 1988 or 1989.

A central part of the scientific strategy of the project is that two antennas be operating simultaneously with equal sensitivity and detection bands. To assure this requirement the Caltech and MIT research groups have agreed to jointly design and construct a pair of receiver elements, one to be installed in each location. The search carried out with these receivers would have highest priority during the first few years of antenna operations. If budget and manpower constraints permit; other receiver elements, optimized for specific searches, could be developed and installed in the facilities providing that they do not seriously compromise the central effort.

The decision for the design of the common receiver elements is to occur as late as possible to benefit maximally from experiences with the prototype antennas now in operation. On the other hand, the decision must be early enough so that with the available staff and realistic estimates of the time required for procurement and construction, the receivers will be ready for the sites at the end of facility construction. Our assumption in this proposal is that the decision will be made two years before the end of facility construction, at the end of 1986. The division of labor between the Caltech and MIT research groups in the design and construction of the common receivers will accompany the design decision. For the purposes of this proposal to assess manpower needs, we assume that the effort will be roughly equal at both institutions.

The proposed work at MIT is tightly coupled to the Large Baseline Gravitational Antenna Program and coordinated with research at Caltech. It consists of several parts which include:

1) The continuing development of the existing MIT prototype gravitational antenna,

2) The development of techniques to produce, modulate and manipulate high laser power,

3) The design and testing of mirrors and mirror coatings that retain optical figure at high light power, and have low thermal noise in the gravitational detection band,

4) The development of low thermal noise suspension systems with active and passive seismic isolation,

5) The engineering tests of a sample vacuum chamber of the design to be used in the large baseline facility. The vacuum chamber will also serve to test components for the large baseline antenna.

6) The development of data analysis techniques for the three classes of sources,

7) The testing of alternative interferometer geometries with the purpose of economizing on the vacuum space required for a single receiver element as well as to develop interferomter designs for specific gravitational wave searches,

8) The engineering design of the facilities and the design of the joint receiver elements,

9) At the appropriate time in the collaborative effort when a decision has been made on the joint receiver elements, to construct that part of receiver hardware mutually agreed upon by Caltech and MIT.

HISTORICAL BACKGROUND OF THE PROJECT AT MIT

The concept of laser interferometric gravitational antennas was developed at MIT in 1972 and independently at about the same time at Hughes Aircraft. At that time a 10 meter prototype antenna was designed at MIT employing a multi-pass Michelson interferometer using independently suspended masses. The design incorporated RF fringe phase modulation to enable the entire interferometer to be operated as a null servo system using electro-optic controllers and active feedback to the suspended masses. The system was to be constructed at a seismically quiet site in Weston, Massachusetts. The original support for the research came from military funds which within two years after the inception of the project were terminated. After several unsuccessful attempts to gain support for the project including an effort to interest NASA in a space based version of an interferometric antenna, the project got started again in 1979 with the arrival of NSF support. The project was scaled down to a 1.5 meter prototype so that it could be accomodated in an on-campus laboratory. In 1981 the research group grew to include several graduate students and Dr. Paul Linsay. More progress began to be made on the prototype and a separate experiment was started to demonstrate an active ground noise isolation system. The prototype came into full operation in 1983.

In 1982 we made the decision not to build a larger prototype as this was being carried out at Glasgow, Caltech and at the Max-Planck Institute, but rather to focus on a study of the feasibility, engineering, siting and costs of a large baseline laser interferometric antenna system. At the beginning of the study Dr. Peter Saulson joined the group and took on the study of the magnitude of gravitational gradient fluctuations and the analysis of multi element vibration isolation systems.

During 1982 and 1983 we became immersed in the study. We went to Arthur D. Little of Cambridge, Massachusetts for consultation on vacuum system designs and costs and to the engineering firm of Stone and Webster of Boston, Massachusetts for consultation on construction techniques at both mine and surface sites and a preliminary survey of sites for the project. The result of this study "A Study of a Long Baseline Gravitational Wave Antenna System" was presented to the NSF in November, 1983 and can be made available to the reader on request from the NSF.

The study confirmed that the extension of interferometric antennas to baselines of several kilometers would bring the gravitational wave search into an astrophysically interesting regime. The major part of the gain in sensitivity is achieved by increasing the interferometer arm lengths. No new noise terms were uncovered which would invalidate the sensitivity scaling. The noise due to gravitational gradients, one of the few noise sources which could have scaled as the gravity wave signals, proved to be smaller than other noise terms in the 10 Hz to 10 KHz band.

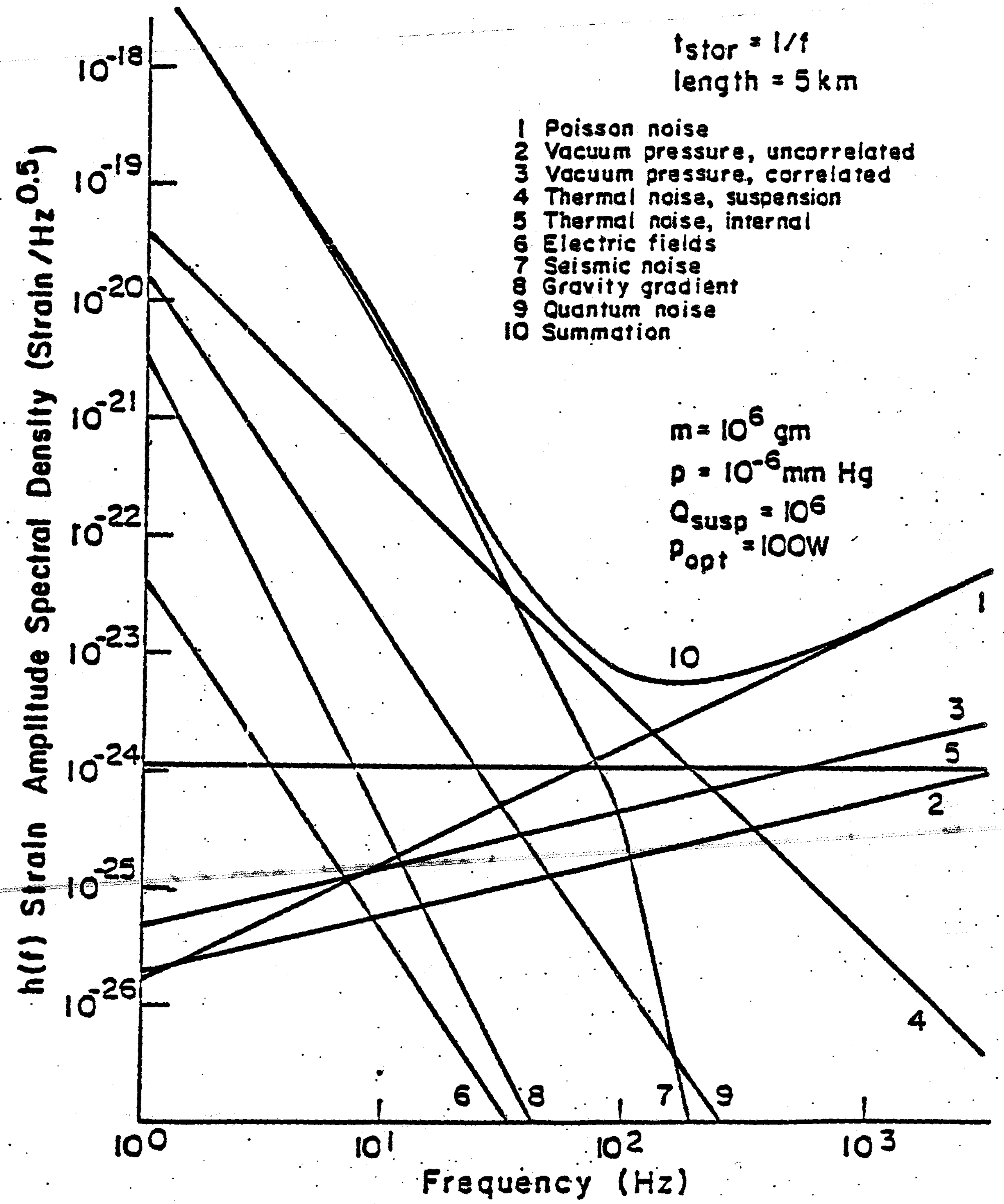
The vacuum specifications could be met in a practical system. A summary of the noise budget of a sample 5 km antenna using realistic system parameters is shown in Figure 1. Figure 2 shows the system noise scaling with arm length.

Two extrapolations over the present state of the art in the interferometric antenna prototypes were made. Neither is considered technologically new but they have not yet been demonstrated. The first is an increase in light power modulated by the interferometer. At present the maximum modulated power is about 50 mW. The study assumed 100W could be achieved either by direct injection or by recycling the light in the interferometer. The second extrapolation were suspension systems with adequate seismic and acoustic noise isolation and suppression of thermal noise that could operate in high vacuum. The suspension system designs with the required specifications have been extensively studied but have not been implemented to date in the prototypes. Much of the experimental work at MIT in the early part of this 5 year program is dedicated to these two areas.

Another result of the study is that there is substantial margin in the long baseline antennas, using the present performance specifications, before fundamental physical limits will be reached. The standard quantum limit lies many orders of magnitude below the present projections in the 10 Hz - 10 KHz band. The importance of this is that the proposed antenna system will be able to improve with further advances in technology.

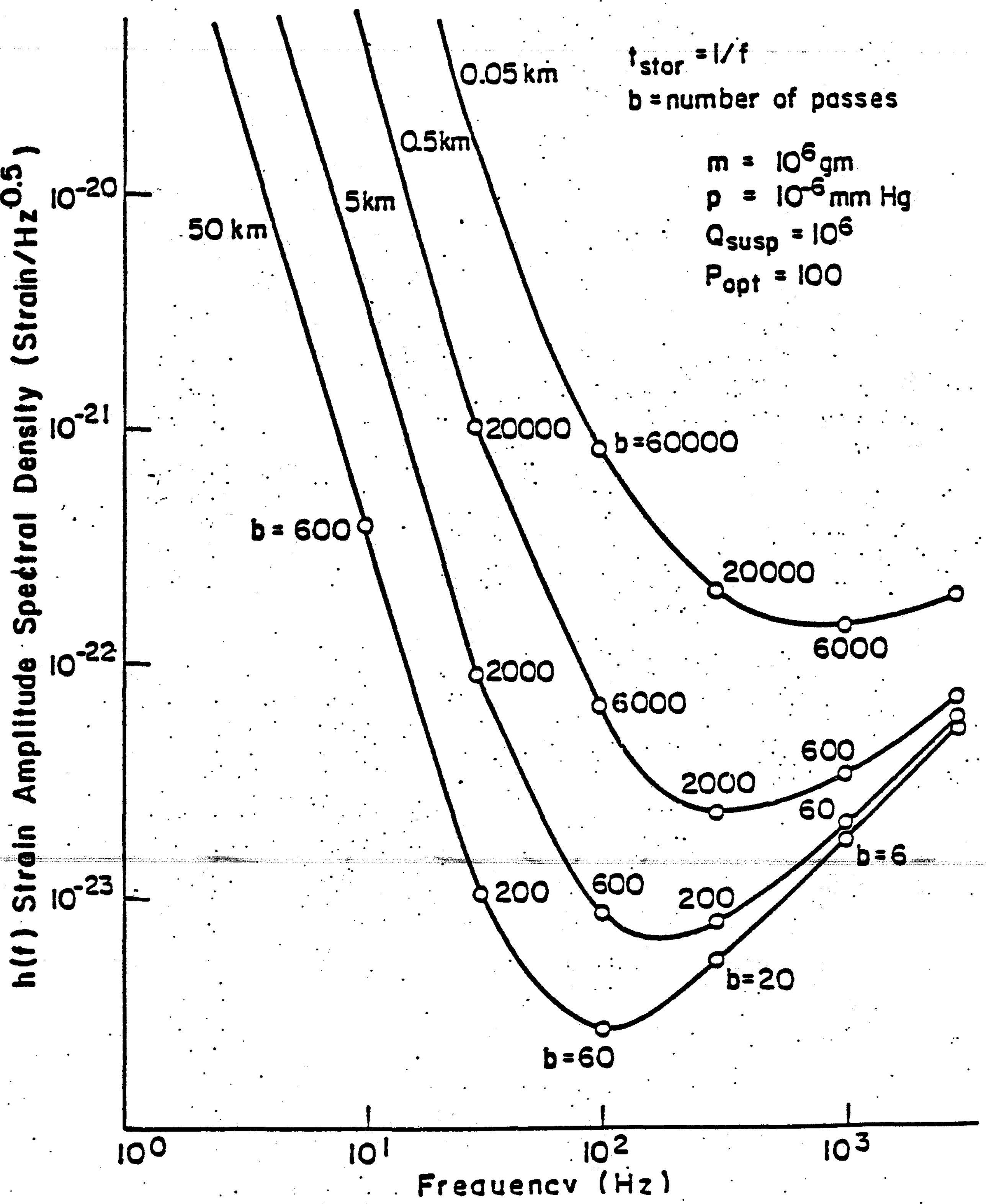
A not unexpected result of the study was that the costs for such a long baseline gravitational wave antenna system are in the range of $50m (1983) and that the scale of the effort was too large for a single group to carry out.

FIGURE 1



t_{stor} = 1/f
length = 5 km
1 Poisson noise
2 Vacuum pressure, uncorrelated
3 Vacuum pressure, correlated
4 Thermal noise, suspension
5 Thermal noise, internal
6 Electric fields
7 Seismic noise
8 Gravity gradient
9 Quantum noise
10 Summation
m = 10^6 gm
p = 10^{-6} mm Hg
Q_{susp} = 10^6
P_{opt} = 100W
h(f) Strain Amplitude Spectral Density (Strain/$Hz^{0.5}$)
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
Frequency (Hz)
10^0
10^1
10^2
10^3
1
2
3
4
5
6
7
8
9
10

FIGURE 2



t_stor = 1/f
b = number of passes
m = 10^6 gm
p = 10^-6 mm Hg
Q_susp = 10^6
P_opt = 100
0.05 km
0.5km
5km
50 km
b = 600
20000
b = 60000
20000
6000
2000
6000
2000
600
60
b = 6
200
600
200
b = 20
b = 60
10^-20
10^-21
10^-22
10^-23
10^0
10^1
10^2
10^3
Frequency (Hz)
h(f) Strain Amplitude Spectral Density (Strain/Hz^0.5)

THE MIT PROTOTYPE DETECTOR -- CURRENT STATE

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

A schematic of the interferometer is shown in Figure 3. The interferometer mirrors are attached to massess suspended on pendula with periods of 2 seconds. At frequencies large compared to the pendulum resonance frequencies, the masses are free in inertial space and isolated from external acoustic and seismic perturbations. Capactive displacement sensors for all six degrees of freedom of each of the 3 masses are used to drive electrostatic controllers to critically damp the pendula without adding noise in the gravitational wave frequency band. The interferometer is operated in a vacuum of 10^{-6} mm Hg, maintained by ion pumps, to reduce gass pressure fluctuation forces on the masses and index of refraction changes in the optical paths.

On entering the vacuum, the light is split by a 50/50 beam splitter and then enters the interferometer arms through holes in the mirrors. The light traverses each arm 56 times and reemerges through the same hole by which it entered. The multi-pass geometry, formed by spherical mirrors, is called a Herriott delay line. The number of beam transits is determined by the mirror radii and their separation. When properly aligned, the optical path length in the arms is first order sensitive to mirror displacements along the optic axis

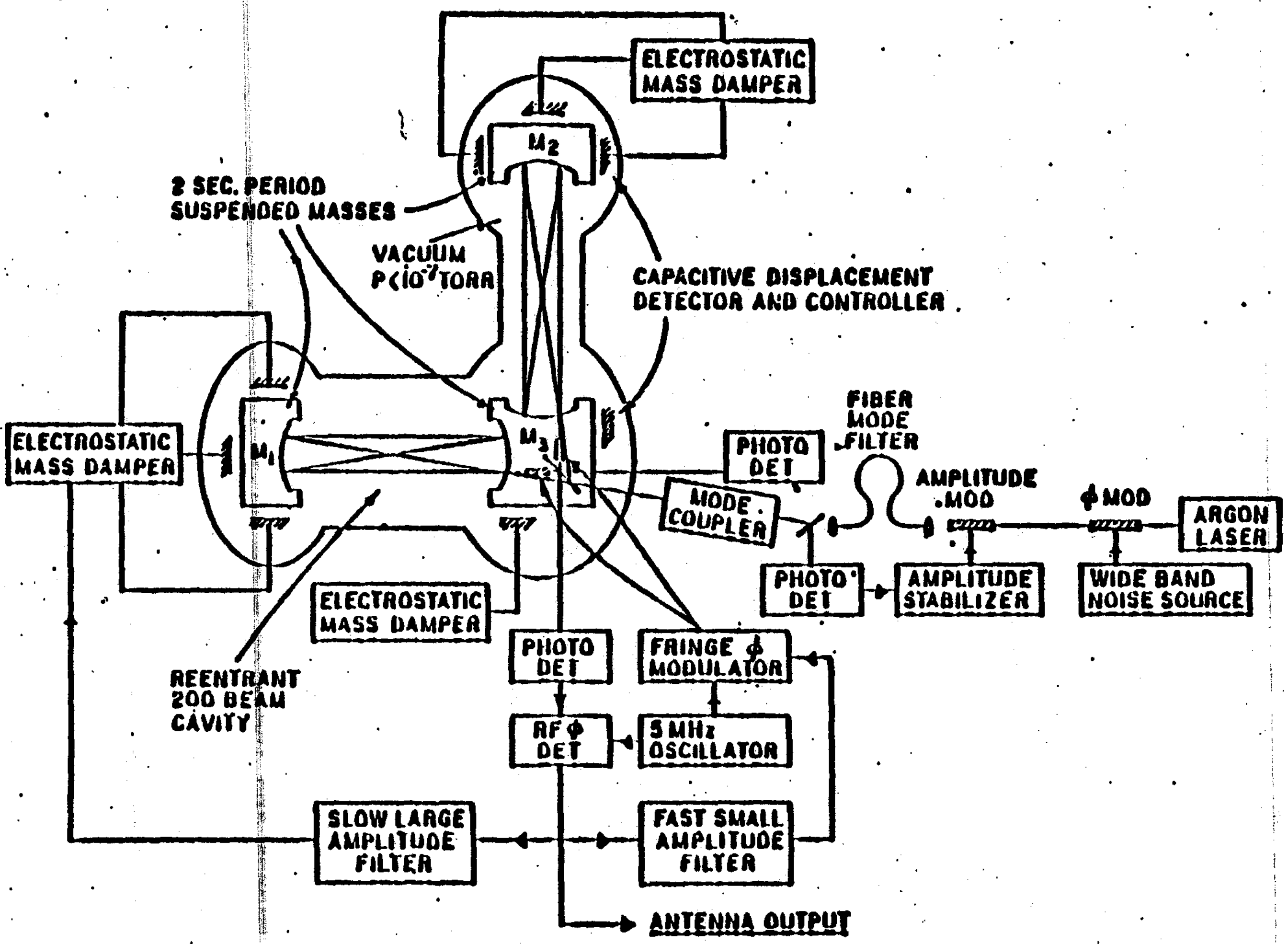


FIGURE 3

The Prototype Antenna at MIT

and second order sensitive to all other motions. After leaving the delay line the light passes through electro-optic phase modulators (Pockel's cells), one in each arm, and then is recombined. Both the symmetric and antisymmetric outputs are measured at photodetectors.

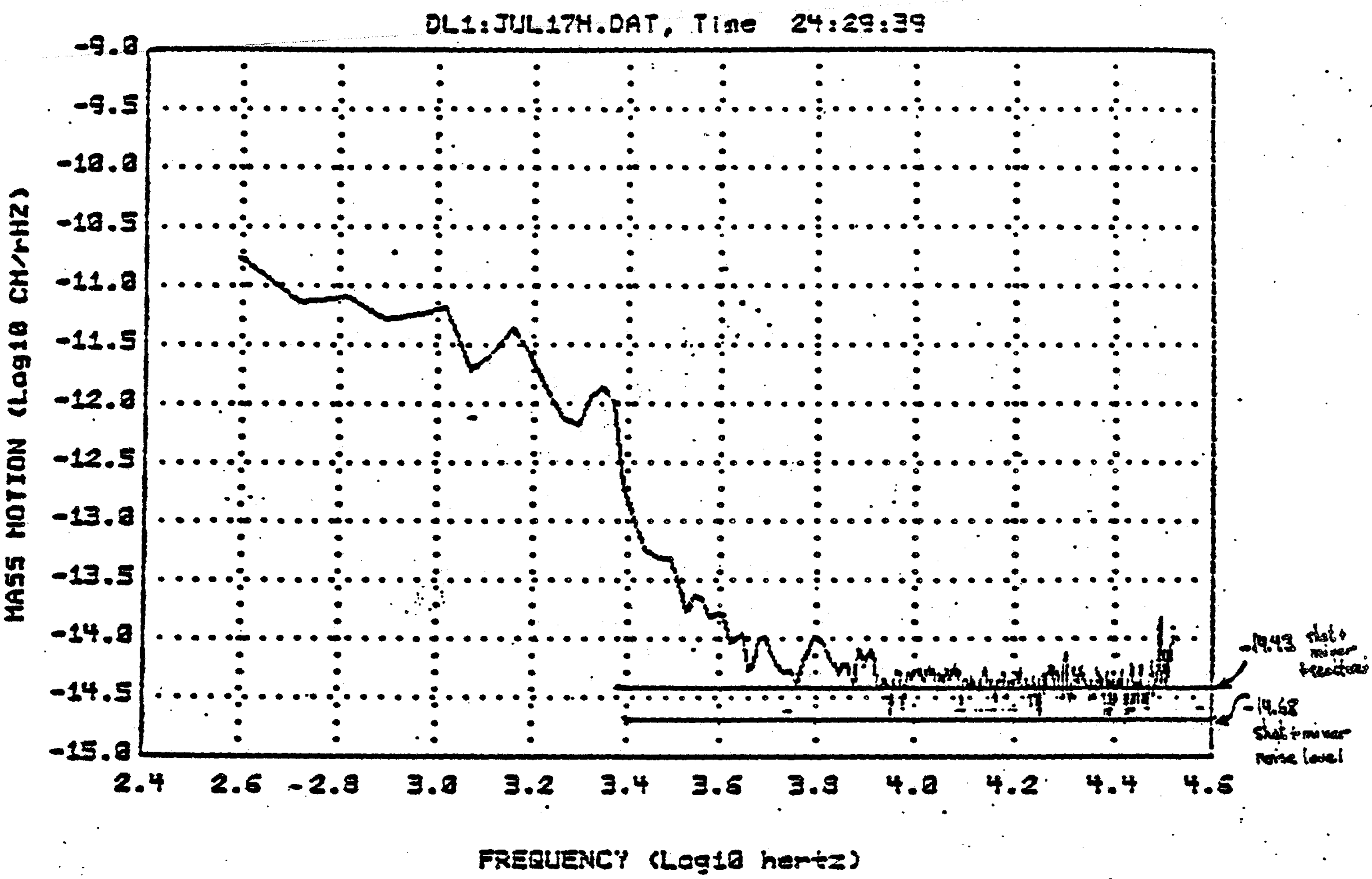
In order to determine the fringe motion a 5.3 MHZ phase modulation is impressed on the beams by the electro-optic modulators. When the interferometer is at a symmetry point of a fringe, the photodetector output contains only signals at even harmonics of this frequency, if the fringe moves from the symmetry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

The light source is a 1/4 W argon ion laser operating in a single mode at 5145A. After leaving the laser the instantaneous line width of the light is broadened to a Lorentzian line of about 1 GHz width using an electro-optic phase modulator driven by wide band Gaussian or periodic random noise. The frequency broadening suppresses the interference modulation of the main beam in the interferometer by scattered light. Scattered light will generally have taken different times than the main beam to reach the output of the interferometer. Due to the frequency broadening the interference between the scattered light and the main beam will undergo rapid phase fluctuations which result in an amplitude noise spectrum that can be made as small as the shot noise in the scattered intensity. The technique requires that the interferometer be held near the zero path length difference fringe. The precision of the path length equality is determined by the amount of scattering.

The laser light is injected into the interferometer by way of an assembly of spatial mode matching lenses and a single mode optical fiber. The fiber, a few meters long, serves to isolate the laser's mechanical noise from the interferometer. More importantly it reduces the noise from laser beam position and angle fluctuations that would be converted to phase fluctuations at the output of the interferometer due to imperfect alignment of the instrument. The residual amplitude noise produced by the fiber can be removed by an amplitude stabilization servo, however at present this does not appear necessary.

The performance of the instrument (July 1984) is shown in Figure 4. The displacement noise at frequencies above 5 kHz is 3×10^{-15} cm/sqrt(Hz) with 22 mW of power modulated by the interferometer. The idealized shot noise limit for this power and a light storage time of .28 microsec (56 passes in 1.5 meters) is 2×10^{-15} cm/sqrt(Hz). The excess noise at frequencies below 5 kHz is accounted for by acoustic and seismic noise coupled through the simple pendulum suspension. At present the suspension is a single 1/4 inch aluminium rod attached directly to a flange at the top of the vacuum enclosure.

FIGURE 4



Averages: 4; Points: 256; Apodization: Hanning
Omega Symm. As in 'G.DAT except 47.00 MHz 1 dB Digimod.
AC on. 2444. VPR off, 13 mW average power. Delta=.80

contrast = .86

13 mW average power

PROPOSED WORK ON RECEIVERS

Overview

The principal goal of receiver development at MIT in the next 3 years is to develop and demonstrate the techniques required to achieve the sensitivity projections shown in Figure 1. If the proposed 5 km vacuum systems were now in existence, it would be reasonable (and exciting) merely to take the present day technology used in the prototypes and apply it directly to the long baseline system. The prototypes are approaching displacement sensitivities of 10^{-15} cm/sqrt(Hz) and the control of the stochastic forces (seismic, acoustic, and thermal fluctuations) on the masses at frequencies above 500 Hz is sufficiently good not to compromise the displacement sensitivity. In a 5 km system the strain sensitivity would then be of the order of a few times 10^{-21} strain/sqrt(Hz) over a kHz in bandwidth; a factor of 10 to 100 in improvement in amplitude sensitivity over the best present acoustic (bar) detectors in the kHz burst search. The projections we have made assume another factor of 100 improvement in amplitude sensitivity to an uncompromised displacement sensitivity of a few times 10^{-17} cm/sqrt(Hz) at frequencies above 100 Hz. In order to achieve these sensitivities it is necessary to increase the light power modulated by the interferometer and to further reduce the stochastic forces on the masses.

Without extensive modifications of the present prototype we will not be able to carry out this development program in it. We intend therefore to carry out a substantial portion of the development in auxiliary experimental apparatus designed to accomodate receiver components on the scale required for the long baseline antenna. In particular, the development of the high power optics and the suspension research is to be done on a scale directly applicable to the large baseline system.

Improvements in the Existing Prototype

We will continue technical improvement of the prototype to the point where the problems being solved and the techniques that would have to be developed no longer apply to the large baseline system. Limitations with the prototype are: the tubing and mirror diameter of 4", the volume at the ends will not accomodate masses much larger than a few 10's of kg, the important scattered light times are short (10^{-8} sec) and the laboratory environment is noisy. The ground noise between 1 to 100 Hz is a factor of 100 to 1000 times larger in amplitude than the levels we expect to encounter at any projected site for the large baseline system.

Our estimate is that the present prototype can be used to develop and demonstrate techniques to the sensitivity level of a few 10^{-16} cm/sqrt(Hz) at frequencies above several hundred Hz. The remaining factor of 10 in displacement sensitivity and in the reduction of stochastic forces will have to be carried out in other apparatus.

In the near term we will improve the prototype in several ways. A major improvement is the installation of an acoustic and vibration isolation stage between the pendulum support and the top of the vacuum tank on each of the three masses. The isolation stage, designed to operate in high vacuum ($P<10^{-7}$ mm Hg), consists of stainless steel plates and fluorogold (teflon and glass fiber) coupling springs. The stage is expected to provide 50dB of isolation above 200 Hz. The aluminum pendulum rod will be replaced by a single wire to further improve the isolation by approximately 30dB. The power modulated by the interferometer can be increased by about a factor of 10. A new argon laser, to be delivered in the fall of 1984, should provide 1 Watt in a single mode, a factor of 4 increase. The optical efficiency of the system from laser to photodetector is about 8%. The transmission budget is given below.

	now	improved
external phase modulation	.80	.95
fiber coupler	.30	.5
mode matching optics	.80	.95
entrance/exit ports and photodetector reflection	.78	.99
internal phase modulators	.94	.99
beam splitter + delay line mirrors (56 beams)	.66	.85
net optical efficiency	.08	.37

The improvements are primarily incremental: Brewster angle optic in the phase modulators and other plane optical components and 1/2% AR coating on lenses. The delay line mirrors were .997 mirrors before becoming dirty and will be cleaned or replaced.

The improvements in the optics should also reduce the light scattering. At present the scattered field intensity is about 10^{-9} of the main beam at the photodetector. The major part of the scattering occurs at optical delays that are multiples of the single pass transit time in the delay line, implying that the scattering occurs at the hole in the mirror or on the Pockel cell at the output of the delay line. At present the technique of broadening the laser line width is able to bring the scattered light interference modulation to the shot noise limit of the main beam. We have had to resort to using digital periodic random noise phase modulation to tune away from acoustic resonances in the external Pockel's cell phase modulator which otherwise produces excess amplitude noise at the fringe interrogation carrier frequency. With the present clocking rate and the small number of steps in one repetition frame of the digital random noise generator, we are able to reduce the noise due to scattering by 30dB. As the laser power is increased the rejection may become inadequate and we will have to do one or all of the following; eliminate the acoustic resonances in the Pockel's cell and return to using wide band Gaussian noise modulation, reduce the scattering, or increase the complexity and clock rate of the digital phase noise generator.

The development of the prototype and a low sensitivity search for gravitational radiation from periodic and impulsive sources in new regions of the frequency spectrum are the subject of the Ph.D. dissertations of Daniel Dewey and Jeff Livas. The thesis work is to be completed during 1985. Data runs are planned for the first quarter of 1985.

DEVELOPMENT OF TECHNIQUES TO PRODUCE, MODULATE AND MANIPULATE HIGH LASER POWER

In the short term we have the intention of developing receivers for the long baseline antenna with a strain sensitivity between 10^{-22} and 10^{-23} strain/sqrt(Hz) in the 100 to 3 kHz band. In this frequency band, especially at high frequencies, the receiver will be limited by displacement sensitivity rather than by perturbations due to stochastic forces. In a 5 km interferometer with a 1/2 msec light storage time, several 100 Watts of fringe modulated power is needed to achieve the required displacement sensitivity of 10^{-17} cm/sqrt(Hz).

All the experience up to now in the prototypes has been with fringe modulated powers under 50 mW using the 5145 A line of the argon ion laser.

The lasers are operated in a single transverse and longitudinal mode with output powers of around 1/4 to 1 Watt. The optical efficiencies of the instruments have generally been less than 10%.

To meet our goal we will have to:

1) Develop lasers with over 100 Watt output power and/or implement the recycling scheme proposed by Drever using high power frequency stabilized lasers,

2) Improve the efficiency of the optical systems by using coated and Brewster angle optics,

3) Develop electro optic modulator systems that can handle the light power and

4) Develop single mode light fibers able to transmit 100 Watts for mode filtering.

High Power Lasers

The light sources needed for both Fabry-Perot and optical delay line interferometers are single transverse and longitudinal mode lasers with small amplitude noise. In order to reduce the symmetry requirements in the interferometer the amplitude noise in the gravitational wave band should be small and the noise at frequencies near the fringe interrogation carrier should not greatly exceed the intrinsic photodetection (Poisson) shot noise. Frequency stabilization of the laser is required for multiple interference systems like a Fabry-Perot while delay line or other interferometric concepts that recombine light after a doscrete storage time make less stringent demands on the frequency excursions of the laser. Nevertheless to implement the techniques that have been developed to suppress scattered light in delay line systems, it is necessary that the laser be operating in one coherent mode, otherwise the phase randomizing technique used to control scattering will produce amplitude modulation sidebands that will exceed the shot noise.

Laser sources for the large antenna have not only to meet the above criteria but also more practical requirements of high efficiency and reliability.

At this time two possibilities exist to meet our requirements. One strategy is to enhance the power of the argon ion laser now used in the prototypes. Several schemes for doing this without extensive development of the lasers themselves have been proposed. Brillet has proposed and partially implemented a technique of injection locking one argon laser to an other and coherently adding the outputs. As a demonstration of the technique he has achieved an output power of 1.5 Watts in a single mode at 4880A without requiring an etalon. The next stage would be the coherent addition of many injection locked lasers. Ezekiel has proposed a somewhat different strategy using a ring cavity system which will reduce some of the isolation problems encountered in coupling multiple lasers together.

Another scheme is to use a 1 to 10 Watt single mode oscillator followed by an amplifier. The amplifier is a large bore diameter (1 cm) argon discharge used in a single pass or an open cavity configuration. The oscillator mode is expanded to match the cross section of the amplifier. The experience gained in prior work on multi-mode high power argon lasers (Alferov et al., 1983; Weber, 1977; Fendley, 1970; Herzinger, 1969) indicates that the amplifier-oscillator combination could have a 10 times larger ratio of optical output power to electrical input power than the individual lasers themselves. This is due to the more efficient discharge conditions in the larger bore tube and the fact that radiation trapping does not appear to be a bottleneck in depleting the lower laser level in the argon ion laser. The small signal gain of the discharge is 2%/cm and spontaneous emission in the amplifier becomes unimportant for input intensities larger than a few mW/cm^2.

The power efficiency of the argon system can be no higher than 5×10^{-2}. An amplifier-oscillator combination could approach 5×10^{-3} efficiency for single mode output in a 1.5 meter long amplifier delivering 150 Watts. The present laser systems are operating at an efficiency of 4×10^{-5}. The major drawback in developing the amplifier is that the discharge tubes are not commerically available and would have to be designed and constructed at MIT or in industry as special items.

The alternative laser technology that appears to have the capability of high power CW operation is the optically pumped nd:yag solid state laser at 1.06 microns. The Nd:YAG lasers have not been used in the prototype gravitational wave antennas up to now. Multi-mode CW systems with output powers of 500 Watts and single radial but multi-longitudinal-mode lasers with up to 50 Watts are commerically available. These lasers are not applicable to the gravitational antenna project without modification. The principle difficulties with them are: (1) amplitude and frequency instability because of mode hopping due to spatial hole burning in the gain medium, (2) polarization scrambling due to thermally induced stress birefringence in the cylindrical laser rods and (3) biaxial defocusing in the rods again due to temperature gradients in the rods, (4) the short (200 hour) life of krypton discharge lamps that accomplish the optical pumping. The major attributes of the Nd:YAG laser are its ultimately very high power efficiency (5%) and reliability. The disadvantage of the longer wavelength, which reduces the interferometric displacement sensitivity and increases the antenna mirror size by 1.44, is more than compensated by the reduction in scattering and substantially higher intensity allowed before damage is incurred in electro optic materials and coatings. If green light is needed, the 1 micron output of a sufficiently high power Nd:YAG laser cam be frequently doubled with an efficiency approaching 50%.

The technology of Nd:YAG lasers is at present undergoing rapid development. In particular a laser group at Stanford under the direction of R. Byer is developing CW single frequency Nd:YAG lasers for precision spectroscopy. They have demonstrated optical pumping of Nd:YAG with light emitting diodes and a ring resonator geometry to avoid spatial hole burning.

A solution to the depolarization and self focusing in high power Nd:YAG lasers is the use of slab geometries (eggleston, 1984) -- the lasing medium is a rectangular parallelepiped with the crystal axes parallel to the faces. The rectangular symmetry, besides increasing the medium aspect ratio, causes thermal distortions to be uniform over the wave fronts and eliminates depolarization. By causing the light beam to follow a zig-zag path in the crystal the defocusing is eliminated in first order. The slab zig-zag Nd:YAG laser crystals are available from several vendors and complete high power lasers will be marketed in 1985.

The prospects are that these systems in oscillator-amplifier combinations will provide over 100 watts of single radial and longitudinal mode power at 1.06 microns. Frequency and amplitude stabilization servo systems will most likely be required but this is well within the technology now in hand.

The development of high power light sources is clearly an important element in all large baseline interferometer designs and research in this area will be coordinated with the Caltech group.

DEVELOPMENT OF OPTICS FOR THE LARGE BASELINE SYSTEM

The principal differences between the optical components in the prototypes and those planned for the large baseline system are in cross section and power handling capability. The minimum beam diameter for the TE_{00} Gaussian mode scales as $(\lambda \ell)^{1/2}$ where λ is the light wavelength and ℓ is the antenna arm length. The critical parameter that determines the onset of nonlinearity and damage in the optical components and coatings is the optical intensity. For a fixed intensity the beam power, which ultimately determines the displacement sensitivity, scales as $I_{max} (\lambda \ell)$. To maintain the same intensity, the scaling from 1.5 meter, the present size of the MIT prototype, to 5 km would allow a power ratio of 3000/1. This is more than adequate to make the extrapolation from the presently used power to 100 Watts. As a consequence, our present projections for the large baseline antenna do not need to place untested demands on the material properties of the optical components. They will however place demands on the size and therefore on uniformity and workmanship, which will be reflected in cost. In some components it may prove economical to increase the intensity over present values or at least discover where one begins to get into difficulties.

We plan to develop electro-optic modulators, light fiber waveguides and mirrors for the large antenna. We will work with suppliers of these components in testing them at MIT. These tests where appropriate will be carried out on the prototype and on a larger scale in a new stationary interferometer with physically common arms so as to be insensitive to ground and thermal noise and also insensitive to gravitational waves. The new interferometer will be placed in the vacuum system to be used for tests of the large baseline antenna vacuum components (described in another section of the proposal).

The work on electro-optic modulators will concentrate in two areas. The first is the development of Brewster angle AD*P and KD*P RF phase modulator systems with a clear aperature greater than 10 cm, bandwidths of 10 MHZ and the ability to phase modulate by at least π radians at 5145 A. The modulators are intended to be controllers and FM modulators in the antenna arms. The most straightforward technique would be electrodeless cavity mounted longitudinal modulators using kilovolt/cm RF fields. If this proves unacceptable we will develop a matrix of transverse modulators.

The second area is the development of GHz bandwidth phase modulators for the control of scattering. The modulators are designed to operate at moderate optical powers, 1 to 10 Watts, and will be placed between the oscillator and the amplifier in the laser sources described previously. We will use AD*P, $LiTaO_3$ or KTP for this application. AD*P and $LiTaO_3$ are able to handle intensities of 10^4 Watts/cm^2. KTP is alleged to work at intensities of 10^8 Watts/cm^2.

Single mode optical fibers have proved to be useful in the prototypes in transporting light from mechanically noisy lasers to the interferometer. They rare used to establish mode purity by acting as efficient wave guides beyond cutoff for all but the lowest spatial mode and give a spatially fixed injection condition for the interferometer. In the large antenna it is likely that single mode fibers would be employed for both input and output directly from the central mass and be incorporated into the suspension. Using fibers as single mode output couplers will help reject scattered rays. At present commercially available fused silica single mode fibers in the green will handle intensities of 5×10^7 Watts/cm^2 in lengths of several meters before the onset of stimulated Brillouin and Raman scattering. In order to use single mode fibers at 100 Watts, larger diameter single mode fibers than are now commercially available must be developed. A step index fiber with core diameter of 20 microns and refractive index difference between core and clading of 10^{-4} would handle a 100 Watts in the HE_{11} mode. Several fiber manufacturers have indicated that such fibers could be made using borosilicate glass rather than fused quartz. The homogeneity of the index is easier to control in borosilicate glass than in quartz. We have not measured the onset of non linearities in fibers made with this glass. We intend to pursue this in the next year as larger diameter single mode fibers will be useful in improving the coupling efficiency to the prototype.

Mirrors for the Large Baseline Antenna

The specification, design and construction of mirrors, mirror mounts and mirror coatings for the antenna arms of a large baseline antenna raise some issues that have not been encountered in the prototypes. The main differences lie in the larger beam diameters, smaller angles and the higher power being projected.

The minimum beam diameter at the mirrors of the TE_{00} mode in a symmetric cavity or delay line configuration at the 1% power point is 8.6 cm for 5145 A for a 5 km arm. The beam diameter scales as $\ell^{1/2}$. the relevant angles in the optics determined by the ratio of beam diameter to the arm length scales as $\ell^{-1/2}$. The characteristic angles are 2×10^{-5} radians (4 arcsec).

The most important impact of this change in scale is the necessity in both delay lines and Fabry-Perot cavities to pay more attention to long wavelength -- cm size -- figure errors and shallow slope errors than has been the case in mirrors for the prototypes. In Fabry-Perot cavities mirror errors contribute to mixing radial modes while in delay lines they perturb the desired spot geometry. The mirrors for the large baseline antenna will have radii comparable to the arm length. A 20" diameter mirror will have a sagitta of only 5 microns.

The fraction of the incident power thrown into scattering by surface irregularities or into nearby diffraction from large wavelength surface ripples is given by

$$(\pi\delta/\lambda)^2 \quad \text{for} \quad \delta/\lambda \ll 1$$

where δ is the rms surface irregularity on scales larger than an optical wavelength and λ is the wavelength. For example a surface with irregularities of order $\lambda/20$ will scatter out about 2.5% of the incident radiation. To make full use of the excellent mirror coatings now being manufactured for laser gyro mirrors which have an absorption or scattering loss of less than 10^{-4}, the mirror irregularities over the beam must be less than $\lambda/300$. Mirrors with this quality of surface have been tested on scales of a few cm. Several of the mirror manufacturers we have contacted will grind and polish mirrors with diameter greater than 50 cm to a level of $\sim \lambda/30$, adequate for first generation receivers.

Another new consideration is the thermal behavior of the mirror. A study is needed of the temperature gradients and the attendent figure distortions induced by the absorption of the laser power. At this time the best choice of mirror material is not obvious, as both metal and glass mirrors are contenders. Metal mirrors cannot be polished or diamond point cut to match the performance of the best glass mirrors but metal mirrors will have much shorter thermal diffusion times than those of glass. Typical thermal diffusion times for aluminim mirrors of 10 cm thickness will be a minute while for glass this time is several hours. The thermal time constant of the mirror and associated antenna mass, if of the order of a ton, will be a few days as the only thermal coupling to the room is by radiative transport at 300K.

More care will have to be taken in the mechanical and thermal design of the mirror suspension system to make sure that the mirror figure is not distorted by gravity loading or by differential heating of the surface and supports. It is difficult to estimate the effects of gravitational loading on the mirror figure without a particular suspension design in mind. A NASTRAN or equivalent finite element analysis will have to be made of the mechanical configuration to insure that the distortions will be within acceptable tolerances. A rough estimate indicates that thermal distortions of the mirror surface of the order of a tenth of a wavelength of light will occur if there is differential heating of the surface by a few milliWatts. When the interferometers are operated with high power (>10 Watts) this will place a premium on cleanliness of the mirror surface and low absorption coatings to prevent local hot spots. These analyses which have application to all interferometric designs will be carried out in conjunction with the Caltech group.

The mirror specification for a first generation receiver using delay line optics could be quite simple. A storage time of 0.5 millisec requires 30 beams -- 15 encounters with each mirror. A reentrant geometry with a circular spot pattern, as is now used in the prototypes, would require a 20" diameter mirror to give a 1% overall diffraction loss at 5145 A. The most stringent requirement on the mirror comes from the path length equality condition which demands that the radii of the mirror be both matched and accurate to 0.1%. For a fixed number of beams the condition is relaxed in direct proportion to the mirror size. Interference noise due to the intensity of the spot overlap and mirror scattering would be controlled by the light "whitening" technique now used in the MIT prototype. The unwanted light will have suffered much larger delay times than now encountered in the prototype and the technique will be easier to implement.

An alternative but more complex strategy for a 0.5 msec storage time receiver is the use of separate mirrors for each beam. For example, 15 small mirrors could be mounted on a large antenna mass. If need be they could be made separately steerable. The problems with such a scheme, in particular the thermal noise of the mirror internal modes and the overall structure, has to be studied.

More ambitious receiver designs with longer storage times or the application of the light recycling technique proposed by Drever will require better mirrors. The simple circular spot geometry would allow a 1msec storage time with the largest mirror (40" diameter) that could be accomodated in the proposed vacuum facilities. The delay line geometry could be used more efficiently if the spot packing on the mirror were to cover more of the mirror.

Several schemes have been tried on small delay line systems. The easiest to implement is to astigmatize the mirror. The spot patterns become lissajous figures on the mirrors and there is then no limit, short of mirror reflectivity and scattering, on the number of beams that can be accomodated. The mirror figure tolerances, primarily the tolerance on the two radii, become more stringent as the square of the number of spots. Geometries of this type will require servo control of the mirror radii assuming no advances in the state of the art of mirror manufacture and testing. Another technique for achieving long storage times and simultaneously controlling scattering is described in the section on alternative interferometer concepts.

SUSPENSION DESIGN FOR THE LARGE ANTENNA

Design of the suspensions of the interferometer test masses is an important part of the design of the gravitational wave antenna system, since it is through the suspensions that most of the "stochastic force" noise terms act, principally seismic and acoustic vibration as well as thermal noise (Brownian motion). The test mass suspensions must be constructed in such a way that they eliminate, or at least attenuate, these noise forces. With an inadequate suspension, acoustic noise and thermal excitation of resonant modes of the suspension will be important noise terms throughout the frequency band of interest. Even with an "adequate" design, stochastic force noise will dominate the noise budget at low frequencies. Thus it is likely that the key to improved sensitivity at low frequencies will be progress in suspension design, until fundamental limits such as gravity gradient noise or photon recoil noise (the quantum limit) are reached.

We are undertaking a design of a suspension appropriate for a large antenna. This work is going on essentially independently of the prototype antenna. This is useful, in part, so that our test of the new design is not compromised by having to fit into the pre-existing apparatus (and also so that the demands of suspension development don't prevent other work on the prototype antenna.) In this design, we plan to take advantage of the ideas and experience of all of the groups working in the field, especially the Caltech group.

The most important reason for beginning a whole new suspension design effort is that it looks fruitful to use large test masses (of order 1 ton). This is in order to minimize thermal noise, which scales as $(MQ)^{-1/2}$. Since the masses in prototypes built before have been in the 10 kg range, this represents a substantial increase in the scale, so that more careful attention will need to be paid to the structural engineering than heretofore. We plan to pay a good deal of attention to the problem of maximizing the quality factor Q as well. Since the dominant damping should occur in the flexure of the pendulum support wires, we have begun a program to measure the mechanical Q (in flexure) of rods and fibers of various materials, beginning with sapphire and quartz.

In the current conceptual design, the 1 ton test mass will be suspended by a short set of wires from a second mass, which is in turn suspended by a 1 meter long set of wires from a ceiling. Short wires are used so that the string mode resonances, which compromise isolation and provide thermal noise peaks as well, occur at high frequencies. The ceiling is isolated by acoustic stacks and springs from legs which support it at the proper height above the floor of the vacuum chamber. Alignment and control forces and servo-controlled active damping forces are applied to the upper mass. A design such as this which relies primarily on pendulums for isolation can be successful in part because of the insensitivity (in first order) of a properly aligned interferometer to motions transverse to the optical axis. Thus isolation in the vertical direction should be of secondary importance. Indeed, for the end masses (although not for the central mass), there is only one horizontal direction to which the interferometer is sensitive in first order.

Construction and testing of such a suspension system will be the major task of the first two years of the grant period. In so far as it is possible, construction will be modular to allow modifications to be easily made and tested. For example, we may choose to initially suspend the masses with stainless steel wires, but the clamps will allow a change to quartz or sapphire wires later. Transducer and actuator designs may iterate as well. It looks fruitful to put some effort early in the design phase into higher sensitivity RF displacement transducers using resonant cavities. The transducers used now in the prototype have a sensitivity limit of between 10^{-10} and 10^{-11} cm/sqrt(Hz). It looks feasible to construct cavity transducers three orders of magnitude quieter. Electrostatic actuators which give a force independent of displacement would also be quite useful. Early in the program we will test a design based on interleaved sets of capacitor plates. If these designs are successful they will be very useful in the operation and testing of the suspension, for alignment as well as for damping.

The design of the test masses themselves has a strong impact on the performance, and will require careful thought and testing. The displacement of the mirror surface due to internal thermal noise has a white spectrum below the lowest resonant mode, and contains noise peaks at each resonance. The thermal noise advantage gained at low frequencies by using a large mass has to be weighed against the fact that a large mass has its resonances at lower frequencies than a smaller mass. In addition, the white noise floor is at a higher level if the resonances have lower frequencies. For this reason it will be necessary to undertake an investigation of the internal normal modes, in order to understand how their frequencies depend upon the shape of the mass. This is most likely accomplished by actual measurement on scale models, since for reasonable aspect ratios the calculations are very difficult. To avoid introducing a low frequency resonant motion of the mirror in its clamp to the test mass, it may be desir able to have the mirror and the mass be one block of material. Knowledge of the Q of the modes in various possible materials is also quite important. It should be noted that not all internal modes are equally deleterious to the antenna's performance -- only certain modes (such as longitudinal modes) will affect the optical path length. Preliminary estimates of the size of the internal thermal noise indicate that it is not a serious problem at the 10^{-17} cm/sqrt(Hz) level, but will become important if shot noise is reduced an order of magnitude or more below that.

Testing the suspension has several aspects to it. The mechanical transfer function, or isolation, is presumably linear over a large range in amplitudes, so the isolation can be tested by driving the system with large amplitude signals. This puts rather modest demands on the sensitivity of the transducers. This procedure tests most of the important aspects of the suspension, since isolation of external vibration is what it is designed to do. Indirect information is also available concerning thermal noise, through study of the resonant frequencies and their quality factors.

To truly verify that the residual motion, including Brownian motion, is sufficiently low appears to be a formidable task. This is because we would like to show that residual motion spectral density is below a level of a few times 10^{-17} cm/sqrt(Hz) if the antenna is to be shot noise limited with 100 Watts of modulated laser power. Until we have an interferometer operating at the design sensitivity at either Caltech or MIT, we will not have a transducer sufficiently quiet to explicitly verify that the suspension is functioning properly. This is not as bad as it sounds, since it ought to be possible to model the thermal noise based on measurements of the resonant frequencies and quality factors. When this is combined with the product of the measured transfer function and the ambient noise spectrum, the residual vibration of the end masses can be predicted with confidence.

Further Suspension Development

Active isolation systems are an attractive solution to the long-range goal of low noise in the 10 Hz region or below (Robertson et al., 1982; Saulson, 1984). In current passive designs, the limit to low frequency isolation is set by the fact that a 1/2 Hz pendulum already has a length of 1 meter, and the resonant frequency is decreasing only as the square root of the length. Compact devices with low resonant frequencies can be made (by carefully balancing the restoring force of a spring with a destabilizing force of gravity, for example in an inverted pendulum). Schemes such as this suffer from the fact that the oscillator's Q is essentially equal to the internal Q of the spring material, while a pendulum Q can be much higher because most of the restoring force comes from gravity. A feedback system which nulls the displacement of the test mass with respect to the mass from which it is hung can give the suspension an effective resonant frequency which is much lower than its natural frequency. Working models of such systems have been constructed recently at Glasgow, JILA, and MIT.

The challenge of making substantial improvements in suspension performance is twofold. Firstly, a large increase in isolation requires a large servo loop bandwidth. (Isolation starts at a frequency $f_L=f_0^2/f_{bw}$, improves until f_0, then levels off until f_{bw}, above which frequency the servo loop yields no improvement.) The bandwidth is likely to be limited by the extra phase shifts due to internal mechanical resonances in nominally rigid parts of the suspension. Secondly, the noise level in the feedback loop itself must be low enough so that it does not introduce substantial mechanical noise on the test mass. If readout noise is not to be the limiting factor at 10 Hz, then we require a transducer with noise at or below 10^{-15} cm/sqrt(Hz). This is quieter than is needed for the simpler passive system, so it is likely that additional development work will be necessary. When these challenges are met, there remains the requirement that cross-coupling between motion in one direction and feedback in an orthogonal direction be held to an insignificant level.

In spite of these technical challenges, the promise of extending gravitation wave sensitivity to lower frequencies is so great that it is worth a substantial effort to solve them. Once a successful passive suspension design is demonstrated as a model for installation in a first generation system, we intend to begin development of an active isolation system. A great deal of the experience gained in building the passive systems will, of course, be directly applicable to the active system as well. In particular, identification of the mechanical resonances which have a deleterious effect on the servo loop bandwidth will already have been performed in the testing of the passive suspension. Development of the ultra-low noise transducer system is a separate project which will be the first order of business once the passive suspension design is completed.

ALTERNATIVE INTERFEROMETER CONCEPTS

The primary effort is to develop the first generation receivers for the large baseline facility. The expectation is that these will be similar to the Fabry-Perot cavity or multi-pass Michelson systems now being developed in the prototypes. In this section of the proposal we describe two interferometer concepts (which have not been demonstrated) that may find application in the large baseline system. These concepts might merit consideration either as second generation receiver designs or if unforseen difficulties arise in the implementation of the first generation receivers. The first is the application of a concept described by Drever here suggested by P. Linsay as a technique to search for high frequency gravitational radiation. The second is a concept that has occurred to both R. Weiss and R. Drever to make delay line Michelson interferometers more compact and simultaneously reduce the effect of scattering by frequency tagging the individual beams.

High Frequency Gravitational Wave Receiver

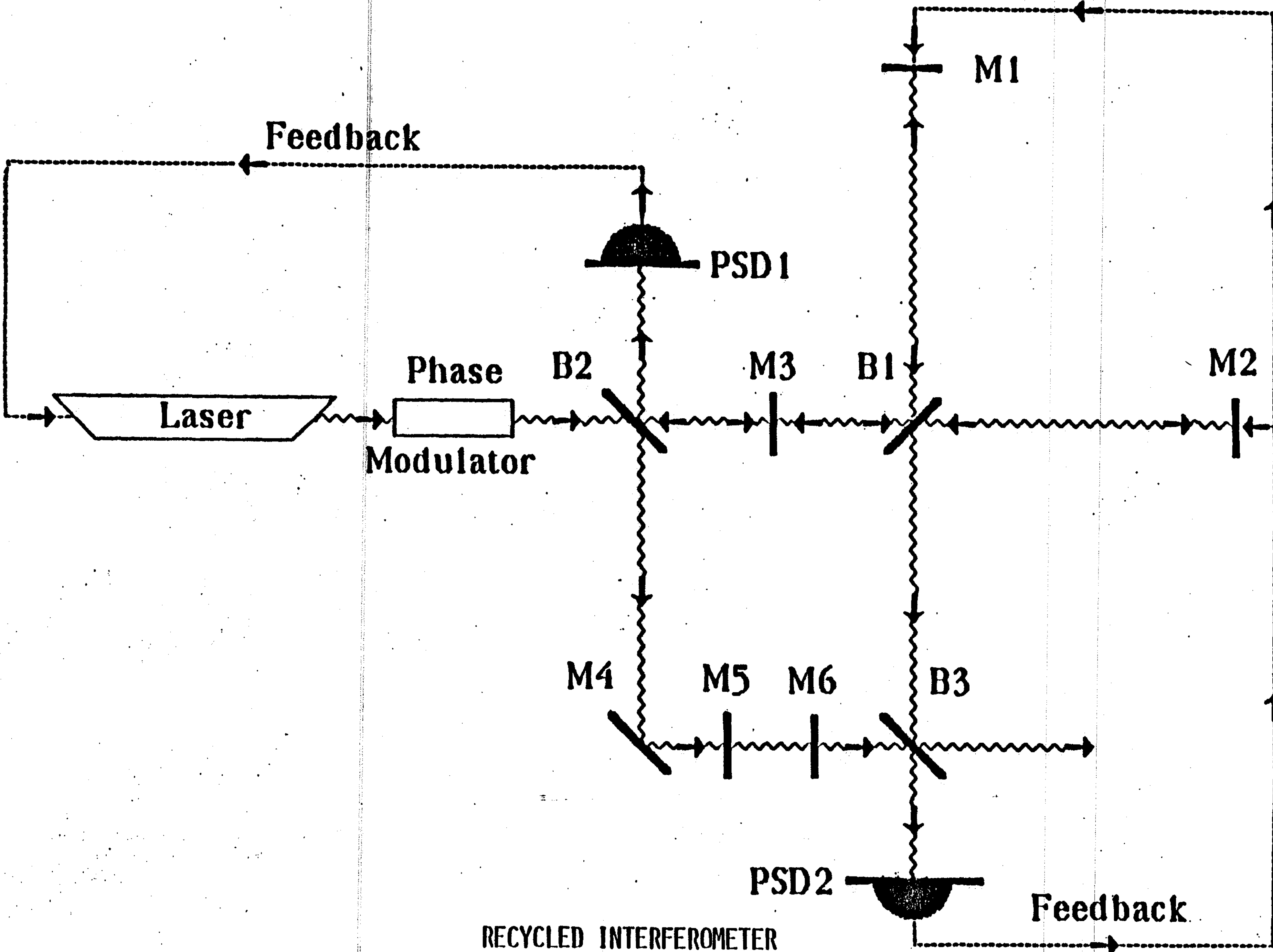
The current generation of short (less than 100 meters) gravity antenna interferometers achieve their sensitivity in two ways: by increasing the storage time of the light in the interferometer arms and by increasing the light power in the antenna. It is straightforward to show that the sensitivity of an antenna is proportional to T_{stor}^{-1} but only improves with laser power as $I^{-1/2}$. Consequently the present generation of antennas has concentrated on improving sensitivity by increasing storage time rather than laser power. One can also show that the basic frequency response to gravitational radiation goes as

$$\sin(\pi f T_{stor})/(\pi f T_{stor}).$$

for an interferometer. Most of the useful frequency response of the antenna is below $1/T_{stor}$. One rapidly loses sensitivity at high frequencies. This was not a problem until recently because the short antennas had storage times of the order of one microsecond which meant that systems were sensitive to frequencies as high as one megahertz. If one had sufficient data taking bandwith one could in principle detect a one solar mass black hole which radiates into quasi-normal modes with a frequency of roughly 16 kHz and into harmonics at even higher frequencies. The new long antennas (5 km) being contemplated also plan to achieve their sensitivity by increasing the storage time of the laser light. In current designs this storage time is as long as one millisecond which implies a poor frequency response above one kilohertz. In conjunction with a lower frequency limit of roughly one hundred hertz imposed by local seismic noise one has reduced the signal bandwidth of what was once a broad band device from many kilohertz to only a few hundred hertz. In principle one could have a frequency cutoff of 30 kHz in an antenna with 5 km arms if the light only travelled to the end of an arm and back once. The loss in sensitivity due to reduced storage time would then have to be replaced by an equivalent increase in stored light power in the interferometer.

A possible interferometer design which would have both high signal bandwidth and high sensitivity is shown in Figure 5. Its performance is achieved by using the techniques of "recycling" and laser stabilization (Drever, 1982).

Referring to the figure, mirrors M1 and M2 and beamsplitter B1 form the basic Michelson interferometer which is intended to detect gravitational radiation. As with other interferometric antennas the three optical elements are free to move in inertial space and this is accomplished by, say, suspending each one on a pendulum. The partially transmitting mirror M3 is



RECYCLED INTERFEROMETER

FIGURE 5

the recycling mirror which effectively turns the entire interferometer into a large Fabry-Perot cavity with an unusual geometry. Phase stable light tuned to a cavity resonance enters through this mirror and builds up to a maximum intensity determined by the mirror reflectivities and the absorption of the optical elements. The laser frequency is locked to a cavity resonance by means of a phase modulation technique. The phase modulating crystal PM adds modulation sidebands to the laser electric field that differ in frequency by νm from the central frequency of the laser light. These side bands are directly reflected from the mirror M3 whereas the central frequency electric field passes into the cavity if it is on resonance. Any light returning from the cavity interferes with the reflected sidebands and is sensed at the modulation frequency νm by the phase sensitive detector PSD 1. This feedback signal is then used to adjust the laser frequency to minimize the intensity of the light returning from the cavity. The readout of the interferometer is performed using similar techniques. Some of the laser light is passed through the cavity formed by the mirrors M5 and M6 which acts as a filter and only passes one of the modulation sidebands, for example, the one at $+\nu m$. This is combined with the output of the interferometer at the beamsplitter, B3, and the beat at νm is detected by the phase sensitive detector, PSD 2. This feedback signal is then used to adjust the positions of mirrors M1 and M2 so that the output of the interferometer is nulled.

If the mirrors 1 through 3 have reflectivites of R and the losses in the cavity are, A, the stored power in the cavity is greater than the light power incident on the cavity in the ratio

$$\frac{I_{cavity}}{I_{injected}} = \frac{1}{1-R(1-A)}^{2}$$

If one uses mirrors with R=0.9999 (this is currently available) and A is less than roughly 5×10^{-6} the cavity power would be 10^4 times the injected power and the sensitivity of the interferometer would be equal to the sensitivity of a multi-pass system with 100 beams in each arm of the interferometer. (Even with 100W of injected power and thus 10^6W of stored power, the photon shot noise is larger than the photon pressure noise above 10Hz.) In order to achieve such low losses the beam splitter would probably have to be made using the same high quality coatings as used for the mirrors. Power densities in the cavity will be manageable. A diffraction limited spot in a 5 km cavity is typically 3 cm in radius. If the injected power is 100 W the stored power will be 10^6 W and the intensity on the mirrors would be 3.5×10^4 W/cm^2 which is well within the capabilities of present day coatings.

Since the parameter A includes all losses from the cavity no more than 5×10^{-6} of the stored power can leave the interferometer at the output. This implies that the servo must be able to hold the phase difference between the arms of the interferometer to less than 5×10^{-4}.

A Frequency Tagged Multi-Pass Michelson Interferometer

The delay line Michelson has the property that the interference of the light takes place after the beams have made many transits in the interferometer arms. If the travel times are close to equal in the two interferometer arms the interference fringe becomes insensitive to the frequency of the light (white light fringe). Operating at this point reduces the requirements on laser frequency stabilization and permits the frequency "whitening" technique for the suppression of scattering. This is the attractive attribute of the delay line Michelson configuration.

The unattractive part is that the beam separation, to accomplish the multi-pass, is done geometrically which necessitates larger mirrors than are needed for a Fabry-Perot cavity. An alternative would be to let the multiple beams spatially superpose but to give each beam a separate identity by making its frequency different from the others. Besides allowing smaller mirrors, this strategy would also reduce the noise from scattering without the need to "whiten" the input light. The frequency separation of the beams must be made larger than the gravitational wave frequencies. One scheme for doing this is to use a Fabry-Perot etalon with transmission maxima at frequency intervals Δf as the input mirror of a delay line. With each transit of the beam through the arm the frequency of the light is shifted by an amount δf either by moving the mirror at the other end of the arm at constant velocity or, by shifting the frequency with a travelling wave phase modulator or by an acousto optic shifter. The returned beam is moved off the transmission resonance of the etalon and trapped by reflection until after n transits, $n = \Delta f/\delta f$, the beam reemerges from the delay line to interfere with the beam in the other arm which has been treated in the same manner. The scheme automatically reduces scattering pertubations and does not require precision frequency stabilization. The storage time of the arms can be made variable by changing the etalon spacing.

ENGINEERING TESTS OF A SAMPLE VACUUM SYSTEM FOR THE LARGE BASELINE FACILITIES

The final decisions on the vacuum system components for the antenna facilities will be made in the engineering design to be carried out in 1985 and 1986. The engineering design will set specifications and identify vendors for the type of high vacuum pumps, valves, bellows expansion sections, flanges, tube manufacture and material, outgassing and cleaning strategy and the instrument vacuum containers. The expectation is that most of the vacuum system components will be commercially available. It seems prudent to assemble a small scale test vacuum system of the same design using the identical components as those specified for the large baseline system before the full scale procurement and construction of the facilities.

A test system would indicate if there are flaws in the design and would determine the following parameters important to the gravitational wave project that are not precisely predictable in a design that does not include the construction of hardware.

1. the ultimate pressure
2. the molecular constituents of the residual gas
3. the short period temporal behavior of the outgassing as a function of wall temperature
4. the short period pressure fluctuations both impulsive and periodic produced by the high vacuum pumps
5. the outgassing rate as a function of bake temperature
6. the porosity characteristics of the specific tubing design
7. the leak rate of the valves

Each vacuum system has its own idiosyncracies even when two are made as identical as possible. For example, the leaks are rarely in the same places. For this purpose a test system is of little value but there is merit, once having eliminated the leaks, to look at the system's intrinsic performance.

The test of a sample vacuum system could be done at a subcontractor, JPL, Caltech or MIT. We propose to carry this out at MIT for several reasons. Two people in the group, R. Benford and F.J. O'Brien, have experience with large vacuum systems and an interest in the tests themselves. Benford and Tucker, a physics undergraduate student, have for the last nine months been carrying out an experiment to look at short period (10 Hz - 5 kHz) pressure fluctuations in a small vacuum system. The results indicate that the fluctuations in the number of molecules residing in a fixed volume do indeed obey classical statistical mechanics. This experiment was done in a small glass system. They have constructed a much larger apparatus to do the same experiment in a stainless steel tube pumped by a liquid He trap.

A second reason for doing this at MIT is that we have need for a larger vacuum chamber to test both full scale optics and suspension designs to be used in the large baseline antenna.

The costs of the test vacuum system listed in the enclosed budget have been estimated on the basis of the A.D. Little design.

DATA ANALYSIS

The most important part of any experiment, once the equipment is working, is the data analysis. At this writing, no laser interferometer experiment has made an attempt to search for gravity waves with the exception of one specialized search for a signal from the millisecond pulsar (Hereld). Since these are broadband antennas the data analysis techniques developd for bar antennas are not applicable and new generalized methods of searching for signals will have to be developed. The method of analysis will depend on the nature of the signal which can be placed in three categoriers: pulses; periodic waves; and stochastic sources. Each type of signal requires a different strategy and will be treated in turn below. As the current generation of interferometers is completed these techniques will be used and undoubtably others developed as well.

<u>Impulsive Sources</u>

The only reliable method of searching for impulsive sources is to look for a coincidence between signals from two (or more) well separated antennas. Since the output of each antenna is noisy each signal will be required to be larger than a certain threshold to prevent accidental coincidences between noise pulses from overwhelming true signals. One would like this threshold to be as low as possible in order to have maximum sensitivity to incoming gravity waves. This in turn implies that both antennas should be as noise free as possible and be parallel to each other so that they both have the same antenna response to an incoming wave. It is possible, if for example they are oriented at 45 degrees with respect to each other, for one to have full response and the other to have no response to an incident wave. Analysis of the frequency spectrum of pulse candidates is straightforward and well within the currently available computation techniques. Since we will be dealing with Fourier transforms of a few thousand points and the data rate will be of the order of ten kiloHertz, standard array processors will be able to analyze this data in real time.

One filtering strategy is to scan the incoming data with templates that select a particular wave form. Detweiler and Nakamura and coworkers (Detweiler, 1978; Nakamura et al., 1983, 1984) have predicted the pulse shapes generated by objects dropping into black holes. A match between the incoming signal and the template would be a possible indication of the detection of a gravitational pulse. The technology required to perform these computations is available and does not require significant development.

Periodic Sources

The high resolution search for unknown periodic sources presents a formidable problem in data anlysis and computation encompassing two difficulties. The first difficulty is the enormous size of the Fourier transforms if the signal is to be integrated for more than a few minutes. Assuming a bandwidth of 2 kHz the Nyquist criteria requires that the data must be sampled at a rate of 4 kHz so that in a little over four and half minutes one has sampled a million points. It is currently possible to perform a 10^6 point Fourier transform in aproximately 2 minutes on a general purpose high speed CPU not optimized for this type of calculation. (This has been done on a FPS 164 arithmetic processor, Douglas Wilmarth, Floating Point Systems, private communication.) A good array processor is capable of performing a 1024 point Fourier transform in 2 to 3 milliseconds. Extrapolating from these examples, the design and construction of an array processor that can perform a million point transform in under five seconds is probably well within the capabilities of current technology. If one would like to achieve the resolution possible with an integration time of 10^6 seconds it is necessary to perform a transform on 4×10^9 points of data. This can be done in real time if the difference between the data taking time and computation time is not completely used up by the time needed to store and retrieve data and intermediate calculations on mass storage devices. At its most optimistic this represents 5.6 hours of continuous computation compared to 11.5 days of data taking so that, considering the Doppler shift discussed below, one could investigate 50 points in the sky as the data was being taken. In a years time one could study roughly 1500 points in the sky. If one were willing to scan at lower resolution full sky coverage may be possible in a search for periodic sources. Although the hardware is essential to the analysis one cannot neglect the fact that the huge amount of data to be scanned for candidates will require the development of powerful software tools to search for them and test their statistical validity.

The second problem encountered in searching for periodic sources is the Doppler shift of the incident gravity wave due to the earth's daily rotation and annual motion around the sun. The Doppler shift spreads the signal energy over a frequency band proportional to the product of the signal frequency and the earth's velocity relative to the source. The energy is distributed into modulation sidebands centered on the signal frequency and separated from it in frequency steps that are multiples of 1.2×10^{-5} Hz (=1/day) and 3×10^{-8} Hz (=1/year). (With the integration times contemplated we will not be able to resolve sidebands at multiples of 3×10^{-8} Hz.) A simple calculation shows that the earth's rotation will spread a 1 kHz signal over a frequency bandwidth of 5.41×10^{-4} Hz. This frequency resolution can be achieved in a half hour integration of the signal. If one integrates the signal longer than this without correcting for the Doppler shift one will start to reduce the signal to noise ratio because the signal will be distributed into more than one frequency bin. A major difficulty now becomes apparent, in order to correct for the Doppler shift the position of the source must be known to an accuracy of 2×10^{-3} radians (6 minutes of arc) to achieve the resolution possible in 10^{6} seconds of integration. With present day computer technology a generalized search for periodic sources of both unknown frequency and position is not possible. This could change with the rapid development of supercomputers and is therefor one of the interesting computational problems associated with this project.

Without further improvements in computers several options are available. One can simply guess at likely locations of sources and make the appropriate correction. Possible choices might be the center of our galaxy, M31, several pulsars, and quasars. This strategy carries the risk of bad luck, as the sources might be at locations different from the ones that were searched. The choice of an efficient computational technique can speed up the search a great deal and allow a large number of points in the sky to be investigated. The important fact to keep in mind is that addition is much faster than multiplication. Suppose that one wanted to search for candidates in M31 using the resolution possible in a 6 hour integration. One could break the time series into approximately 30 minute segments, co-add them, and then perform the Fourier transform to search for sources. (Before co-addition one would apply a simple time shift to the data points to remove the Doppler shift at all signal frequencies.) Since co-addition narrows the bandwidth by roughly the number of segments added, one would have to choose several different segment lengths to cover the full spectrum, in the example this would be 12 different lengths, and Fourier transform each co-added segment. Even though a number of transforms must be performed it is always faster to Fourier transform several short time series than it is to transform one long one, and can be considerably faster if the long transformation involves moving large amounts of data and precomputed constants on and off mass storage devices. The co-addition of the time series can be done in real time if desired so that essentially no time would be lost for this step of the calculation.

Stochastic Sources

A search for a stochastic background of gravitational radiation requires the cross correlation of very long time series of two gravity antennas. The long time series are required since the error on measuring a correlated source of noise in the presence of uncorrelated noise only improves as $T^{1/4}$ where T is the integration time. The problems in performing this computation are much the same as those involved in a long integration to find a periodic source (except the Doppler shift can be ignored) if no segmentation and co-addition of the time series is performed.

SCIENTIFIC GUIDANCE OF THE DESIGN AND CONSTRUCTION OF THE FACILITIES

The task of preparing the detailed engineering design of the facilities will be performed by an outside contractor as described in the accompanying joint proposal. Our experience in carrying out a study of a long baseline system with industrial engineering contractors and consultants was that scientific guidance of the effort was essential at all stages. Merely setting a list of specifications and waiting for the results could be a prescription for a disaster. The members of the scientific research groups will inevitably become involved in technical aspects of the engineering design, in particular in guiding trade offs by performing calculations and making estimates of the impact of various design decisions.

To facilitate the technical supervision of the engineering design it will be useful to designate individuals on the scientific staff as "experts" on the different subsystems of the facilities and for the overall system engineering function. For example, one team member will be primarily concerned with the vacuum system, another will check on construction and installation, a third will consider the electrical power supply and distribution, and so on. The role of expert will not entail any management authority. Rather, the experts will work in conjunction with the Project Office to aid in verifying that the product of the engineering design will meet the specifications. Much of this activity will probably be associated with the preliminary and Critical Design Reviews, as described in the proposal for the engineering design.

Again, during the procurement and construction phases there will occur demands on the time of the team members as problems arise.

The manpower estimates made in this proposal assume that part of the time of the research staff will be devoted to these activities.

FIRST GRAVITATIONAL WAVE SEARCHES, DETECTION SYSTEM AND RECEIVER DESIGN

The Caltech and MIT research groups have agreed that the highest priority for the first use of the facilities will be given to a joint search for gravitational radiation. The experiment will be jointly designed, constructed, and operated by the two groups.

The experiment strategy and the design of the receivers to implement this strategy will be decided as late as possible in the project to benefit from the advances being made in the prototypes but with sufficient lead time so that receivers can be ready for tests as the facilities become available. Our expectation is that the decision will occur between the end of the facility engineering design and the start of facility construction.

We expect that the experiment plan and common receiver design will be formulated in meetings of the Caltech and MIT research groups extending over several months. One model is that these meetings will result in a mutually agreed upon division of responsibility for the subsystems of the experiment between the groups. By this means one would hope to match the interests and skills of the individual scientists and engineers in the two research groups without redundancy. The schedule, coordination and budget for the joint effort will be managed through the Project Office.

The construction and testing of the receiver components will be a mix of university laboratory research and industrial subcontracts. Many of the specialized techniques that have been developed in the research groups cannot easily or economically be turned over to industrial contractors so that a substantial part of the actual hardware construction will take place at Caltech and MIT.

Although the joint meetings to decide the experiment strategy and receiver design will not take place for several years; it is worth indicating in this proposal, which is intended to give a view of the research program for the next five years, an example of how the subsystems might be structured. Presently identifiable subsystems are the following.

Overall Antenna Subsystems

1) systems analysis of the antennas

2) data formatting

3) data analysis and storage

4) real time links to other astrophysical observations (x-ray, neutrino, radio and optical telescopes)

5) inter site communications link

Subsystems Internal to a Site

1) systems analysis of the instrumentation

2) data acquisition system

3) local disturbance monitoring instrumentation (magnetic fields, seismicity, acoustic noise, cosmic ray showers, radio frequency interference, pressure fluctuations in vacuum system, temperature, line power fluctuations, fluctuating gravitational gradients)

4) computer control, status and monitoring of the receiver, housekeeping functions (pointing servos, fringe lock servo, frequency lock servo, laser power monitor, laser cooling system, etc.)

5) intra site communication links

Subsystems internal to a Receiver

1) high power single mode lasers
2) amplitude and frequency stabilization systems for the lasers
3) electro optic phase modulation and drive electronics
4) cavities or optical fiber for mode cleaning
5) mode matching optics
6) interferometer arm mirror and coatings (specification, test and procurement)
7) suspension design and construction (controllers and electronics)
8) pointing and alignment servo electronics and optics
9) fringe lock electronics and optics
10) photodetectors and RF signal electronics

This is of course a partial list not all entries have equal substance. During the course of the project the headings will become considerably sharpened and better defined. In this proposal we assume for manpower estimates that roughly half of the subsystem design and construction will take place at MIT.

EXCHANGE PROGRAM WITH THE GRAVITATIONAL RESEARCH GROUP AT THE MAX PLANCK INSTITUTE IN MUNICH

The group formed under Professor Billing, now retired, at the Max Planck Institute has been active in the development of laser gravitational wave antennas since the mid 1970's. They have constructed and tested a 3 meter version of a delay line Michelson interferometer and have recently begun the successful operation of a 30 meter system. In the course of their research they have developed many of the techniques now used in the interferometric antennas. At the moment they are demonstrating the best displacement sensitivity in the prototype antennas.

David Shoemaker one of the people involved in prototype development at MIT is now at the Max Planck Institute and through him the coupling between the two groups has become tighter than previously.

The Max Planck Group has expressed interest in eventually constructing a third large baseline antenna in Europe, to be run in coincidence with the Caltech-MIT antennas. The plans for this German project are still tentative. We are encouraging this initiative as it would provide a substantial scientific benefit to the entire field. A third antenna of comparable sensitivity would allow better source position determinations and increases the statistical significance of any detections.

The plan we have is to continue the exchange of scientific personnel between the Max Planck Institute and MIT with typically one person of either group in residence at the other for a period of a few months to a year. No exchange of funds is expected to take place between the two institutions for this program.

PROPOSED SCHEDULE, MANPOWER AND BUDGET

Figure 6 shows the anticipated schedule for both the overall project and for the work to be carried out at MIT. The proposed project schedule is described in more detail in the accompanying joint Caltech-MIT proposal. Here we discuss the schedule and manpower requirements for the MIT part of the effort.

An important consideration is that for the first time in the history of gravitational radiation research at MIT the project will be carried out at a rate and on a scale to raise the hope that the protracted technical effort will produce scientific results in gravitation. This has the consequence that one can involve junior faculty in the program without their having to divide time between this and what might be considered by some to be less risky but more productive physics research. Furthermore, it becomes possible to offer meaningful physics rather than purely technical doctorate theses topics to graduate students.

Figure 7 shows the proposed manpower distribution arranged by topic and year. In the manpower and budget estimates the assumption is made that all the scientific manpower for the project and the specialized engineering manpower required for the development of the receivers and their operation will be included in the separate five year proposals of Caltech and MIT. The equipment purchased for the joint receivers as well as the equipment to fulfill the data analysis and instrumentation requirements of the detection system will be funded by the general grant for the facility. The general grant will also support the manpower needs specific to facilities operation such as maintanence and safety.

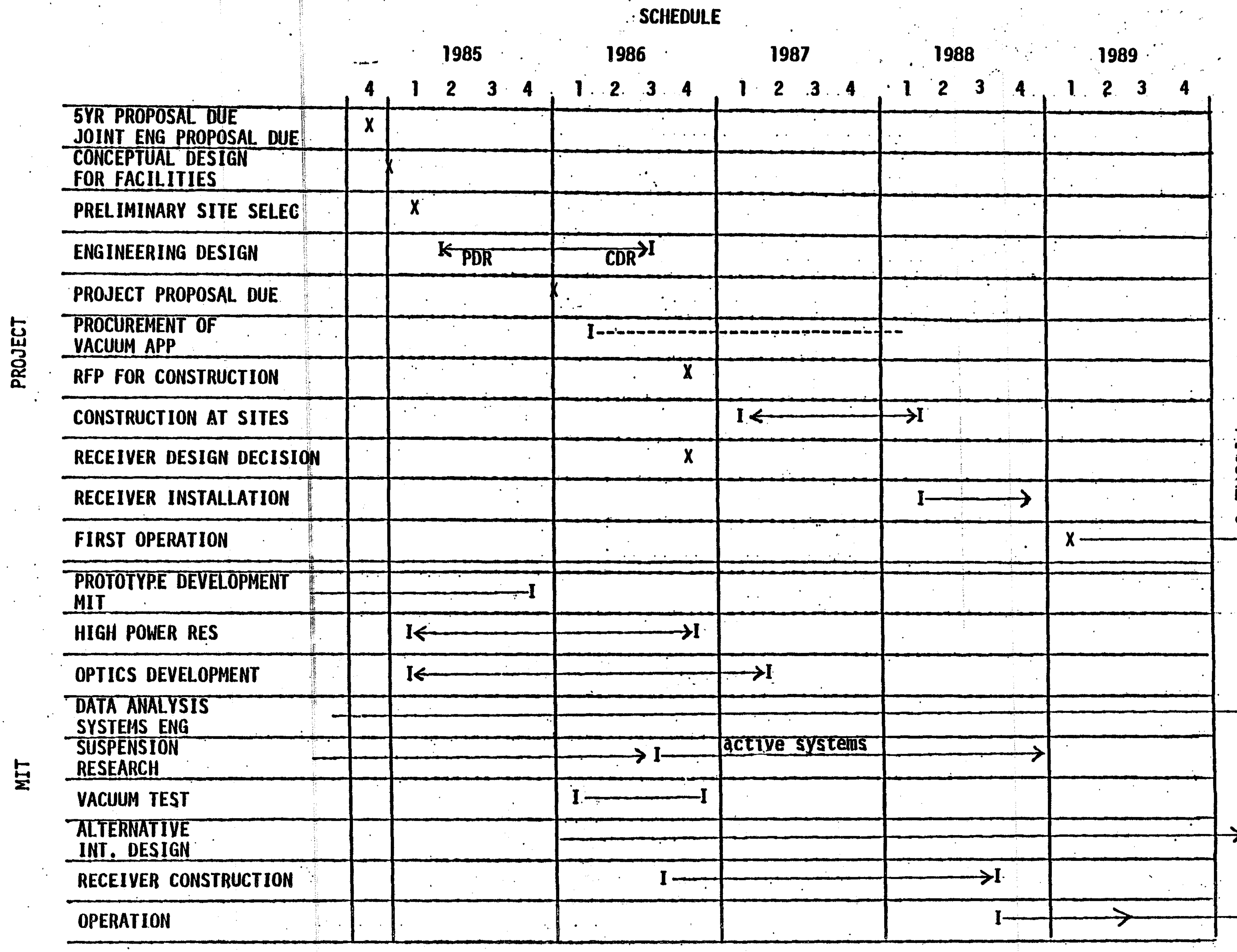

SCHEDULE
1985
1986
1987
1988
1989
4
1 2 3 4
1 2 3 4
1 2 3 4
1 2 3 4
1 2 3 4
PROJECT
5YR PROPOSAL DUE
JOINT ENG PROPOSAL DUE
CONCEPTUAL DESIGN
FOR FACILITIES
PRELIMINARY SITE SELEC
ENGINEERING DESIGN
PDR
CDR
PROJECT PROPOSAL DUE
PROCUREMENT OF
VACUUM APP
RFP FOR CONSTRUCTION
CONSTRUCTION AT SITES
RECEIVER DESIGN DECISION
RECEIVER INSTALLATION
FIRST OPERATION
MIT
PROTOTYPE DEVELOPMENT
MIT
HIGH POWER RES
OPTICS DEVELOPMENT
DATA ANALYSIS
SYSTEMS ENG
SUSPENSION
RESEARCH
active systems
VACUUM TEST
ALTERNATIVE
INT. DESIGN
RECEIVER CONSTRUCTION
OPERATION

FIGURE 6

FIGURE 7

MANPOWER DISTRIBUTION AT MIT

	1985	1986	1987	1988	1989
senior faculty	2	2	2	2	2
junior faculty	0	1	2	2	2
prototype	½/ 0 /1	----	----	----	----
high power lasers	½/ ½ /0	1/ ½ /½	½/ 0 /½	----	----
optics	½/ 0 /0	¾/ 0 /½	½/ 0 /½	----	----
suspension	½/ 1 /1	1/ 1 /1	½/ 1 /1	½/ ½ /0	½/ ½ /0
facilities engineering	½/ ¼ /0	½/ ¼ /0	½/ ¼ /0	----	----
vacuum	0/ ½ /0	0/ 1½ /0	----	----	----
system engineering data-analysis	½/ 0 /1	½/ 0 /1	¾/ 0 /1	1½/ 1 /2	2/ 0 /2
facility receivers	----	----	2/ 2¾ /2	3/ 2½ /3	----
alternative receivers	----	¼/ 0 /0	¼/ 0 /0	1/ 0 /1	1/ ½ /1
operations	----	----	----	----	3½/ 3 /3
TOTAL	3/ 2¼ /3	4/ 3¼ /3	5/ 4 /5	6/ 4 /6	6/ 4 /6

Key to the TOTAL entries (research scientist / technical and engineering / graduate student):

- graduate student
- technical and engineering
- research scientist

CONSTANT: 3 undergraduate students for the summer
1/2 secretary

The budget for scientific and technical manpower throughout the five year period is well defined. The equipment budget for the first two years is specified while for the remaining three it is not itemized. The equipment needs depend strongly on the division of tasks between the two research groups during the course of facility receiver developments and, at the end of the grant, on the division of tasks during facility oeprations. These issues will be decided during the course of the next several years.

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"Vibration Isolation for Broad-Band Gravitational Wave Detectors" P.R. Saulson, Review of Scientific Instruments 55, 1315 and Bull. Am. Astr. Soc. 14, 940 (1984)

"Transfer Function of Interferometric Gravitational Wave Antennas" Y. Gursel, P.S. Linsay, P.R. Saulson, R. Spero, R. Weiss, S.E. Whitcomb (paper in preparation)

"Analysis of a Multipass Interferometer Using Tagged Light Beams and a Compact Geometry for Gravitational Research" (paper in preparation)

APPENDIX IV

NATIONAL SCIENCE FOUNDATION

PROJECT SUMMARY

FOR NSF USE ONLY			
DIRECTORATE/DIVISION	PROGRAM OR SECTION	PROPOSAL NO.	F.Y.

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

Massachusetts Institute of Technology

ADDRESS (INCLUDE DEPARTMENT)

Center for Space Research
Massachusetts Institute of Technology
37-287
Cambridge, MA 02139

PRINCIPAL INVESTIGATOR(S)

Rainer Weiss, Principal Investigator

TITLE OF PROJECT

"Interferometric Broad Band Gravitational Antenna"

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

The aim of the research is to detect gravitational radiation of astrophysical origin. The direct detection of gravitational radiation has been a first rank goal in both physics and astrophysics for the past decade. The observations would provide confirmation of a major prediction of relativistic gravitation -- the waves themselves. They could determine the propagation speed and polarization states of the radiation field and provide detailed information of relativistic gravitation in the untested strong field -- high velocity regime at the radiation sources. In an astrophysical context, the detection of gravitational radiation will most likely open a new view on the universe.

The technique of laser interferometry between "free" masses is used to determine the gravitational wave metric perturbations. A detection system comprised of two 5 km long antennas separated by continental baselines is required to achieve sensitivities that will intersect present estimates of the astrophysical gravitational wave flux incident on the earth.

The project is a joint effort of the California Institute of Technology and the Massachusetts Institute of Technology. The plan is to have the detection system operational before the end of this decade.